# Reinventing college physics for biologists: Explicating an epistemological curriculum

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(Received 29 July 2008; accepted 25 March 2009)

The University of Maryland Physics Education Research Group has done a five-year project to rethink, observe, and reform introductory algebra-based (college) physics, which primarily serves life-science majors. We refocused the class on helping the students learn to think scientifically—to build coherence, think in terms of mechanisms, and to follow the implications of assumptions. We designed the course to tap into students' productive conceptual and epistemological resources, based on a theoretical framework from research on learning. The reformed class retains its traditional structure in terms of time and instructional personnel, but we modified existing best-practices curricular materials. We provided class-controlled spaces for student collaboration, which allowed us to observe and record students learning directly. We also scanned all written homework and examinations and administered pre-post conceptual and epistemological surveys. The reformed class enhanced the strong gains on pre-post conceptual tests produced by the best-practices materials while obtaining unprecedented pre-post gains on epistemological surveys instead of the traditional losses. 

[DOI: 10.1119/1.3119150]

## I. RETHINKING ALGEBRA-BASED PHYSICS FOR BIOLOGY MAJORS

Algebra-based (college) physics is one of the largest service courses in most physics departments. At the University of Maryland we teach approximately 800 students a year in each term of this two-semester class. The population is increasingly dominated by science majors, including pre-health care, such as premedical, predental, pre-physical therapy, preveterinary, and a growing number of pre-research biologists.

In the years 2000–2005, the University of Maryland's Physics Education Research Group carried out an NSF-supported research study to observe student behavior in algebra-based physics and to explore reforms in the course.[1] The reforms we created for the class were based on our reading of the current needs of modern biology students,[2–4] interviews with biology faculty, a theoretical framework that gives us insight into how students think and learn about physics,[5–7] and our experiences in small seminar courses for college students and in high school courses.[8–10]

Every course contains not only explicit content but elements that are traditionally not made explicit in descriptions of the course—an implicit curriculum.[11] For example, traditional instructors tend to assume that students learn how to think about and do scientific reasoning while doing traditional class activities, such as reading the text and doing end-of-chapter problems. Some students do learn how to think scientifically successfully, but research indicates that most do not and some pick up bad habits and inappropriate modes of thinking.[12] We chose to focus the course on helping students learn how to learn science, content that is implicit in most courses and that research has convinced us needs to be addressed explicitly.

Many of these implicit elements are epistemological issues about the nature of scientific knowledge: how we know what we know, how to create new knowledge by problem solving, how we make inferences, what makes sense, and how to build physical intuition. These issues have particular importance for the biology majors currently dominating college physics classes, but they are equally important for other populations of physics students. The implicit epistemological content tacitly taught in traditional courses often is not what we want our students to learn; rather, it encourages poor approaches to learning such as rote memorization and the denigration of everyday experiences and intuitions.[13]

Students bring epistemological assumptions into our classes as a result of their experiences, especially in their previous science classes. To understand the match or mismatch between student epistemologies and what we want them to learn, we transformed the course to encourage student learning to take place in class-managed areas where it could be observed and videotaped. We collected large amounts of written data, including pre-post conceptual and epistemological surveys, and digital scans of all written homework and exams. The instructor encouraged students to reflect briefly on the class in written essays. In addition, researchers in our group who were not part of the instructional team interviewed some students about their experiences before and after the class. In this paper, we present the reforms we developed and review the evidence of their success.

We achieved what we believe to be the first documented large gains on an epistemological survey in a large lecture introductory physics class. We did it while not only retaining but enhancing high values for the fractional gain on a mechanics conceptual survey. We produced large gains compared to traditional classes on a split task postinstruction concept survey that measured not only students' knowledge of the correct results but their intuitive comfort with those results. We also documented the kinds of epistemological difficulties students encounter during the course and the extent to which those difficulties can be overcome. These observations were done within the context of a traditional environment with the same resources provided to our standard large lecture class.

In Sec. II, we describe our motivations for choosing the reforms we did. In Sec. III, we describe the theoretical basis for our analysis of our goals and the instructional tools we chose to reform. We describe the reforms we carried out in Sec. IV. In Sec. V, we describe our methods for observing and evaluating the class, and we present our observations and conclusions in Sec. VI. What we learned from detailed research studies that contribute to our understanding of how an individual student learns physics is described in Refs. 14–18.

