Can we use the processes of physics to guide physics instruction?

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Abstract

Educational studies indicate that students accept all knowledge as “facts,” without understanding how it was constructed. This paper describes one of the ways in which physics knowledge is constructed and organized by physicists, and suggests how to replicate these construction processes and this organization in physics instruction. It offers a way to help students learn physics through answering the question “what is it that we know, how do we know what we know and why do we believe that this is true?” and acquire scientific epistemological beliefs.

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Introduction

Could it be that students' lack of success in physics is due to the way it is taught?[1] Usually in a physics course the students first hear lectures that reiterate material from the text, then solve well-defined quantitative problems in recitations or for homework. Experiments are usually done in a separate lab course. Students struggle to connect these largely unrelated pieces of conceptual and process knowledge.[2 ,3, 4]

What students fail to acquire in a typical introductory classroom is a coherent knowledge of the structure of physics.[5] The absence of this structure turns many students away from physics and decreases the level of confidence of those who continue to study it.[6] Physicists understand the knowledge structure[7] as a "small number of concepts that are the basis for many diverse applications".[8] Students approach every problem as new without recognizing the basic principles behind it.

But there is another aspect of knowledge structure that can be used to strengthen conceptual understanding in physics and to make learning easier. This is epistemological knowledge, or the understanding of what elements constitute physics knowledge and how physicists construct knowledge. Students have their own epistemological beliefs[9]. If you ask a student who has just completed an introductory physics course to state Newton's second law, you may well hear "Force equals mass times acceleration". If you ask the same person how she/he knows the law, you will most likely hear: "Why, you told us." For the students knowledge consists of facts to remember, and most of them are happy to accept any idea if it comes from an authority without questioning its history or validity. Their epistemological beliefs are different from the epistemological beliefs of physicists.

Why is it important that students recognize how physics knowledge is produced and appreciate its structure? Recent studies by the American Institute of Physics,[10] the new engineering ABET accreditation standards,[11] the U.S. Department of Labor,[12] and the National Science Foundation[13] have reported the characteristics that the 21st century workplace desires for future employees in science and engineering. Former physics majors working in industry spend much more time designing products and designing, performing and analyzing the results of scientific investigations than they do using pure physics knowledge. Two of the eleven engineering ABET accrediting criterion 3 requests include the desire for engineering graduates who have: an ability to design a system, component, or process to meet desired needs; and an ability to design and conduct experiments, as well as to analyze and interpret data. Both these studies are asking for graduates who have learned the practice of science and are able to learn on their own in the future rather than the regurgitation of scientific facts and laws.

Knowledge in science and in the world of technology changes rapidly. But the processes of constructing that knowledge and using it effectively remain fairly stable over time. These processes are important and are the desired outcomes of our education as indicated by those in the workplace.

Physics educators agree that focusing on these processes is extremely important. McDermott et al.[14] suggested, "physics should be taught as a process, not as an inert body of information". This point of view is supported by Duchovich et al.,[15] Arons,[16] Romer,[17] Zollman,[18] Hammer,[19] Elby[20], and many others. Tyson et al. emphasized that "the procedures used by learner to represent and organize knowledge and the learner's epistemology and ability level are all crucial factors that influence the manner in which students learn."[21]

In this paper we will discuss an approach to teaching physics, which helps students to undergo a transition from their authority-based naive epistemological beliefs (their understanding of what constitutes physics knowledge and how they acquire it) to epistemological beliefs[22] of practicing physicists (what constitutes physics knowledge and how physicists acquire it). We will first discuss the epistemology of physics in its ideal form and then show how to structure instruction in an introductory physics course so that the students acquire knowledge in ways similar to that used by practicing scientists.

Epistemology of physics: Structural elements

In this section we will discuss the structural elements that constitute physics knowledge. We call structural elements simple constituent parts of physics knowledge that are context independent. These structural elements of physics are

phenomena,
models of phenomena and models of objects,
physical quantities,
instruments to measure physical quantities,
laws that relate these quantities and predictions based on the laws,
experiments especially designed to test predictions, theories, and
applications based on all of the above.

Examples for each are shown in Table 1.

