AC 2008-2378: PHYSICS FUNDAMENTALS, ENGINEERING DESIGN, AND RESEARCH: AN INTEGRATED APPROACH TO THE DEVELOPMENT OF A THREE-WEEK SHORTCOURSE

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1. Abstract

Many outreach programs offered by universities provide pre-college students an opportunity to explore careers in science and engineering. For high-achieving students who already have an interest in these areas, these types of programs can introduce students to advanced concepts, develop their understanding of scientific methodologies, and expose them to science and engineering research. One such program, the Young Engineering and Science Scholars (YESS) Program, is a three-week summer residential program created to bring exceptional high school juniors and seniors from underrepresented minority groups to study at the California Institute of Technology (Caltech). The program is intended for motivated students who wish to broaden their knowledge of science and engineering beyond that offered by their high schools. During the three-week program, students take science courses and are exposed to laboratory tours, faculty lectures, and college admissions workshops.

The creation and implementation of an integrated curriculum for a physics and introductory engineering YESS course is the focus of this paper. The 2007 physics and engineering curriculum was designed with four main objectives in mind: to ensure that students had a conceptual understanding of mechanics fundamentals, to challenge students to use their knowledge of mechanics in an engineering design competition, to expose students to advanced topics in physics, and finally to provide students with an opportunity to conduct guided research. Several assessment methods were used to determine if this type of fast-paced and integrated curriculum would be successful in achieving the aforementioned objectives. These include a pre- and post-examination, student performance evaluations, and student surveys and feedback.

This paper provides a description of the program, a discussion on the teaching philosophy, a breakdown of the physics course structure, and a presentation of results obtained from the assessment. From these results, it is concluded that an integrated approach to increasing student understanding of physics fundamentals, design, and research can be accomplished in a shortcourse setting. It is therefore expected that the 2007 YESS physics curriculum presented here will serve as the educational model for the YESS Program in subsequent years.

2. Program Description

The YESS Program at Caltech is a three-week summer residential program for high-achieving rising high school juniors and seniors who are underrepresented in science and engineering fields. The program is free of charge to admitted students. YESS aims to strengthen students’ interests in science and engineering; develop students’ understanding of scientific methodologies; provide early exposure to science and engineering research; and recruit incoming students to Caltech.
During the summer program, participants take two science courses, Physics and Neuroscience, as well as a computer programming course focused on MATLAB. Caltech graduate students and institute staff lead each course. Course instructors are hired in the spring preceding the program and meet weekly to develop the course curriculum. Through lectures, hands-on experiments and homework assignments, each course exposes participants to fundamental science principles while giving students the opportunity to propose further questions in the fields. As a culminating project for each course, participants produce a group research project with the help of a YESS instructor. The successful completion of the project relies upon all the skills and concepts that the students acquire throughout the courses. At the end of the program, students present their project findings to Caltech faculty, administrators, and peers.

In addition to taking courses, YESS participants meet with Caltech admissions officers through workshops, informal gatherings and small group discussions. The Admissions Office leads workshops that present specialized advice and tips for strengthening college applications. The program also hosts faculty lectures, allowing participants to interface directly with Caltech faculty and learn about their research.

2.2 Participant Selection

The YESS program is open to rising juniors and seniors from across the country. The program has space for 30-35 participants. Applicants must be U.S. citizens or permanent residents and are selected based on the following criteria: academic performance (particularly in math and science); standardized test scores (PSAT, SAT, ACT); evidence of interest in and aptitude for science and/or engineering; and letters of recommendation from teachers and/or counselors.

In 2007, the program received 459 applications. The applicant pool was highly competitive and is attributed to increased targeted marketing efforts that included a mailing to over 300 schools and contacts, a letter sent directly from the Director of Admissions to prospective applicants, and materials distributed at several national conferences.

Successful applicants have excelled in math and science courses and demonstrate an interest in science and/or engineering. Additionally, these students are on track to complete calculus and physics by the end of their senior year in high school. Most admitted students have completed calculus or pre-calculus by the time they arrive to the summer program.

