NEXUS Grant Summary

Edward Santilli

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1 Introduction

One year ago, PhilaU's general physics course (PHYS 101) was designed to be a standard-issue non-calculus course in mechanics, perhaps to provide a rigor offered by other universities. The problem with such a course is that it attempts to teach far more than is possible in one semester. In fact, many of the topics covered are completely irrelevant to non-scientists (ballistics, for example). This leaves the students knowing no more physics than they did on day one, questioning the purpose and validity of the topic as a whole. Oddly, and quite irresponsibly, the pitfalls of this kind of comprehensive physics education have been known for years [3, 1, 8, 12], yet it is only in the recent years that few schools have tried to take action.

In order to avoid shallow discussions of a wide range of irrelevant topics, we first need to consider what we really want our non-science majors to gain from such a class. For brevity, I will discuss the two shifts in focus that I feel were crucial over the last year.

- *Encourage communication with scientists*. We are not training physicists, yet physicists are becoming increasingly important in the modern world. If our students leave the course feeling that physics is purely academic and purely self-serving, we have failed to provide a modern education. Will those students trust the recommendations of a physicist or engineer when it matters? Will those students ever think to simply talk to a physicist or engineer when a physical problem presents itself? Will those students even be able to identify a physical problem when it presents itself? As the instructor, we must keep in mind that we are not teaching physicists. Even if a student is able to navigate though the large list of topics in a traditional physics class and earn an A+, they are not physicists. They are not the engineers. Rather, they need to be taught what tool belt a physicist wears and keep a line of communication open if needed. To this end, I have taught the basic concepts of physics without becoming too bogged down in the mathematical how-to. Interestingly, I learned that you can teach mechanics quite thoroughly by only relying on proportional reasoning! (If you'd like to read about why I think fundamental concepts should be taught using proportional reasoning, there is plenty of literature about how our senses inherently work in this manner [5, 9].)

- *Build trust in the scientific method*. There is a general lack of trust by the general public toward the scientific community, even among people to openly trust scientists [2]. Much of this seems to be due to a lack of understanding of the scientific method as a whole. This should not come as a surprise. We set up our physics classes completely backwards. First, we tell students that something is true during a lecture based on intuition and mathematical theory. Then, we set out to demonstrate the theory in lab by ignoring realistic frictional issues. When a lab result does not reflect the theoretical expectations, we say the lab results are wrong and press on. With this lesson plan, we are effectively teaching our students that all practicality is subject to deprecation by a theoretical scientist's snobbery. I reiterate – is there any surprise that people do not trust scientists or understand their methods? The new general physics course attempts to put the horse before the cart by teaching physics using the scientific method itself without ignoring real-world effects. This is where classroom equipment purchases became necessary. More on this in section 2.

2 Change of delivery

Having laid out the new directions of our general physics course, how do we proceed? This has been the subject of some evolution over the last year. Some of the ideas presented in the original grant proposal worked, some needed modification, and some ideas were outright abandoned. Again, for brevity, I will only outline those changes that I feel have been most impactful on student learning in their most evolved form.

- *Rely on proportional reasoning*. From a psychological point of view, if you want to explain physics in its most rudimentary form, you need to cast it into a form that plays to our minds' most basic operations – and algebra isn't it. Of all of the mathematics that we learn, it seems that proportional reasoning is quite special. It is a form of mathematical intuition that we develop independently during the transition from childhood to adolescence, making it a good candidate for the title "basic operation." From an experimental point of view, any hypothesis drawn from proportional reasoning can be demonstrated quickly and effectively due to its simplicity. From a theoretical physics point of view, I've learned that most of the PHYS-101 subject matter, including all three of the fundamental conservation laws, can be derived from proportional arguments. Meaning that there is a direct path that takes us from a simple experiment to proportional reasoning to a physical conservation law. All in all, this forms an educational procedure – I begin a discussion or provide a simple demonstration that leads students to make a hypothesis based on proportional reasoning. We test the hypothesis and reiterate if needed. Once the hypothesis stands up to scrutiny, we generalize the hypothesis until we arrive at the physical law I originally set out to teach. At no point do the students rely on complex mathematics, nor are they required to blindly trust a lecture. Furthermore, when their intuition fails, it is addressed *before* the final lesson is taught, which has been shown to increase the lesson's absorption by physics education researchers [11].