The structural elements of physics knowledge are analogous to structural elements of any system. For example, most transportation vehicles have engines, transmissions, drive trains, and cabs for passengers, brake systems, tires and so forth. If a person understands what these parts are and how they work together for one vehicle type (such as a car), she/he can more easily understand how other vehicle types, such as pickup trucks, and buses work. The first step in building physics an epistemological knowledge structure is recognition of these elements in a given conceptual area. The next step is building epistemological connections among the elements. By epistemological connections we mean the place and relationships among the structural elements in the process of building physics knowledge. Building these connections we will use some of the processes that scientists use to construct their knowledge. Of course we understand that these processes with be simplified and idealized compared to real scientific inquiry.

Epistemology of physics: The relationships among the structural elements

In this section we will relate processes by which physicists acquire knowledge to the structural elements of physics thus building epistemological connections among the elements.

What are these processes of real science? There is no single method for doing science. But if we tried to find most common patterns in scientific discoveries, we would see that a great deal of physics comes from purposeful observations of natural *phenomena*—observations of the motion of the Moon were used by Newton to calculate its acceleration and compare it to the acceleration of free fall on Earth. Sometimes physicists use thought experiments; examples are famous Einstein's thought experiments. On the other hand, some discoveries started with accidental observations—for example, Becquerel's observation of the mysterious radiation of a uranium-laden cross.

Observations are affected by many factors. Practicing scientists regularly decide what features of their observations can be ignored at this first stage of understanding.

Subsequently scientists study these "*simplified cases*" qualitatively and quantitatively. For the quantitative description they invent *physical quantities*. Through continuous analysis using experimental or theoretical investigations, scientists discover stable, repeating *relationships among these quantities*—these are *laws*. Then, scientists design *experiments to test* the laws. They use the invented law to predict the outcome of a new experiment. The law may be confirmed by thousands of new experiments Ultimately the goal is to *apply* the law for practical purposes. Physicists never consider laws to be permanent constructions; they know that future experiments will inevitably reveal their *limitations* (Fig. 1). Physics understanding encompasses <u>all</u> these elements related to a specific set of phenomena.

Example: Newtonian mechanics

> "Both Galileo and Newton were absolutely clear about the inductive character of the new philosophy; the theories which they formed by synthesis of experimental results were used for suggesting new experiments, and if these tests were favorable, the theory was considered as confirmed. This is a legitimate method of science…"[23]

Here we will use Newtonian mechanics as an example of the above knowledge structure. The *phenomenological* foundation of the theory is represented by observations of falling objects, objects moving down inclined planes, and the motion of celestial objects (Brahe’s and Galileo’s observations), and observations of colliding objects (Newton’s experiments with pendulums). Today, we can see what *simplifications* were developed to describe and understand these phenomena. To some extent the notions of absolute time and space can be considered as simplifications (the length interval and the time interval between two events were the same in all reference frames and independent of the surrounding). These ideas eventually led to an idealized reference frame - an inertial reference frame. Objects were also considered to be ideal - either particles or rigid bodies. Further simplifications included frictionless environments (for the purpose of having one unbalanced force acting on an object). The *physical quantities* of force, mass and acceleration were used to describe the behavior of objects in inertial reference frames. *Newton's laws* revealed the cause-effect relationship between the forces acting on objects, their masses, and their accelerations. Information about the acceleration of the Moon (it can be calculated from observational data), acceleration of falling objects on Earth, and the relationships between the forces with which objects interact (Newton's third law) led to the *law of universal gravitation*. This was the first great unification of seemingly unrelated phenomena - the Earth’s gravitation and celestial gravitation. The discovery of Neptune and Pluto and observations of comets in predicted locations are some examples of how the *predictions* of Newtonian mechanics were *tested experimentally*. Applications of Newtonian mechanics surround us – beginning with the construction of buildings and bridges to the flights of the spacecraft. The motion of the planet Mercury is a demonstration of the *limitations* of Newtonian mechanics. There is a tiny observable discrepancy between the predictions and the actual orbit of Mercury.

Similar structures can be built for many other theories - molecular, electromagnetic, optical, and atomic. Also, one can apply the same sequence (phenomena – simplifications - physical quantities - laws - predictions - experimental proof or disproof – limitations - applications) for separate concepts.