## II. DECIDING WHAT MATTERS

One of the most significant transformations in science in the past half-century has been the growing strength of biology as a fundamental science. There is broad agreement among leading biology and medical researchers that future biology students will need to become much more knowledgeable in basic physics, chemistry, and mathematics. These students require not only a familiarity of the facts and vocabulary of those fields but a deep understanding of the disciplinary patterns of knowledge and process, including a solid understanding of scientific reasoning. Hence, it is essential that physics education go beyond isolated facts and narrow procedures. More than helping students understand established ideas, science instruction must help them understand how those ideas came to be. Students must be prepared to contend with ambiguities, make sound judgments about what to accept and what to question, reconsider past assumptions, and adapt to new discoveries. They must learn what a measurement means and does not mean. They must learn how to evaluate their data and see its implications. In short, they must learn an adaptive expertise—the ability to respond effectively and productively to new situations and new knowledge as it develops.[19]

Science instruction at the university level tends to ignore an explicit focus on helping students develop these elements of adaptive expertise, hoping that they will spontaneously spring into being as a "side effect" of traditional coverage of traditional content. This traditional approach works for a small minority of students after many years of combined undergraduate and graduate training. Our goal in this project was to learn how to help more students develop these broad thinking and learning skills by paying explicit attention to these issues and by developing a curriculum to deal with them.

### A. A resource-based model of mind

Our redesign was based largely on a resources based view of students' knowledge and reasoning[5–7] that supports Einstein's claim that "The whole of science is nothing more than a refinement of everyday thinking."[20] Everyday thinking involves both conceptual and epistemological resources, and learning physics begins by marshalling those resources in productive ways.

Student conceptual resources include their extensive intuitive knowledge about physical phenomena and causal mechanisms,[21] everything from what would happen if someone tried to kick a bowling ball to what it feels like underwater, from how an oven mitt can keep them from getting burned to how a source of light or odor feels stronger up close than far away. Students use a rich but highly fragmented variety of knowledge and experience as they interact with the physical world. Students should draw on those resources while reasoning about questions in physics. In many cases, the ways they are inclined to draw on those resources lead them to wrong conclusions. Students' reasoning that current is used up in light bulbs, for example, draws on resources that would be productive for thinking about how fuel is used up in gas lanterns. The solution for students thinking of current being used up is not for them to stop using their common sense. It is for them to find other aspects of common sense to apply, other resources in their repertoire, such as those they would use to understand how trying to hold a moving rope can burn their hand. Rather than set their common sense aside, students should search within it for other possible conceptual anchors.[22]

A resource-based model of conceptual knowledge takes a dynamic view of thinking that is in apparent contrast to accounts of novice understanding in terms of coherent "naïve theories" and misconceptions.[23] Research on the latter has established patterns of student reasoning that differ from expert understanding, and these findings have been interpreted to suggest that intuitive knowledge is an impediment to expertise. In some important respects that interpretation is the opposite of what the original research established,[24] which was that novice "misconceptions" represent sensible reasoning well-grounded in experience. Much of the difficulty is that the naïve-theories account views intuitive knowledge as unitary, seeing the misconceptions as the one way students have for thinking about the topic. Teachers and researchers who have close contact with students know that students have many ways of thinking. Common sense does not have a coherent organization; it is made up of many parts, and the common sense answer to a question depends on which parts are activated at a particular instant. A resource-based view provides an account of that variability and of how science can genuinely be a refinement of everyday thinking.

The core innovations of our reform attend explicitly to student epistemologies; that is, to how students understand knowledge and learning in physics. Just as students have a vast collection of resources for thinking about physical phenomena and mechanisms, they have a vast collection for thinking about knowledge, about its various forms and sources, and about how it can arise and be used in various sorts of activities. Just as they use their collection of conceptual resources for experiencing and making sense of the physical world, they use these epistemological resources for experiencing and making sense of knowledge and learning. Depending on the situation, they use different epistemological resources for thinking about what knowledge entails, the forms it takes, how it arises, and whether it is valid.

In traditional physics courses, students often learn to set their everyday experience aside.[25,26] They frame the task as a matter of receiving and rehearsing information, information that need not make sense. A primary goal in our courses is to help them frame learning in other ways, tapping productive epistemological resources for thinking about sense-making and argumentation, for understanding physics knowledge as a coherent system of ideas rather than a collection of independent pieces of information. We pursue this goal both explicitly in the instructions and advice we give students and implicitly in the structure and design of assignments, lectures, tutorials, and labs.

