

AC 2009-1696: INCORPORATING SCIENTIFIC ANALYSIS AND PROBLEM-SOLVING SKILLS INTO A PHYSICS AND ENGINEERING SUMMER COURSE

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Incorporating Scientific Analysis and Problem-Solving Skills into a Physics and Engineering Summer Course

Abstract

The Young Engineering and Science Scholars (YESS) three-week summer program offered by the California Institute of Technology (Caltech) recruits and inspires talented high school students towards engineering and science career paths. The program is geared towards high-achieving, but traditionally underrepresented minority students in science and engineering who have demonstrated excellent academic records in math and science. This paper describes the science and engineering course offered by the program including its objectives, teaching philosophies, and its mentoring process for design and research projects. Assessment is performed using the Force Concept Inventory (FCI) and shows excellent student gains when compared with other college-level physics courses. Student surveys and feedback on the program, the course, and general science and engineering attitudes are also discussed, and recommendations for future courses are provided.

Introduction

Pre-college science and engineering programs offer students an opportunity to explore careers in science and engineering. For high-achieving students who have already shown aptitude in mathematics and science a university outreach program can challenge them beyond the traditional classroom environment, providing first-hand exposure to research scientists and engineers as well as an introduction to the university science and engineering culture. The Young Engineering and Science Scholars (YESS) program¹ is for college-bound high school juniors and seniors of underrepresented minority groups who have strong academic credentials and an inclination towards science and engineering disciplines. The goals of the program are to nurture their interests in science and engineering through challenging academic courses, faculty lectures, and tours of the Caltech campus and research laboratories, while introducing them to the Caltech undergraduate lifestyle. YESS builds upon scientific knowledge through analytical thinking that will help students succeed at competitive science and engineering undergraduate programs.

Many other universities have similar outreach and recruitment programs that range in size and duration, and target various student demographics. Programs that most closely resemble the goals and demographics of the YESS program are MIT's Minority Introduction to Engineering and Science (MITES)² and Carnegie Mellon's Summer Academy for Mathematics and Science (SAMS)³. These programs are both longer in duration and enrollment, offer more courses including mathematics, and due to the larger size offer various ability levels for some courses.

In contrast, the YESS program offers only two classes, "Neuroscience" and "Physics and Engineering", each instructed by a team of five graduate students and research staff from a variety of disciplines at Caltech. The courses are designed to be representative of Caltech, providing a glimpse of the undergraduate lifestyle, academic rigor, and active research interests. Similar to the Institute, the YESS program has a remarkably low instructor to student ratio of 3:1, allowing for great amounts of formal and informal interaction with active researchers. Since

instructors each incorporate their research expertise into the curriculum, there is a dominant focus on fundamental science and engineering principles and research similar to the Institute's own research initiatives.

One of the challenges in instructing young students in engineering and science courses is to teach them to think critically and develop efficient and effective problem-solving skills. The YESS program aims to introduce these skills to high achieving students in a non-threatening pre-college environment. This paper discusses the 2008 Physics and Engineering course, designed in the framework of classical or Newtonian mechanics, but with a focus on development of scientific analysis and problem-solving skills. Newtonian mechanics was chosen because it is fundamental to all science disciplines and it is very often the subject of required first-year college physics courses, whose large class sizes and difficult material often deter talented students from science and engineering majors. With an early introduction to these fundamental concepts and a proven toolbox of analytical skills, it is thought that students will become more confident and more encouraged to pursue engineering and science degrees since subsequent high school and introductory college courses will be more manageable and rewarding.

Overview of the YESS Program

The YESS program is a three-week residential program that is provided free of cost to the student, except for transportation to and from campus. Students must be U.S. citizens or permanent residents, but can reside in any state or U.S. territory. In 2008 the program received 391 applications but narrowed it down to 30 students, with an 8% acceptance rate. This compares with a 17% acceptance rate of freshmen into Caltech. Selection criteria include SAT/PSAT scores, high school transcript, student essay, and letters of recommendation from teachers. Students are expected to have completed pre-calculus, excelled in their science and mathematics courses, and show interest and aptitude in science and engineering.