As Duchovic et al. mentioned, physics is “a process by which humans observe the physical universe, construct models consistent with these observations, use the models to make predictions, and finally, test those predictions with further observations”.[24]

Learning physics through an epistemological approach

In this section we will show examples of structuring instruction in a regular physics course so that the students can identify the structural elements of physics and construct their understanding of a concept using the relationships among the elements described above.

For example you have students studying projectile motion after they studied the kinematics of linear motion, the kinematics of free fall, and Newton’s laws. In lecture students observe that the small metal ball, launched vertically from a stationary cart, landed in the cart. Then they observe that when the ball was launched from a horizontally moving cart, it still landed in the cart. They ask the instructor to vary the speed of the cart to make sure that independently of how fast the cart was moving, the ball still landed in the cart. Students record their observations.

Then the students are asked to explain the observed phenomenon. Some will come up with the explanation that the ball moved up and down while continuing moving horizontally (or that the two motions were independent of each other). To test this explanation, the instructor can ask the students to predict the results of an experiment with two balls on a metal rod connected by a spring. If the spring was compressed and then released, one ball would fall straight down and the other one would leave the apparatus moving forward. Students see the apparatus and predict whether the balls will land simultaneously based on the explanations of the first experiment. Then they can observe the experiment and hear the sound of the balls landing simultaneously.

After this qualitative analysis, students can be asked to use their previous knowledge to describe quantitatively the motion of an object thrown at an angle. They use Newton’s laws to decide if the motions were with constant velocity or constant acceleration, and use the familiar quantities of force, mass, acceleration, velocity, time, and distance. They can derive the range equation. To test the equation, they can be offered a problem: “You have a gun with a spring inside. You need to shoot a ball into a box that is placed on the table on the first try. What do you need to do?” After students devise a plan and solved the problem, they have to actually perform an experiment and observe whether the ball landed in the predicted location. The fact that it lands a little short will show them that air friction should be taken into account. After they qualitatively include the effects of friction, the ball will land in a box.

In this example students conduct observations of physical phenomena and use prior knowledge to derive relationships among the quantities. They test these relationships by performing new experiments.

For some concepts it is difficult to engage students in direct observations or testing experiments. Then the instructor can use the history of physics to lead students to understanding. Examples of historical developments can be the history of understanding of atomic structure, or nuclear structure. For both one can identify observational experiments, several models explaining them, and experiments that were performed to test the models.

How to build a course on this approach

In this section we will discuss how to use this approach in a regular physics course.[25]

No radical changes are needed in the sequence of topics. The approach works well with almost any textbook. The major change is in the sequence of students' learning experiences. Often an instructor explains a concept to the students and then illustrates it with some experiments. We suggest that this approach be replaced by cycles that involve building relationships among structural elements. The cycle for a unit involves students' original observations of physical phenomena (can be done in lectures or labs), qualitative explanations and explanation testing (can be done in lectures), choosing physical quantities, deciding about the relationships between the quantities (laws) with the help of observational data or based on already known relationships (can be done in lectures or recitations),[26] devising testing experiments (can be done as a part of a homework) and performing these experiments (can be done in lectures or labs). Consequently for each concept an instructor decides what phenomena to provide the students for their original observations in lectures and/or labs. Then the instructor decides how the students will construct physics laws. If it is impossible to conduct quantified observations, the instructor might provide students with data already collected by scientists. For example, to help students construct the law of universal gravitation, the instructor might provide them with data on the Moon's motion. To help students devise testing experiments for the law, the instructor might provide them with data on the periods of different planets and their distances to the sun.

Interpretation of the results will depend on the students. Sometimes students derive a law mathematically using the laws that they tested previously. For the testing experiments, the instructor might provide students with the list of the available equipment and invite them to design a testing experiment for the explanations or laws that they invented.[27] They can later observe the experiment performed in lecture or conduct it in a laboratory. Students can also design devices that work based on a concept or a law that they discovered. For example, they can use a bathroom scale to measure the force of the scale on their body when in an elevator. They can then calculate the acceleration of the elevator and then compare it with the parameters of the elevator.[28] This is another way to test the concept or the law.