The 2007 YESS class was composed of 30 students (16 female and 14 male students). The majority of participants (28) were rising high school seniors. The students came from high schools from across the country and many were the top students in their high-school class. Participants’ math SAT or PSAT scores ranged from 600-800 and nearly half (14) had completed Calculus.

3. Physics Course Curriculum

The physics portion of the YESS Program utilized a four-part focus in the development of a problem and applications based curriculum. In the first week of study, the students were exposed to the fundamentals of physics (mechanics), which included lectures, small group recitation
sections, homework, and laboratory assignments. During the second week of the program, students were required to draw upon their knowledge of fundamentals to compete in a catapult/trebuchet design competition. Additionally, the lectures transitioned from fundamentals to more advanced topics, such as fluid mechanics, elasticity, optics, and simple relativity during the second week. This transition helped to prepare students for group research projects in the third and final week of course instruction.

3.1 Fundamentals of Mechanics

The fundamentals of mechanics curriculum covered five basic concepts over the course of seven days. These areas were Kinematics, Force and Motion, Work and Energy, Impulse and Momentum, and Circular Motion. Each class period contained a review from the previous day, a new lecture, a small group problem solving session, and a visual learning activity such as a hands-on lab assignment or a tour of a Caltech facility. Additionally, students were given the opportunity to attend optional review sessions in the evenings outside of regular class time to help with understanding the theory and homework assignments.

The lectures were limited to one hour in length and instructors were encouraged to focus on a conceptual non-calculus approach to teaching that would help cater to an academically diverse group of students. This conceptual approach was implemented to shift the students’ focus from memorizing and applying equations to learning problem solving tactics in physics. An example of this comes in the presentation of the well-known kinematics equations for bodies under constant acceleration. Given that there are five unknowns in these types of problems (displacement, initial velocity, instantaneous velocity, acceleration, and time), many physics teachers use the approach of presenting five equations to the students, which appears to encourage memorization of equations over physical understanding. Only two equations are independent though, so these two equations were derived in class directly from the definitions of velocity and acceleration. From there, students were required to derive three other expressions as an exercise. It was furthermore emphasized that one need not remember all of the kinematics equations if the definitions of velocity and acceleration were retained. We reinforced this approach of starting from basic information whenever students were unsure how to start or proceed with a problem solving exercise.

The class lectures were always followed by small group problem solving sessions. During this time, which usually lasted anywhere from forty minutes to an hour, students would assemble into groups of 2-4 and work on an assignment that reinforced the lecture material. The students were encouraged to work together to solve the problems and to utilize the knowledge of their classmates. The instructors were available during these sessions to assist when needed and to ensure that students remained on task. The small group sessions provided an excellent opportunity for students to clarify points that confused them during the lectures as well provided a basis to understand the homework problems, which were usually more challenging.

Homework during the first half of the program was given every night to reinforce the concepts learned in class that day. One hour long optional sessions, or office hours, were offered in the evenings for students that needed additional help. Many students chose to attend these optional help sessions, which allowed those that had not taken physics before additional time to work
with instructors individually. Beyond making sure that no student was being left behind, the office hours served two secondary purposes: it made the students responsible for their own learning and time management and it gave them a glimpse into college life, where choosing to go or not go to office hours can tremendously affect class performance.

On select days, the students would be given a group hands-on learning exercise to complete during class. There were a total of three exercises, each focusing on a different topic. The first used the track and field “shot put” event to demonstrate projectile motion. Using imitation shots, timers, and measuring tape, students would compete against one another and record their data (e.g. time of flight, distance traveled, height of thrower, and angle of release). They were then asked to use equations to estimate the initial and final velocities of the shot and to summarize their findings in a report. The next exercise focused on forces, particularly the spring force and frictional forces. The purpose was to use different masses hanging from a spring to estimate its spring constant and to estimate the coefficients of static and kinetic friction of two sliding bodies using force equilibrium. The last exercise was focused on momentum and collisions using the concept of a croquet game. The goal was to use conservation of momentum and energy to determine information about the different types of collisions. These were simulated using a mallet striking a croquet ball, a mallet striking a tennis ball, and a mallet with Velcro striking a tennis ball with Velcro (as to coalesce). Each exercise required a typed group report upon completion.