The instructors are selected in February and meet regularly in the preceding months to create a challenging and engaging curriculum personalized to the team's expertise. Caltech undergraduate students serve as residential counselors and are in charge of non-academic activities.

The participants have a rigorous schedule of two three-hour classes each day, broken into smaller modules and divided among the team of instructors. Classes are completed by 4pm, followed by a two-hour relaxation or study period before dinner. After dinner there is often an evening activity such as a faculty lecture, admissions workshop, research laboratory tour, or an informal gathering with members of the Caltech community. Instructors also hold optional office hours in the evening to assist with homework, go over material, or aid students in projects and presentations.

The 2008 YESS class was composed of 29 students (11 females and 18 male students). The majority (26) of participants were rising high school seniors, and many were the top students in their class. Nearly half (14) of the students had completed a high school physics course prior to attending the program. Math PSAT scores for the group ranged from 59-80 and the average score was 69.

Physics and Engineering from a Newtonian Mechanics Framework

The physics and engineering course teaches classical mechanics intertwined with relevant research and design topics. In 2008, the five physics instructors had diverse backgrounds from research groups in mechanical engineering, aeronautics, materials science, bioengineering, and particle physics. Although various forms of engineering and science careers are mentioned, the course is not designed to explicitly be an overview of various engineering majors. It is also not meant to be comprehensive of the material and is not a substitute for an AP or college course. Instead, it should be regarded as a short course in mechanics fundamentals that supplements previous physics classes and helps prepare the student for future courses. More importantly, it aims to cultivate and develop a scientific or analytical way of thinking and solving problems such that participants will aspire towards an advanced degree in science or engineering.

The 2008 curriculum was based on previous years' experience and feedback, and was designed to highlight the strength of the Institution and the instructors by placing an emphasis on fundamental science and engineering research rather than on applied technologies and innovation. The curriculum can be summarized through three main objectives:

- 1) Students should achieve a conceptual understanding of Newtonian mechanics and the physical laws that surround us in our daily lives
- 2) Students should acquire an appreciation for the depth and scope of active physics and engineering research and its connection to Newtonian mechanics
- 3) Students should understand how to analyze and solve basic physics and engineering problems

Objectives are achieved by a combination of lectures, laboratory exercises, small group problems, and homework, in addition to two projects on engineering design and scientific research. The topics included kinematics, Newton's laws, momentum, energy, and circular motion. Each instructor also prepared a lecture and an activity on their current Caltech research area, and was required to connect it to fundamental mechanics. These special topics included fluid mechanics, orbital mechanics, waves and optics, and an intro to particle dynamics and quantum mechanics, to demonstrate where and how classical mechanics is not sufficient. Advanced topics required no formal homework or student preparation outside of scheduled class time. Together with a faculty lecture series, the purpose is to give participants an overview of Caltech research, as well as to demonstrate the applications of mechanics that are utilized in state-of-the-art research.

Mechanics Teaching Philosophies

During the lectures the material is presented from a conceptual framework with a minimum number of equations in a pre-calculus formulation. Many physics courses provide students with equation sheets so that they do not have to memorize all the formulas they may need in order to solve a problem. This encourages students to 'plug and chug', or to find the formula that has the same variables as those given in the problem and compute the answer without thinking about, and thus without learning, the physical concept. However, many of these formulas are not unique and are all derived from the same basic principles with varying assumptions or initial conditions.

The concept of beginning from basic principles and thinking about the physics and initial conditions of a problem is a skill many learn in undergraduate engineering or physics programs, but are not commonly exposed to in high school.

YESS encourages all students to solve problems from the most basic concept introduced in class, in which more specific equations are purposely not presented. A perfectly completed homework problem was to include the fundamental equation or concept (e.g. $\Sigma \mathbf{F} = m\mathbf{a}$), all assumptions, a sketch of the problem (including separate free body diagrams if applicable), all mathematical steps in symbolic form, and final mathematical expression before numbers are calculated. There was a strong focus on the concept and process rather than the final answer. Homework problems often lost points for insufficient explanations even if students had the proper answer. Students were encouraged to discuss and explain their thought progression, right or wrong, with instructors and peers.