For example, we implemented the approach in the first quarter of the freshmen engineering honors introductory calculus-based physics course at The Ohio State University[29]. The course lasts for one quarter (10 weeks) and each week consists of three large room meetings (48 minutes each), two recitations (48 minutes each), and a laboratory (100 minutes). In the fall of 2000 there were about 210 students broken into two sections for the large room meetings. Approximately 28 students were in 4-person groups in the same recitation and lab classes. The students were grouped homogeneously with one better academic student, two intermediate students and one weaker student.

The quarter was broken in approximately two-week cycles, each emphasizing a different conceptual area (kinematics, linear dynamics, two-dimensional dynamics, energy, momentum, and statics). During the first large room meeting of each cycle students conducted observations of carefully selected phenomena without any explanation from the professor. They recorded their observations and devised qualitative explanations. Then they used these explanations to predict the outcomes of a new experiment. If their predictions were true, then new observational experiments followed in a subsequent large room meeting. The initial experiments were presented again with quantitative measurements so that the students could identify physical quantities to describe phenomena and find relationships between them (find laws)

During the first recitation for each cycle, students used conceptual explanations devised in large room meeting to analyze different conceptual tasks[30]. In the second recitation, students developed quantitative problem solving skills for that conceptual area. In the next week students did a laboratory experiment as an application of the concepts. Each laboratory experiment provided minimal information and required students to design the investigation and sometimes the apparatus. Students solved more complex experiment problems and context rich problems[31] during the second week lectures and recitations.

Students go through the same cycle for many concepts. At the end of each cycle they apply their understanding to explain real life phenomena. The most difficult part here is to provide challenging questions that are based on real life examples so that the students can see that the explanation that they invented "work" or "makes sense" for the real world. For example, a blown fuse burning out when an additional appliance is turned on in a house is an application of Ohm's law and Joule's law to every day life. This sequence allows the students to answer the question "how do I know this?" at every step of the cycle. It is very close to the cycle of conjecture, evaluation and modification or rejection in hypothesis development and model construction described by J. Clement[32] or learning cycle approach described by D. Zollman[33], and approaches used in the high school modeling project[34] and the teacher preparation CPU project[35].

The cyclical structure of the course following the epistemology of science should be supported by adequate assessment instruments that help students reflect on their learning[36] and provide feedback to the instructor. Traditional back of the chapter problems and even conceptual questions do not allow the instructor to assess students' epistemological beliefs.

Formative assessment

We suggest the Weekly Reports[37] that can be used for homework.

Each week students submit electronically or on paper a Weekly Report. A Weekly Report is a structured journal written by students each week in which they answer three questions:

1) What did I learn this week and how did I learn it? (It is answered in two parts: a) What did I learn in lab, and how did I learn it? b) What did I learn in lectures and recitations and how did I learn it?)
2) What remained unclear?
3) If I were the professor what questions would I ask my students to find out if they understood the material?

Summative assessment

One of the ways to assess if students acquire scientific epistemological beliefs is to include special questions in the exams. We suggest that these questions probe student understanding of how to convince somebody concerning the reasonability of an idea or a concept. We tried the following questions in mechanics and electromagnetism.

Mechanics: "You, a nineteenth century physicist, have just developed the idea of the conservation of energy. How would you persuade the scientific community that this idea is reasonable?"

Electricity: "Your little brother is taking high school physics. He is studying static electricity and is having difficulties understanding conductors. How would you convince him that conductors have freely moving charges inside?"

Preliminary results

This approach was used during 9 years of teaching physics in Russia in Moscow's South West High School.[38] The results were similar to the results of Mestre[39] and Zachos et al.[40]--Students consistently outperformed students taught in the regular way in problem solving and on oral exams.[41] Moreover, the percentage of the students who chose physics as a college major was significantly larger. Before the approach was used, the author would have 2 out of 30 students who wanted to major in physics in college. During the years when the new teaching method was used, this number rose to 8-12 students.