3.2 Design Project

Towards the middle of the second week of study, the students were expected to use their knowledge of physics fundamentals to compete in an engineering design competition. The competition was adapted from a high school competition at the University of Missouri and required the students to form teams and compete against one another to design and build a catapult or trebuchet capable of launching a raw egg. The students were judged in four distinct areas: proximity in hitting a target 20 feet away, longest horizontal distance from the launch spot, design aesthetics, and a presentation of the group’s methodology via a poster.

For many of the students, this was the first time that they had been exposed to design principles. As a result, the instructors worked closely with each group during the process to question the feasibility of their ideas and to encourage them to use the physics that they had learned to create the most effective design. For example, they were asked to determine the best angle of release to achieve maximum distance of a projectile launched from some vertical height above ground. They were also asked to think about how to best transmit force during the launching process. Some thought to use springs while others used counter-weights, and the instructors expected them to use physics equations to determine how much force would be needed for their designs.

The students were given approximately four days to develop a design and select and gather materials for the construction of their catapults. Construction did not begin until all teams had a working design. Teams had to work together effectively and be creative given the time and monetary constraints. The two main rules for the competition were as follows: each group had a maximum budget of $25.00 for design materials and the catapult was restricted to a volume of no more than 2 ft. x 2 ft. x 4 ft. (the latter being height above the ground). In both the accuracy and
longest distance categories each group was given a trial launch for calibration and two subsequent launches, with the better of the two being recorded. When a group was not launching, each member had to stand by their posters and answer questions posed by the instructors and other invited members of the Caltech community.

3.3 Advanced Topics and Research

Lectures on more advanced topics in physics were presented concurrently with the design project and continued throughout the final week of the program. These advanced topics spanned five different subject areas: elasticity and structural mechanics, fluid dynamics, special relativity, waves and optics, and finally biomechanics. These five topics were chosen based upon the different expertise areas of the instructors. As with the fundamentals of mechanics lectures, the advanced topics lectures were also limited to one hour in length and were followed by a one-hour project, small group assignment, or lab tour.

The advanced topic lectures provided the students with an opportunity to gain a basic understanding in areas of physics in which they would complete research proposals. The students were divided into groups of three and were allowed to select from among 10 topics the ones that most interested them. Each instructor was responsible for developing and advising students on two of the ten projects. The projects are listed below.

1) Modeling and simulation of bodies under gravitational fields
2) Modeling and simulation of the dynamic behavior of truss structures
3) Mechanics of the human cardiovascular system
4) Biomechanics of human locomotion
5) The physics of shockwaves and supersonic flows
6) The mechanics of baseball
7) The physics and design of roller coasters
8) Atomic force microscopy and single molecule biophysics
9) Understanding black holes
10) Cosmic rays

As can be readily observed, the projects spanned vastly different subject areas allowing for students to select topics based upon interests. At the completion of the projects, each group was required to write a research paper on their topic and give an oral presentation on the final day of the program. The instructors provided students with references and guided the students on what should be focused on during the process, but it was the responsibility of the students to gather information, organize it, and present it both written and orally. Many students were required to use programming tools and software, such as MATLAB and Visual Basic, to present graphs and data and to understand the mathematics that governed the phenomena. Some students got a chance to work with higher-level mathematics, such a calculus, differential equations, and linear algebra. Others were actually given a chance to view and work with experimental setups, such an atomic force microscope and a condensation cloud chamber for cosmic ray detection. The goal of the research portion was to give students an understanding of what academic research is, and what type of research opportunities are available in the field of physics.
4. Curriculum Assessment

The physics curriculum was designed to expose students to three main areas of physics and engineering: fundamentals, design, and research. Accomplishing this end in only three weeks yielded a very high-paced learning environment, where students often had to grasp concepts within a two-day span before moving on to something else. As a result, curriculum assessment was absolutely necessary to ensure that students were having a positive academic experience in the course. There were three main assessment tools that were used to gauge student understanding, performance, and satisfaction with the course; they were a diagnostic examination, student performance evaluation, and student surveys and feedback.