## III. TRANSFORMING THE CLASS STRUCTURE WITHIN EXISTING CONSTRAINTS

### A. The traditional teaching environment

Because the perception of a reform depends on what it is being compared to, we describe briefly the traditional environment for algebra-based physics as it was at the University of Maryland when we began the project in 2000.[27] Our traditional algebra-based physics class is taught in two fourteen-week semesters covering the topics of "mechanics, heat, sound, electricity, magnetism, optics, and modern physics."[28] Each half of the class is taught to 400–500 students per semester, divided into three lecture sections of 100–200 students each. Each lecture section is assigned to a faculty member who is responsible for the content, lectures, assigning reading, and homework. Each lecture section is divided into small group sections of 24 students. Each small group section meets for one 3-hour period per week run by a graduate teaching assistant (TA). The first hour of the period is typically a problem solving recitation; the last two hours are a laboratory. The students purchase a common text, which is typically the source of all homework problems, and a laboratory manual.

Each professor makes a somewhat independent choice as to what content to emphasize within the constraints of the catalog description. Although there is some variation, an attempt is made to keep the first semester fairly common because a significant fraction of students switch from one lecture section to another after the first term. Homework is handled idiosyncratically. Homework may be assigned from the book or from an on-line homework system and may or may not be graded. Laboratories are traditional with extensive write-ups and step-by-step guidance provided. Students work in pairs and create individual lab reports. Ten laboratories are required each term and makeup periods are provided during two weeks of the term in which students can complete missed labs. A separate faculty member is responsible for the laboratories and for training the TAs in managing the lab.

The lecture faculty are responsible for creating, grading, and managing the examinations for their own students. There are no common exams. Typically, there are two to three midsemester exams and a final. Sometimes exams are multiple choice or short answer, but they often include problems and require calculations. Recitation-section TAs are typically recruited to do much of the grading. Typically, the only interaction between the lecture and the lab part of the class is that the same TAs run the lab and recitation sections.

Traditional lectures include demonstrations, derivations, and sample solutions to homeworklike problems. There is rarely much interaction with the students during lecture. Attendance during lecture varies from instructor to instructor and ranges from 25 to 85% of the registered students. Typical recitations are run by TAs as problem-solving mini-lectures, with the choice of problem sometimes guided by student questions. If the recitation does not contain a required quiz and if the TA has been instructed not to solve the current week's assigned problems, the attendance is typically less than a third of the registered students.

One of us (EFR) taught algebra-based physics in this traditional mode for many years reasonably successfully, meaning there was good attendance in lecture (typically more than 75%), high ratings in end-of-year evaluations from students (above departmental averages for the class), and some anecdotal successes (individual students reporting relief and delight that the course was not as impossible as they expected).

### B. The reformed teaching environment

During the five years of the project, the authors were the lecturers of record for a semester of the course 11 times.[29] As a result of our reconsideration of the course goals and on the basis of our resource framework of student learning, we reformed each of the components of the class to be explicit about epistemology. There are many research-based reforms that help build students' conceptual knowledge. Many of these reforms are based on a cognitive-conflict[30] or elicit-confront-resolve[31] pedagogical model in which students are asked to make predictions so as to display their intuitions. The students then see empirical results that show these intuitions are incorrect, and finally the instructor helps the students resolve the conflict. Our experience as teachers and researchers has been that this model often has the negative epistemological side effect that students learn to consider their intuitive knowledge and experience as irrelevant for physics learning; they learn to set it aside, rather than to draw on and refine it. To avoid this effect, we modified each of these conceptually oriented reforms.

#### *1. The lecture*

We implemented three reforms that increased the epistemological emphasis of the lectures: explicit epistemological discussions, adaptations of the Peer Instruction materials,[32] and the use of epistemologically modified *Interactive Lecture Demonstrations*.[33]

*Being explicit about epistemology*

We made the epistemological framing of the course explicit, including through the use of a vocabulary we introduced early in the semester. We designed this vocabulary based on previous work in a small seminar class.[10] One of us (EFR) created and used a series of icons to use in PowerPoint slides and course materials to help reinforce and remind students of the various epistemological framings.[34] The terms include: *shopping for ideas, sense making, seeking coherence, restricting the scope, choosing foothold ideas*, and, *playing the implications game*.

*Shopping for ideas.* The overarching message of the course is that "the whole of science is nothing more than a refinement of everyday thinking." Hence a core activity of the course needs to involve students becoming more familiar with, and critically aware of, their everyday thinking. We use the metaphor of "shopping" to help students think of their own knowledge and experience as having a large inventory of possibilities through which they can browse. We give an example of how to do this with a story to connect to everyday epistemology: Imagine you have met a new person and there's something about him that bothers you, but you can't put your finger on what it is. So you think about it, trying to figure out whether he reminds you of someone or you've met him before. You "shop" in your mind through different sections of your knowledge and experience. You ask "Have I met him before?" and try different possibilities: "Have I seen him at the pool? At the store? In art class?" "Who does he remind me of?" Eventually you may realize that he looks and sounds a bit like a character in a movie you saw recently.