Taking A Scientific Approach To Physics Education

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As physicists, we are taught very early of the debate about the geocentric solar system. The arguments that included physics, philosophy, and religion firmly planted the Ptolemaic model of the universe as the standard. A simpler model by Copernicus led us to understand the heliocentric solar system and explain the paradoxical retrograde motion of Mars. As we became more sophisticated in our observations and mathematical tools, our understanding of what held the heavens in place was replaced as observations by Kepler, Brahe, and Galileo were explained by the physics and mathematics developed by Newton and Leibniz. As we struggled to understand why light bent around astronomical objects, why we could never predict Mercurys orbit accurately, whether we were at the center of the universe or not, why tiny alpha particles bounced off massive gold foil, and how it was possible for an electron to be everywhere and yet nowhere, we developed new physics thanks to Einstein, Hubble, Wheeler, Schroedinger, Dirac, Wigner, Pauli, Curie, Thompson, Heisenberg and many, many others to better predict and to more readily explain our universe and everything in it. As we continue to expand out, testing the limits of physics, we begin to understand that we truly know nothing about our universe and the best we can hope to do is make models that explain our latest observations and make predictions about new ones. This is both the beauty and the challenge of physics: we are never done and we never want to be done. There is always something more to explain, something to understand more deeply. Modern physics research leverages experimental, theoretical, and computational techniques to develop models and explanations of the natural world - and we do that quite well.

But what of how people come to understand physics? How do people know physics? How do people learn physics? How do we help people to learn physics better and more deeply? How do we help people develop an understanding that has taken millennia to construct? That is my job. I am a physicist who studies how people learn and I work to improve the conditions under which that learning occurs. Rather than going by feel, I take a scientific approach to physics education. I also use experimental, theoretical, and computational techniques in my work, but I develop models and explanations of how people learn about the physical world rather than learning about the world itself. The field in which I work is called Physics Education Research (PER). And what we do, we also do quite well.

By comparison to most subfields on physics, PER is a relatively new field truly starting with the early work by Arnold Arons, Robert Karplus, Lillian McDermott, and others about 40 years ago

[1-3]. Much of this early research and some current work, including research I have done myself[4-7], is more akin to applied physics. That is, instead of trying to explain the observed phenomena (e.g., how do students think about buoyancy from a variety of perspectives), we have (historically) attempted to engineer a solution to the problem (e.g., how do we make students think about buoyancy correctly). This applied lens has served the physics community very well. In the last 40 years, PER has consistently demonstrated a number of core principles of instruction at the undergraduate level [8,9]:

- Students learn physics by engaging with course material actively and cooperatively.
- Students learn physics by experiencing physics in authentic ways that align with their interests.
- Student learning in physics is best supported by a community that respects student ideas and experiences.

These principles seem to be fairly strong and consistent predictors of overall student success within a given topic or a given course [10]. In fact, these general principles appear to apply to many disciplines [11].

While this research has assisted us greatly in understanding how to help students learn physics as it is taught presently, our discoveries have pressed us to answer new questions, for example:

- What is the nature of student understanding in physics, and what experiences bring students to that understanding?
- How do students participate in physics and how does that participation shape their future with physics?
- What effects do new technology, pedagogy, curriculum, and teaching practices have on student understanding and engagement in physics?
- How do we broaden participation in physics to include and support students from groups who are historically underrepresented in physics (i.e., women and students of color)?

To answer these new questions, PER has had to evolve. Our field is more interdisciplinary than before, we leverage the work of educational researchers and social scientists outside of our field, much in the way that biophysicists leverage understanding from biology. Our field makes use of theories, methods, and tools from fields such as science education research, educational psychology, sociology, anthropology, and the fields of women and race studies. We are more grounded in the history, tradition, and culture of educational research than the early years. We are gaining stronger and more complete evidence on student learning than before. Our field has matured and developed in ways that are helping to strengthen the research, but still maintain relevance and importance to the physics community. A summary of the birth and evolution of the field of PER was commissioned by the National Research Council and published recently [10].

But I digress. My own work concerns two areas of understanding in physics: (1) mathematics and (2) scientific computing. Both areas of research attempt to answer broad questions:

- What does student engagement in mathematics/scientific computing in physics look like?
- How can we promote stronger engagement?
- How do students come to understand physics through mathematics/scientific computing and vice versa?
- How do students come to understand how to use mathematics/scientific computing to do physics work?
- What are the different experiences with mathematics/scientific computing that shape students relationship with physics?

Each of these questions is quite broad and research projects that support answering those questions is part of what the Physics Education Research Lab at Michigan State University ($http://perl.pa.msu.edu$), which I help direct, does. We have a number of projects in different areas, but here I will highlight only two.

The first project aims to make sense of how students develop their understanding of scientific computing over time. This work has developed out of my prior work to incorporate and to study students use of scientific computing in introductory and upper-level physics courses [7,12,13]. This project leverages variation theory [14] through the use of narrations of students prior experiences in the classroom. We aim to build claims about the different ways in which students working in small groups understand the Python code they write in an introductory physics course and how that understanding changes over the first four weeks of the course (when much of the instruction on scientific computing occurs). Several students taking this introductory physics course where they model physical systems with the Python programming language are interviewed each week.

In each weekly interview, students are presented with the code they had written in class during the previous week. They are asked to discuss what the different lines of code mean and how they came to develop those lines of code in their group. Through this interview and the subsequent discussion about specific features of their code, we develop our own understanding of the different ways students come to write the programs in their course. A final interview (not yet conducted) will ask students to reflect on specific instances when parts of their code were written and what their (and their groups) thinking was at the time. This reflective interview will make use of in-class video recordings where students are discussing with their group mates how to develop and to write the program for that day.

In a second project, we are trying to understand how students come to use sophisticated mathematical tools (such as multivariable integration and vector decomposition in different coordinate systems) facilely. This work stems from my prior research on students use of mathematics in upper-level physics courses [6,15-20]. This second project leverages Resource theory [21-24] and a dyad interview methodology where students explain their approaches to and decisions around solving mathematically-intensive upper-level physics problems to each other. The interviewer takes the approach of encouraging students to discuss together what the students think the proper approach should be.

The point of this research effort is not to judge students solutions as correct or incorrect nor to judge the path they develop to their solution as appropriate or not, but rather to observe the multitude of ways that students approach using mathematics on these problems. Our aim is to develop an understanding of not only what students do when confronted with these kinds of problems, but also why students choose to do what they do. That is, what prior experiences or in-the-moment decisions lead them to solve a particular problem in the way that they did. As a cross-sectional study (one that looks across the physics curriculum from first-year to fourth year), we further aim to understand how those approaches change over time and are influenced by the experiences in more advanced physics courses that students take later.

While there are a number of other studies and research endeavors that our lab is engaged in, I believe these two examples provide concrete illustrations of the approach to physics education that current researchers of undergraduate physics teaching and learning are beginning to take. Ours is an endeavor to understand how students come to learn physics and what promotes different kinds of learning in our physics classrooms.

I will end as I began speaking about evolving models. What we know now about student learning in physics, what models are prevalent and useful, and what tools that provide insight are only as good as the phenomenon they can explain. As researchers develop deeper understanding of student learning, as we ask and answer new questions about how that understanding develops, we must evolve our theories, models, and methods to investigate new phenomena. It is by asking these new questions, testing new models, and developing new research studies that build off prior work that we take a scientific approach to physics education.

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