This was a new approach for many students, especially those who had already completed high school physics. Many resisted the change in teaching and learning style, whereas others were excited to finally learn where an equation came from, and how many were connected to one another. Some students who were encountering physics for the first time struggled with new concepts as well as the problem-solving skills. These students often required more time one-on-one with instructors to walk through all the concepts and steps they should take to solve the problem, but many showed significant improvement throughout the three weeks.

A similar challenge arose during the classroom laboratory assignments, where students were not accustomed to thinking critically about the experiment. Instructors were informed by one honest participant that there is often a negative stigma associated with classroom lab experiments. They are usually given a set of instructions or lab manual, including details of the exact measurements needed, followed by a wordy lab report restating much of the lab manual. Thus, the scientific objectives of the assignment were lost in the busy work.

The 2008 curriculum had two labs requiring written reports, and one was an investigation into Hooke's Law. The purpose, clearly stated, was to find the mass of an unknown object using a spring system and Hooke's Law. Students were given the materials and an outline of the procedure but they had to make decisions such as the proper choice of spring, how many data points were needed, and what size masses were appropriate for the problem. Analysis questions guided the students to plot the data, and determine the unknown object's mass, but also asked more in-depth questions about the procedure such as "how do you know the choice of spring and data points obtained was adequate for the measurement of the unknown mass?" Results and questions were to be discussed in a formal typed report that had a heavy emphasis on the choice of experimental design, analysis and conclusions.

The lab was designed to be an exercise in experimental design and procedure, in addition to learning how to build a spring-scale and take accurate mass measurements. Most students struggled with the procedural steps, and resisted thinking about the various options and consequences, even under guidance of the instructors. Likewise, the lab reports were returned with overall poor grades, and many students expressed frustration that the YESS criteria and lab requirements were different from their expectations. One student offered a suggestion that "lab

assignment” and “lab report” were the wrong name for the exercise, and perhaps it should be renamed in the future to avoid the preconceptions many students have from high school lab experiences. Revisions of the lab report were accepted for higher grades, and almost all the students took the opportunity to listen to the suggestions of the instructors, improve their work, and admittedly learned more about the experimental process.

Force Concept Inventory Assessment

A pre and post Force Concept Inventory (FCI)⁴ multiple-choice test was given to the students on the first and last day of the three-week course. In the previous year¹, the Mechanical Baseline Exam was given instead of the FCI, which showed only marginal improvement compared with

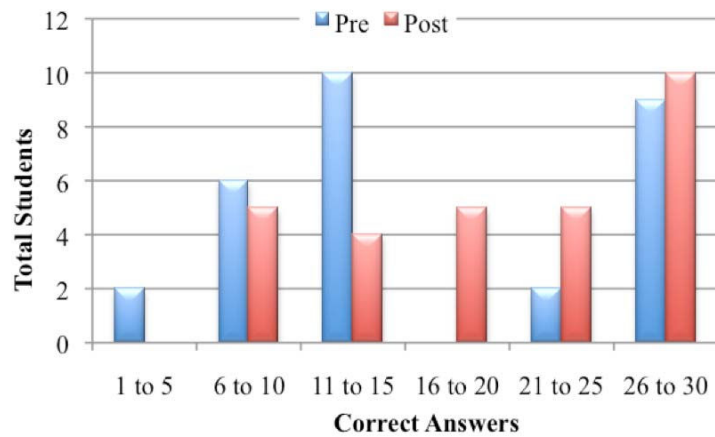


Figure 1: Pre and post-test FCI results.