This approach was used at The Ohio State University in the calculus-based physics courses for first year honors engineering students in the winter quarter (160 students), in the fall quarter (210 students) of 2000 and in the winter and spring quarters of 2001. In the fall 2000 two professors taught the course, one a self-described traditional lecturer who agreed to try the innovations and the other who had developed the cognitively based strategies used in the earlier years of the course[42]. In both quarters the coverage of the material was about the same as in the traditionally taught calculus-based introductory physics course at Ohio State University. Students were given traditional conceptual tests such as the Force Concept Inventory[43], the Mechanics Baseline Test (mechanics quarter) and the Conceptual Survey of Electricity and Magnetism[44] (electromagnetism quarter) to determine if the described approach impeded their conceptual understanding and problem solving abilities. The result on these tests were very encouraging: the FCI pretest score was 53 % and the g-factor gain was 0.56.[45] Students scored 74 % on the Mechanics Baseline problem-solving test (no pre-test was given). These results are comparable to the best results achieved in reformed physics courses.[46] The post-test score on the Conceptual Survey of Electricity and Magnetism (CSEM) was 74 percent (in traditionally taught courses the average post-test score on this test is 50%). The effect size compared to the two previous years when the course was taught by the same professor was 0.50[47].

In both the mechanics and the electricity and magnetism courses we used Weekly Reports to follow student learning. Numerical analysis of how many students acquired the desired epistemological beliefs (there were about 1500 reports to analyze from the fall of 2000 alone) and how many still have mixed states will be a subject for subsequent papers.

On the epistemology exam questions described above in the section on summative assessment in both courses about 80% of the students used experimental evidence in their responses. In the fall quarter (the question about energy conservation) about 15% of the students used testable predictions in their answers. For example one of the students suggested the following way to convince scientific community that the idea of energy conservation is reasonable: “Take a spring and measure its mass and spring constant (by measuring how far it stretches when you hang different masses). Predict how far up the spring will fly if you compress it a certain amount using the energy conservation. Then perform the experiment and measure the height that the spring reached at the top. Compare the predicted height with the actual. If the predicted height matches the actual, the scientists will believe in the idea of energy conservation.” Other students (65%) described different experiments that they would use to illustrate the law. Very few (less than 5%) derived conservation of mechanical energy from Newton’s laws and kinematics and stated that if physicists believe in these laws, they would accept the conservation of energy. About 15% suggested to explain what the conservation of energy means and rely on common sense without doing any experiments and without connecting the law to other concepts. These were the students who definitely did not acquire scientific epistemological beliefs.

Conclusion

The approach to teaching physics described in this paper helps students to emerge from an introductory physics course with an understanding of “what is it that we know and how do we know it”. Students realize how different pieces of their physics knowledge puzzle are connected and the origin of that knowledge. Also, students participate in creating their knowledge, for them physics becomes an activity rather than a body of knowledge. They become contributors, not just sponges that absorb information [48].

With the described students create the understanding of the concepts through similar processes – from observations of phenomena to discussing qualitative and quantitative descriptions (laws) of simplified cases. They design experiments to test their predictions based on these laws and apply their knowledge to solve real life problems. Students taught in this manner are aware of the connections among the structural elements of physics. They have learned the logical processes of science and learning and can use them in any other courses or in their future jobs.

To implement the above ideas you can start with asking yourself the following questions: how do I know this? Why do I believe that is true? Then you need to trace back your own understanding of the concept: was it founded on observational data or was it just a mathematical derivation built on prior knowledge? But where did this knowledge come from? The history of physics is very helpful. How did people find that objects fall with the same acceleration? How did they discover the mechanical equivalent of heat? How did they test if an electron has a spin? Using historical examples and your own experience, decide what simple experiments can be used to help students build the idea and how they can possibly test if their explanations work; what experiments can be done in lectures, and what require a lab setting. It is easier to start with a small concept and try it in class. Projectile motion is one of possible examples. Vibrations and waves, and geometrical optics can be a good starting point as well.