- *Teach conservation laws first and without simplification*. In a typical general physics course, we first teach the ins and outs of Newton's three laws of motion. This is typically a difficult process filled with conceptual and trigonometric pitfalls. Then, somewhere around mid-semester, we teach conservation laws and advertise that all of the things we learned to do via Newton's laws can now be done far more easily and with little to no trigonometry. (And without requiring an intuitive understanding of acceleration!) This leaves the student rightfully asking why we learned Newton's laws first! From another point of view, conservation laws are the language of modern society. Energy conservation is a major modern issue that requires the population to at least have a working vocabulary if we are to properly discuss the issue. And so, I found it very beneficial to teach conservation laws first. This idea was first put forth in *Six Ideas that Shaped Physics* [10]. I have found that students are very receptive to this arrangement. It allows them to develop good physical intuitions and correct physical misunderstandings (that is, learn physics) before dealing with the necessary, but tricky complications inherent in $\vec{F} = m\vec{a}$.

- *Postpone the use of acceleration*. For non-scientists, calculus is inaccessible. This makes any "rate of change" that much more difficult to digest. As it turns out, velocity (the rate of change of position) is such a common quantity that it is understood by our students quite satisfactorily in the first week or so of class. Acceleration is not. First, I found that students come into the class thinking of acceleration incorrectly, internalizing acceleration as speeding up and decelerating as slowing down rather than thinking of acceleration as a vector quantity. While this isn't much of a surprise, it is a subtle difference that leads to pedantic numerical errors. Second, the entire concept of acceleration is difficult to frame into a picture. While velocity can be easily pictured by drawing an object on a piece of paper in two different places then scratching an arrow from one to the other, there is no analogous view of acceleration. This makes acceleration a bit more abstract than velocity, just enough to make it inaccessible as a foundational tool in the general physics class. Over the last year I've settled on two complimentary solutions to this problem. First, during the introductory week, I discuss acceleration qualitatively, using snapshots of moving objects taken at evenly spaced times. I have the students draw such images for various situations – balls falling, people walking at a steady speed, cars screeching to a halt, and so on. Then, once we actually start tackling physics in the third week or so, I avoid using the word acceleration altogether. Rather than teaching $\vec{F} = m\vec{a}$, I teach $\vec{F}\Delta t = m\Delta\vec{v}$, which is functionally identical but conceptually more tractable. During the semester, students independently begin using the term acceleration to describe motion, but they tend to do so correctly because they are internalizing the conservation law involving $m\Delta\vec{v}$.

3 Preliminary results

3.1 Force Concept Inventory

To quantify the effectiveness of this new approach, I administered a conceptual physics test called the Force Concept Inventory (FCI) developed by Hestenes, Halloun, Wells, and Swackhamer [4, 6]. The FCI is a standardized test that is given at the beginning and end of the semester. Learning gains are then computed via $G = (s_f - s_i)/(100 - s_i)$, where s_i and s_f are the student's FCI percent scores at the beginning and end of the course, respectively. The idea behind normalizing the scores with $100 - s_i$ is to ensure all students are on an even playing field – G is a measure of how much a student *did* learn as a fraction of how much they *could* learn. As a reference, national averages put G at 0.22 among teachers who use a lecture/lab approach and 0.39 among teachers who use an active pedagogy. These averages were taken over 450 classes in a wide variety of institutions in the US and Canada [7]. Unfortunately, I only have a few semesters of FCI data for my classes, however I was very encouraged to see a large increase in learning gains. Average gains are currently at 0.27, up from 0.15 in my previous classes and 0.14 in Dr. Yust's FA17 class. It should be pointed out that money from the NEXUS grant bought equipment that significantly modified much of the course, but not all of it. For example, it would have been helpful to have tanks, pressure gauges, and U-tube style barometers in our classes on fluids, but I did not have the money to purchase such tools. That being said, I do not feel that the class was 100% modified. Yet, the increase in learning gains in our current PHYS-101 incarnation is substantial. I hope to collect more data over the following years and further modify the class to increase these gains even more. (Honestly, I won't be happy until I reach an average gain of at least 0.39.)