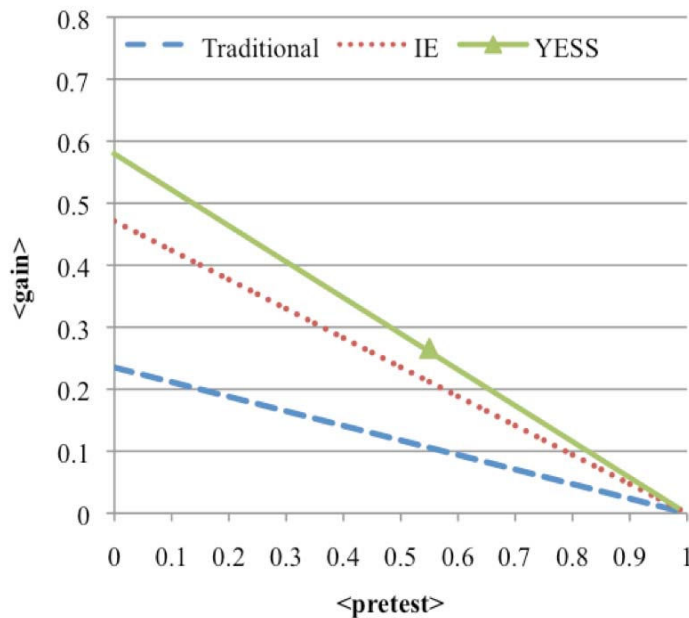


Figure 2: Comparison of <gain> vs. <pretest> with other traditional and interactive engagement style introductory courses.

other courses. The FCI test was chosen this year to gauge the conceptual understanding of the mechanics material, not biased by quantitative skills.

The exam contains thirty questions and the mean for the pre and post-tests were 16.4 and 20.0, respectively. There was no penalty for answering the questions incorrectly. Given that there are five choices, a random test taker would score a 6 on average. However, a student without a Newtonian thought process may have a predisposition to select an incorrect answer.

Out of a pool of 29 students, the standard deviation for the pre and post-tests were 9.0 and 7.3 respectively. Figure 1 shows the distribution of students and their results on the 30 question exam. The pre-test results show that approximately 1/3 of the students performed extremely well (between 26 to 30) before even taking the three-week course. As such, the improvement of these students is difficult to measure using this test. The average normalized gain for these 29 students was 0.266, as defined by

$$\langle gain \rangle = \frac{S_{After} - S_{Before}}{100\% - S_{After}},$$

where S_{Before} is the average test score from the pre-examination, S_{After} is the average test score from the post-examination, and the 100% denotes the maximum achievable test score of 30.

In comparison with previous published data for the FCI test⁵, the $\langle gain \rangle$ of 0.266 compares well with that of traditional courses where it varies from 0.09 to 0.26 and interactive engagement (IE) courses where it varies from 0.18 to 0.67. Because the students in this course received a higher average mark on the pretest than those in the study, a better indicator is a comparison of the slope line of $\% \langle gain \rangle$ vs. $\% \langle pre-test \rangle$ as measured in Figure 1 of the published data⁵. Unlike the $\langle gain \rangle$ indicator, this slope line takes into account the effect of higher average pretest scores. This slope is defined numerically as

$$slopline = \frac{\langle gain \rangle}{\langle pretest \rangle - 1},$$

where $\langle pretest \rangle$ is the fraction of the average pretest score, or 0.546 for this course. The slope line for the current course is 0.585. In comparison to the average of the previous study, for traditional courses it is 0.235, and for IE courses it is 0.471. Figure 2 compares the slopes of the previous published paper and this course. The FCI test results show that the students have improved at a very exceptional level that compares favorably and exceeds that of many full semester introductory level physics courses.

Mentoring Students in Engineering Design

The 2008 engineering design project was to build an egg-launching catapult or trebuchet⁶ that would compete for the longest distance and the most accurate toss to a 25 foot frying pan. Students are divided into teams of 4, and each instructor was assigned to a group as a consultant and mentor. Specifications were given as to the materials, size, cost, and the specific rules of the competition. The winner would have the most total points from four categories: Accuracy competition (30), Distance competition (30), Design and Creativity (20), Poster Presentation (20). Members of the Caltech community including professors, graduate students, staff, as well as local television and newspaper reporters came to the competition where students had the chance to explain their design and give a poster presentation of their analysis, design, and results.

The primary role of the mentor was to teach and guide students through the engineering process. Since the design had to meet the two different objectives of launching the egg accurately at a predetermined distance as well as of launching it as far as possible, students were forced to evaluate the design trade-offs commonly encountered with real-life engineering problems. Other technical challenges involved working within the given budget of \$25 and choosing the right materials for a proposed design. In order to find the relevant parameters, an analysis portion was completed on paper prior to building.