4.1 Diagnostic Exam

A pre and post examination with questions taken from the Mechanics Baseline Exam (MBE) was administered to the students with the goal of understanding if teaching these subjects over a span of approximately eight days contributed to increasing students’ conceptual knowledge of physics. The mechanics baseline exam was used because it was created to test conceptual understanding of physics principles, with little use of mathematics and equations. Results on its effectiveness have been previously published. Every question from the original exam was not used, but questions relevant to the topics and concepts that were focused on during the class lectures were selected. There were 25 questions total.

The exam was administered to the students on the first day of class prior to any instruction and again at the end of the second week after the lectures on the mechanics fundamentals were completed. The same exam was given both times. The bar graph shown in the figure details the amount of questions answered correctly among the students during both the pre and post exams.

The average number of correct answers increased from 11.45 to 13.31 from the pre to post exams. (The number of students tested was 29 and the standard deviations were 4.28 and 5.07, resp.) However, a more detailed statistical analysis of the data provided a two-tailed p-value of only 0.14, which suggests the certainty that this increase is substantive and not due only to chance is 86%. Even given the statistics, the result was definitely promising, especially considering the following two facts: there were about four questions that the overwhelming majority of students got incorrect in both tests and several students did significantly worse the second time around, suggesting that maybe some students became apathetic.

Although the Mechanics Baseline Exam has been around since the early 1990s, many physics program and course instructors have not published on the use of it for curriculum assessment, particularly in the shortcourse setting. However, the test was used in 2002 by Morote and Pritchard as a tool for determining which course elements best contribute to student performance in introductory mechanics classes at MIT. What they found was that high gains from pre to post MBE tests were achieved by using written homework assignments and group problem solving methods in class, strategies that were also used in this shortcourse. For their study, normalized gain is defined as follows,

\[ gain = \frac{S_{after} - S_{before}}{100% - S_{before}} \]
where $S_{\text{before}}$ is the test score from the pre-examination, $S_{\text{after}}$ is the test score from the post-examination, and the 100% denotes the maximum achievable test score.

Quantitative comparison between their results and ours are inherently unfair due to sample size disparities as well as gross differences in length of instruction and student experience in physics. Nevertheless, it should be noted that Morote and Pritchard report that MBE gains from a traditional physics course are around 0.23, whereas gains from an interactive physics course average around 0.48. Both results are much higher than the 0.11 average gain obtained here in our study. Overall, the data suggests that there exist a strong possibility that the lectures, recitations, and labs, despite the accelerated curriculum, could have increased the students’ conceptual understanding of physics; however this increase pales in comparison to courses of much longer duration.

Figure. Results of student performance from the pre and post Mechanics Baseline Examination.

4.2 Evaluation of Student Performance

The students were evaluated throughout the course, and the instructors were required to give feedback on every assignment that was turned in and project that was completed. This allowed the students to know exactly what was expected of them and also served to reward them for work well done. A rule was implemented during the first week of class that prohibited incorrect homework from being submitted. This was a foreign concept to the students, but it motivated students to work together and with the instructors to make sure that they understood every problem. This also increased attendance at nightly office hours, as these sessions provided an avenue for the students to get more personal attention and help with the problems. As one student commented, “…Office hours were helpful and the instructors really made sure that you understood the material.” Also, feedback was provided on the lab reports, and effective technical
writing and data presentation was emphasized throughout the course. In general, students enjoyed getting feedback on their work, which is a necessary component of any course, particularly one that spans only three weeks. As one student summarized, “I really felt like the instructors cared about whether we understood the material instead of just getting the right answer which was really motivating, and the feedback on our work was a huge help as well.”

Students were also judged on the quality of their group work during the design and research projects. Overall, the quality of the students’ work and the effort that was put into these projects amazed the instructors and those in the Caltech community that attended the presentations. The best of the design projects and research proposal papers and presentations were recognized at a closing awards banquet. Technical content and effective written and oral presentation of results were heavily rewarded during both projects. A couple of comments summarize how students felt about the design and research projects: “The catapult/trebuchet was a wonderful project, loved it...” and “…I also appreciated the final week of class in which the instructors introduced more advanced topics.” The instructors believe that the inclusion of a design and research project in conjunction with teaching fundamentals allow students fully understand the impact and expansiveness of physics.