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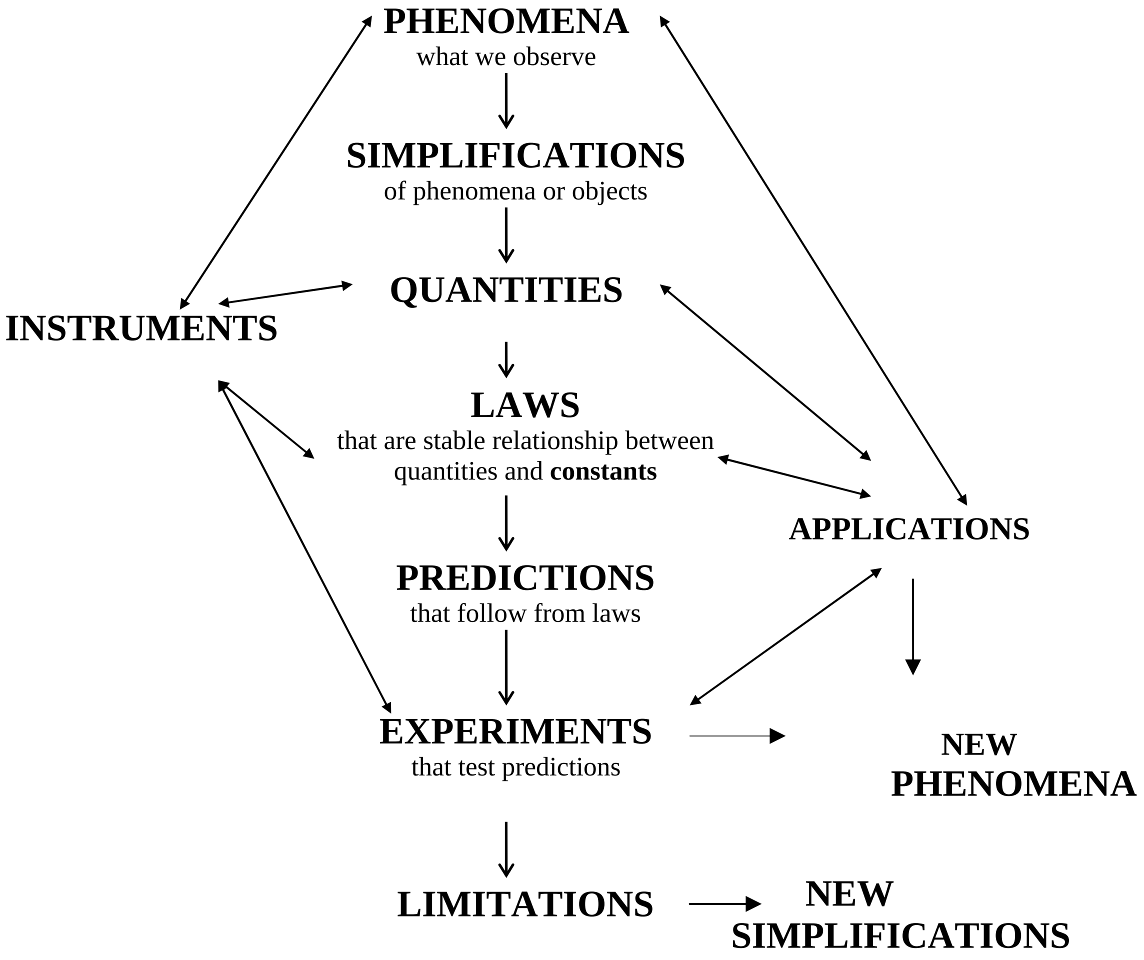
PHENOMENA
what we observe
SIMPLIFICATIONS
of phenomena or objects
QUANTITIES
INSTRUMENTS
LAWS
that are stable relationship between quantities and **constants**
APPLICATIONS
PREDICTIONS
that follow from laws
EXPERIMENTS
that test predictions
NEW PHENOMENA
LIMITATIONS
NEW SIMPLIFICATIONS

Fig. 1.

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[45] The gain measure suggested by R. Hake: g=(post test score – pre-test score)/100%-pre-test score.

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[46] R.R. Hake. "Interactive-Engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses," Am. J. Phys. **66** (1), 64-74 (1998).

[47] Effect size is the difference in the average scores of the two groups treated differently divided by the average standard deviation of the test scores for the two groups.

[48] W. Michaels, "Authoritarianism versus imagination in physics teaching," Am. J. Phys. **25** (2), 82-88 (1957).