Mentoring the students was a challenging role for many reasons. One of the first obstacles was to create a welcoming environment where all ideas were accepted and discussed. Many of these students are not accustomed to working alongside peers that are equally bright and motivated, and would not naturally collaborate. Instructors would repeatedly emphasize the collaborative

nature of the work commonly done by engineers and scientists, and would suggest to groups that potential ideas be presented with a logical scientific basis. For example, designs that were discovered through internet searches should be properly evaluated and critiqued based on the scientific merit.

There were a few groups that worked seamlessly together, listening carefully to the advice of their mentor. However others presented very challenging group dynamics. One group defaulted to a leader who was thought to be the most advanced student in the class, and who single-handedly designed a complicated trebuchet pulley system. Many members did not understand the design but trusted their leader despite concerns from their mentor. When the trebuchet failed to work, the group was distraught. In a thoughtful discussion, students were reassured that this process is common in real-life engineering projects, and they should not be disappointed, but should rather reevaluate and iterate on the design. The result was a tremendous increase in confidence from the three followers, who now understood the value of challenging each other's ideas. Although the final product was rushed and not as perfected as other groups, all of the team members were aware of the valuable analysis and teamwork skills they learned, and the increase in confidence was maintained throughout the program.

Although this was an extreme example, the problem of how to evaluate and critique each other's ideas and analyses was encountered by many groups. Tasks were commonly delegated to individuals, thus causing oversights and mistakes, especially in the analysis. Although the mentors encouraged collaboration between the group members, effective communication and collaboration often fell apart when the mentors were not present. Perhaps a cleverly designed exercise at the beginning of the project could better encourage and teach students to carefully and constructively critique each other's work.

Mentoring Students in Research Projects

The research project began at the conclusion of the design project, and final presentations were held on the last day of the program. Each instructor prepared two research topics for a total of 10. Students ranked their top three choices and were subsequently assigned to teams of three based on common interests. The assignment consisted of researching a relevant mechanics-based topic connected to the active research interests of the instructor. The list of topics were: *Friction and adhesion in gecko toes*, *Solid mechanics and elasticity of bouncy balls*, *Cosmic rays*, *Understanding black holes*, *Hydroelectric power*, *Hybrid vehicles and regenerative braking*, *Rocket multi-staging*, *Interplanetary trajectories: The Hohmann transfer orbit*, *Nanotechnology with the atomic force microscope*, *Transportation efficiency*.

The instructors were to clearly define the projects before the start of the program to ensure they would be within the scope of the students' ability and time constraints. The project was not a literature review or a straightforward report, but rather an identifiable problem or hypothesis for students to investigate and analyze, more similar to an undergraduate research experience. Depending on the project, students performed simple experiments, received personalized tours and explanations of state-of-the-art laboratory equipment, and/or performed advanced theoretical calculations. The final result was a concise and professionally written four-page paper,

purposefully short so that students could focus on their own scientific findings, together with a 10-minute presentation.

Properly mentoring and guiding the students through this experience took much time and effort from the instructors. Most students had not been exposed to this type of project and if left alone to complete the assignment would have given a literature review on the topic without any in-depth scientific analysis. Various strategies were employed to counteract this tendency. One was to have a very detailed list of mini-assignments for the students to follow, including which chapters to read, what questions to answer, and what analysis should be completed. Another approach was to begin the research process with a small, interactive mini-lecture on the group's topic that is specially catered to their ability and knowledge, and which was designed to let the students discover a tangible research question or hypothesis. But even after these initial steps of outlining the project and scope, many groups still needed extra guidance on how to properly analyze the problem in the context of mechanics without becoming side-tracked or reverting to a "book report" style presentation.

As an example, the *Nanotechnology with the atomic force microscope (AFM)* project's scope was modified from a previous year. The AFM is a multi-disciplinary tool that is used for a wide variety of functions by researchers in many fields. Therefore when students do an internet search of AFM there is a surplus of information that they cannot easily sort through, much of which is beyond their level of comprehension, and it easily becomes an exercise in breadth rather than depth. This year's project was narrowed down to an investigation of the mechanical forces that govern an AFM, and references and research questions were carefully selected to keep the students on the mechanics track. The mentor helped his students build a scaled-up AFM model using a laser pointer and office supplies, and helped them derive simple force equations using Hooke's Law. The final report and presentation, rather than being a literature review on the applications of the AFM, demonstrated that the students learned how the AFM works and what it takes to build one.