3.2 Class grades

Throughout the semester, I gave 5 major exams on 5 main topics: 1D Kinematics, Inertia/Newton's Laws, Energy/Thermodynamics, Statics and Rotation, and Fluids. Traditionally, exam 2 on Inertia/Newton's Laws proves to be the most difficult for students, with average scores being 63.6 ± 2.5 in previous semesters. Many of the changes made to the class were focused on addressing this particular issue, and although some of the class has not yet been converted (e.g., fluids), the subjects of Inertia/Newton's Laws were taught entirely using the interactive methods described in section 2. With this in mind, it is interesting to note that exam 2 is now producing the highest grades of 80.5 ± 13.3, with similar results for exam 3 on Energy/thermodynamics. This is extremely encouraging. As time goes on and I continue to create interactive studio-style lessons and activities for the remainder of the class, I am hoping to see the grades for those topics rise as well.

As for the overall average, there was no significant improvement, with averages hovering at 79%. However, the standard deviation did decrease from the high teens to less than 10%. This means that less students received a D or an F. While I am glad to see less people getting low grades, I cannot be certain that this is due to the new class format until the trend continues for several semesters.

3.3 Attitude Assessment

The results of the Colorado Learning Attitudes about Science Survey (CLASS) was administered to probe students' beliefs about the purpose and usefulness of physics as well as their ideas about best practices for learning physics. Just as with the FCI, this survey is administered on the first and last days of class to look for changes in attitudes. Student responses are received using a 5 point Likert scale. Most of the average responses did not change from pre to post test, and the responses that changed by at least 1 point were quite surprising. I have listed those results here with changes that I consider to be a step in the wrong direction listed in red.

+2 It is possible to explain physics ideas without mathematical formulas.

+1 It is useful for me to do lots and lots of problems when learning physics.

+1 After I study a topic in physics and feel that I understand it, I have difficulty solving problems on the same topic.

+1 As physicists learn more, most physics ideas we use today are likely to be proven wrong.

+1 When I solve a physics problem, I locate an equation that uses the variables given in the problem and plug in the values.

+1 There is usually only one correct approach to solving a physics problem.

+1 If I want to apply a method used for solving one physics problem to another problem, the problems must involve very similar situations.

+1 In doing a physics problem, if my calculation gives a result very different from what I'd expect, I'd trust the calculation rather than going back through the problem.

+1 It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct.

-1 To learn physics, I only need to memorize solutions to sample problems.

-1.5 There are times I solve a physics problem more than one way to help my understanding.

As you can see, I have my work cut out for me. Considering the increase in FCI scores, I may be helping students *do* physics rather than *understand* physics, which certainly was not my intention! Looking at these questions, it is easy to identify where students began struggling as I tried to push them through Bloom's Taxonomy – at the apply/analyze interface. Unfortunately, this survey was never administered at this university before, so I am not sure how these results compare with previous semesters. Nevertheless, modifying the class activities to shift attitudes about physics in the right direction needs to be a priority in the coming semesters. It seems to be a key factor in helping students properly apply what they learned and draw connections among various lessons.

4 Reflection

The results present a mixed bag. The understanding of basic physical concepts are improving, but attitudes are not. Less people are failing, but class averages remain the same. On a personal level, I think the students enjoyed this format more than the traditional lecture. They seemed more engaged and willing to come to my office for help. They were also very willing to tell me what activities they felt were successful. Even my PHYS-201 students, who are friends with many of the PHYS-101 students, repeatedly said that they wished their class was taught in the active format. Also, as soon as we went into a more traditional setting when studying fluids, I was able to see a difference in the students' engagement. This is clearly reflected in the exam scores. Moving forward, I think each in-class experiment should be followed by a student reflection that will ask questions about what they learned in a way that sheds some light on their attitudes. This will provide early feedback that I can (hopefully) use to change their attitudes before they become set in stone. It will also be interesting to look for trends across different classes in the students' semester-long attitude evolution.

I am excited to bring the other physics teachers on board to gather their input and see how this class style works for others. In the process, it will be crucial for us to develop interactive lessons for the remainder of the class (primarily, the fluids section). It may also be necessary to rethink the amount of material covered in this class. For example, I taught conservation of angular momentum in the section on rotation. Is this necessary for our PHYS-101 students? Would the time be better spent tackling other issues? Specifically, I would like to spend more time letting the students solve complex problems that force them to draw connections and differentiate among ideas learned throughout the semester. The problem, as usual, is finding the time.

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