Lastly, students received course performance evaluations from the instructors at the completion of the program. These comprehensive evaluations served to access each student’s strengths and weaknesses and were presented in a very constructive fashion to aid in their future development. The instructors as a unit were very pleased with almost every student’s performance, and many students subsequently the instructors for college recommendation letters.

4.3 Student Surveys

Student surveys provided an excellent opportunity to assess how each student felt about the program as a whole. Students were asked very pointed questions regarding the curriculum, their understanding of the material presented in the course, quality of instruction, organization, etc. The comments regarding the physics course were exceptional. The comments from the students centered on the following themes: organization, instructor enthusiasm and involvement, and finally curriculum assessment.

The students really felt the course was organized and well planned. Some comments to this effect are listed below:

“Well planned curriculum”
“It was very well organized.”
“The physics course was very well planned and taught.”
“Physics instructors were…prepared and worked well together.”
“I loved the physics course. It was very well organized.”

Planning for the course began in February of 2007 and the program began at the end of June. The instructors were required during this planning period to develop lectures and small group and homework problems, and each was subject to rigorous scrutiny by the other instructors.
Advanced planning is definitely identified as a necessary requirement to implementing an integrated curriculum over such a short time span.

Secondly, students commented frequently on the quality of instruction and instructor involvement and concern. Some of these comments are identified below:

“The instructors were fun and presented their material well.”
“The instructors were very concerned with making sure that everyone understood everything.”
“The instructors really made me feel that it was important to understand the material and they were very encouraging.”
“Huge shout outs to all of the physics instructors, they each brought something fun and interesting to the table when they were helping us learn some new concepts.”

Lastly, students submitted positive comments regarding the curriculum, but many characterized the course as hard or challenging. Here are some of the comments regarding the curriculum:

“…I may not have done that well on any of the homework assignments, but I still feel like I learned a lot.”
“…The first week was difficult though because there was so much material to learn. I learned a lot that will help me in the future in physics. It solidified my decision to go with physics as a major later.”
“Physics was HARD but I think that the challenge will pay off. I liked that we only had lectures for about an hour and then broke into small groups to discuss questions we had over the material.”
“I’ve never taken physics and this course really made me excited to learn more.”
“This course rekindled my love for physics.”
“I liked how the Physics Course was not all composed of presentations but rather lectures that took up only one hour and then we had two hours to build upon what we had learned through class problems and homework.”
“Office hours were by far more helpful than class at times, but that’s because of my own personal difficulty with the class (and the instructors helped clear the confusion right away). I was extremely pleased with the class.”
“I thought this course would be repetitive for me since I have already taken AP Physics but all of the instructors kept me interested and with such challenging problems I was never bored.”
“The instructors wanted everyone to understand the fundamentals, not just be able to answer problems correctly as some high school teachers do.”
“I was never strong in physics but this led me to gain a new understanding and even develop a personal interest...They helped me develop my weak physics background into a more solid base.”
“NOT HAVING PHYSICS WAS A LITTLE INTIMIDATING TO ME, BUT WHAT I GAINED HAS SURELY PREPARED ME TO TAKE IT THIS FALL!”
“This course gave me a better understanding of physics, even though I had taken a course before.”

The student surveys seemed to serve as an indication from the students that most of our goals in designing an integrated physics curriculum were achieved. Students understood the breadth of
physics as a major, and its importance in different areas of engineering. Students also paralleled this experience with one that is very similar to college learning. Students grasped and enjoyed learning at a rigorous level that challenged them conceptually. And finally, students enjoyed and learned a lot from working together in teams.

6. Changes from 2005 to 2007

Some of the 2007 physics curriculum was adapted from the YESS 2005 course, while other aspects were changed following recommendations for improvements. (The YESS Program was not offered in 2006.) There were really four main differences from the 2005 course to the 2007 course.