The quality of the final presentations was mixed, and some were lacking a proper discussion of the required mathematics and physics analysis. The groups that performed the best had a well-defined scientific question or hypothesis formulated in advance by their mentor. Success was also very dependent on the group's dynamics and level of interaction with their mentor. The students whose personalities favored approaching their mentor, asking questions, and becoming proactive in the research process generally performed better than the students who did not actively seek guidance.

Student Surveys

Student surveys were distributed approximately three weeks after the program's completion to assess the program. A second follow-up survey was sent six months after completion. Over those that completed the survey, 91% strongly agreed that the program was a positive experience overall, and 91% also indicated they would recommend the program to their friends. When asked if they had the opportunity to explore Caltech as a possible college option, 91% strongly agreed with the statement, and 96% said they would apply to Caltech as one of their top choices.

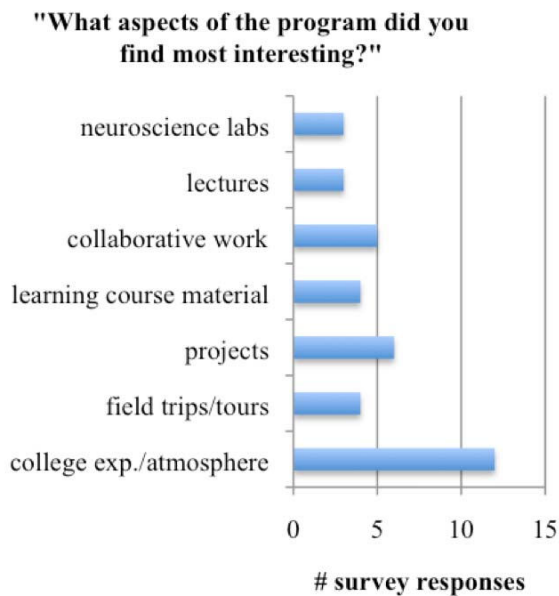


Figure 3: Summary of open-ended responses to what aspects were most interesting.

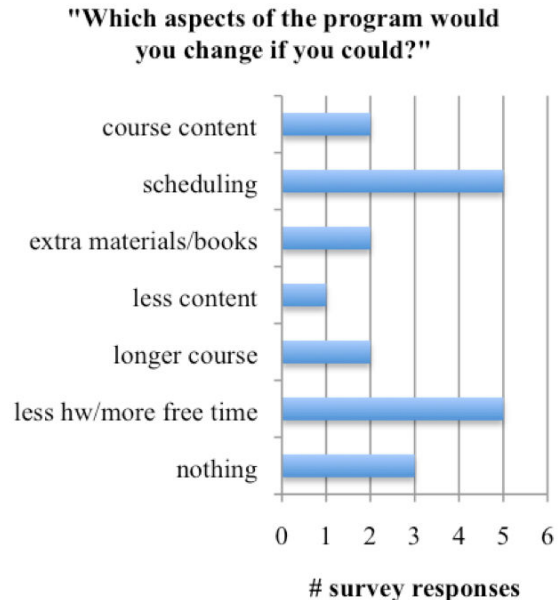


Figure 4: Summary of open-ended responses to what participants would change.

In addition, participants were asked open-ended response questions about the most interesting aspects of the program, summarized in figure 3. The most popular response mentioned the college experience or the general atmosphere and community of the program or Institute. Students appreciated the level of interaction they were exposed to within the Caltech community and the experience of being around students with similar interests. Many enjoyed working collaboratively, which included time spent in the instructor-run physics office hours. Another common response was the design/research projects. One student who elaborated indicated he/she “enjoyed the simple introduction to an advanced topic, which really sparked my interest.”

Students were also asked what aspects they would change, summarized in figure 4. A theme throughout the replies is too much work and not enough time. Many students did not like the hectic schedule and recommended making field trips optional so they had more time to do homework, or coordinating assignments between courses so deadlines don’t overlap. The program is intentionally rigorous, and is designed to prepare students for the academic schedule and workload of a Caltech undergraduate. Although there are more frequent assignments, students are only taking two courses as opposed to five or six in which undergrads are typically enrolled. In addition, many of these students are at the top of their class in their respective high school, and have never had the opportunity to take an academic course load that challenges them. Therefore, an adjustment to the fast-paced academic environment is expected since the curricula are intentionally designed to challenge the students.

Table 1: Initial survey results of science and engineering attitudes and program experiences.

	Strongly agree	Somewhat agree	Neither disagree nor agree	Somewhat disagree	Strongly disagree
Overall my experience has increased my interest in pursuing a career in science and/or engineering.	73%	18%	5%	5%	0%
I have a better understanding of what is required for me to succeed in college than I did before attending.	73%	18%	9%	0%	0%
As a result of participating, I am more likely to choose a science or engineering related career.	46%	36%	18%	0%	0%
I have strong doubts about whether I am suited for a career in science/engineering.	0%	0%	0%	18%	82%
I have a better understanding of how science and engineering research is done.	91%	9%	0%	0%	0%

Table 2: Follow-up survey results.

The YESS program influenced my current choice in college major.	35%	35%	24%	0%	6%
The YESS program introduced new fields of science and engineering that I was not aware of before attending.	41%	41%	0%	12%	6%
After the YESS program, I can identify more examples of science and engineering research.	53%	47%	0%	0%	0%
After participating in YESS, I am better able to identify examples of physics and engineering in the world around me. (include examples from TV, leisure books, magazines etc.)	41%	35%	18%	6%	0%
YESS Physics helped me in preparation for the physics course I am currently enrolled in.	65%	12%	6%	0%	6%

Table 3: Initial survey feedback on the physics and engineering course.

Class activities kept my interest.	23%	55%	9%	5%	9%
It seemed to me that the instructors had a good understanding of the subject area they taught in this class.	77%	23%	0%	0%	0%
The instructors showed concern for how well I learned the material.	77%	9%	5%	9%	0%
The pace of the class was too slow for me.	5%	14%	18%	23%	41%
Labs were interesting.	19%	57%	14%	10%	0%
I didn't understand a lot of what was presented in class.	5%	9%	18%	36%	27%

I gained a lot from interacting with my instructors.	77%	18%	5%	0%	0%
Office hours were helpful.	86%	5%	5%	0%	0%
As a result of taking this class, I became more interested in the subject matter.	64%	18%	9%	5%	5%
I learned something in this class that I think will help me in my future studies.	77%	23%	0%	0%	0%

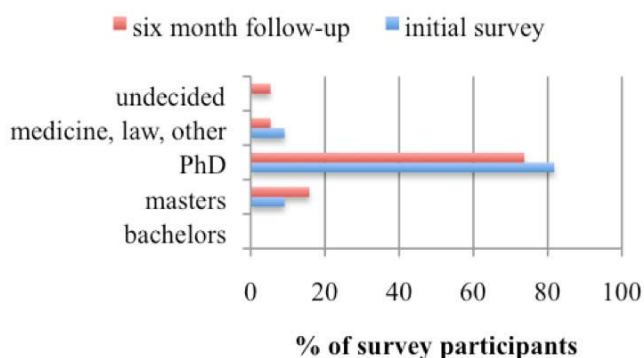


Figure 5: Survey results “What is the highest degree you want to pursue?”

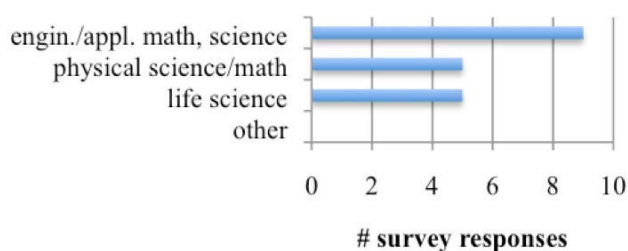


Figure 6: Top choice in college major 6 months after completion of the program.