The first difference was that the 2007 course lectures were much more conceptual than in the 2005 course. Then, a problem-based learning approach was utilized with lectures that provided students the equations and strategies for solving the problems on each topic. With such a short time span and academically diverse group of students, this approach often confused those that had not taken physics, and bored those that had. Making the course more conceptual allowed the students to rely on their intuition and understanding to solve problems, many of which were solved symbolically.

The second difference was found in creating a design project that required the students to construct the design. In 2005, students did a design project on paper, and what was observed was that many were unable to determine if their ideas were feasible or not. Actually being required to implement a design helps to ensure feasibility.

The third main difference is the inclusion of a research project. This had not been done in 2005, but the instructors believed it to be an integral part of the learning process. What distinguishes Caltech from many other institutions is its intense focus on research and theory, even on the undergraduate level. The instructors wanted to provide a similar experience to the YESS students.

Lastly, and probably the most important of the differences, students were exposed to computer programming for the first time in the history of the YESS program. This allowed the physics instructors to use MATLAB as a tool in better understanding physics phenomena and presenting more quality data for reports. Many students were excited to learn programming, as it was something that most were unfamiliar with.

7. Conclusions

The conceptual and slightly more theoretical approach worked well with students that had not taken physics before. It allowed these students to rely more on their intuition to help with the problem solving process. Also, some have even reported that now they are enrolled in physics at their home schools and they are mastering the material. In contrast, however, some of the students that had taken physics previous to the program had some slight difficulty with the paradigm shift in the teaching style. These students were used to a more “plug-and-chug style” of problem solving that may be taught or emphasized in a high school course. Even though there
was some initial reluctance among this group of students to embrace a conceptual learning approach, many commented at the end of the program that a lot of concepts that were previously unclear to them were clarified and that they were more comfortable with mechanics overall. Finally, there was a much smaller group of very advanced students (about five of thirty) in the class that didn’t have a problem with this new learning approach or had experienced this teaching style previously. For these students, the first week proved to be somewhat repetitive and so we had to find other ways to challenge them. (e.g., these students were asked to explain topics on the board to the rest of the class).

Also, the students really appreciated the small group sessions, the design project, and the research proposals, and these components of the curriculum provided students with more of a collegial academic experience. This type of integrated curriculum actually follows closely with the educational model of undergraduate engineering programs, but condensed into three weeks. Students enjoyed the group work, taking responsibility to attend office hours, managing their time effectively, interacting with instructors, and learning more than is required to do well on an exam; each of which are tools that will aid in becoming a successful college student.

Even though the feedback from the assessment was mostly positive, there are still some areas that the instructors believe can be improved upon. The biggest area of concern is designing a joint curriculum for students the have and have not taken physics before. Perhaps, in the future, the students will be divided into different rooms for lectures, one room for those that have taken physics, and another for those that have not. This could allow the instructors to move at a more comfortable pace for each group during the lectures on fundamentals. A second and less desirable option is to set a physics course pre-requisite for admission to the program. This would decrease much of the applicant pool from less accelerated high schools where physics may only be offered during the senior year. Another concern is with the length of class time. It has been noted that the three-hour long class times can often contribute to boredom and/or weariness among students. This was a particularly important issue in the physics course, as it was held from 1:00pm – 4:00pm--the second class of the day and directly after lunch. In the future, shorter class times and more breaks in the day are being considered to combat student exhaustion. Lastly, the high workload imposed on the students may actually be counter-productive to learning the material. The instructors struggle with giving enough assignments to fully develop the concepts, while also providing enough time for the students to submit high-quality work. All of these issues are currently being addressed in preparation for the 2008 program.

Overall, the results from the assessment lend validation to using an integrated approach in teaching physics in a short course setting. With this in mind, this approach will be employed in subsequent years as the educational model for the entire YESS program courses, with the same positive outcomes expected. It is the hope of the program organizers that the YESS program will become the premier recruiting tool for underrepresented and minority students and will be able to give them broad exposure to what life may be like as an undergraduate at Caltech.

References