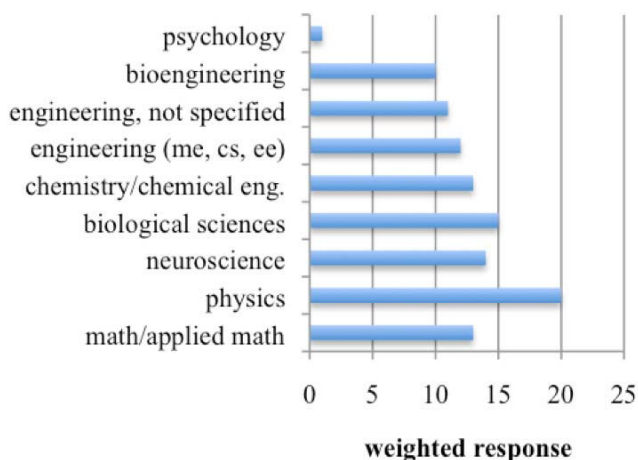


Figure 7: Top three major choices, weighted as described in text, as reported 6 months after the program.

Results from the initial survey regarding program experiences and science and engineering attitudes are shown in Table 1. Since the program’s admission criteria require a pre-existing inclination towards science and engineering, the questions try to ask specifically how the YESS experience has influenced them. Over 90% of the participants said the experience has strongly or somewhat increased their interest in a science or engineering career, and similarly 82% said they are now more likely to choose a career in science or engineering. Everyone who participated in the survey indicated they felt well suited for such a career.

Additionally, 64% of students replied that their thinking about science and/or engineering changed over the course of the program. When asked to elaborate how, most responses indicated an increased interest in related careers and felt more informed about various fields. Others learned about the multi-disciplinary nature of science and engineering, and how many subjects are related to one another, which was a major goal of the physics curriculum. Students were also asked about the highest degree they planned to pursue, and both surveys showed everyone planned to receive an advanced degree, with a majority inclined towards a PhD, as shown in figure 5. This could be indicative of the level of research exposure throughout the program, and

the close interaction with current researchers.

In the follow-up survey, students were asked their current top three choices for a college major shown in figure 6. Every student who responded indicated a science, engineering or mathematics discipline as his/her top choice. Since the number of participants is small, a weighted response of the top three majors of each respondent is given in figure 7. The first choice is weighted by 3 points, the second choice by 2, and the third choice by 1 point. Using this system, physics, biological sciences and neuroscience were the top choices in majors, which corresponds to the curriculum of the two YESS courses. Table 2 shows science and engineering attitude responses from the follow-up survey, with 70% indicating YESS had an influence on their current choice in major. Participants also overwhelmingly indicated that the program introduced them to new fields of science and engineering, and that in the past six months they have become better able to identify examples of science and engineering in the world around them, indicating an increased awareness of the applications and impacts of science and engineering in their everyday lives.

Individual feedback on the physics and engineering course is given in table 3. The results were positive concerning the course structure and the instructors. The instructors received excellent remarks as a whole, with 77% of students indicating that they gained a lot from interactions with them. Students also expressed that instructors had a good understanding of the material, and that they showed concern for how well students learned the material. One student commented about the instructors, “one could tell, [they] enjoyed the subject that they were teaching; and it was this fascination and admiration for the subject they had that most struck me.” However, the majority only “somewhat agreed” with the statements “class activities kept my interest” and “labs were interesting”. Given the variety of class activities, future surveys should ask the students to rank various portions of the course separately.

A challenging part of the curriculum development was to engage a range of academic levels, from those who have completed AP physics to those who have never taken a physics course. Survey results indicate that the course was well designed for both extremes. Only 5% strongly agreed they didn't understand a lot of what was presented in class and only 5% strongly agreed that the pace of the class was too slow. In addition, a sample of open-ended student comments include:

“The class was well suited for all students, whether they had physics before or not.”

“As I am already an avid physics lover, this class helped me stay in practice and keeping my hunger for physics knowledge abated.”

“Even though I already had a year of AP physics it still had my attention and still made me a lot better.”

“Physics was definitely challenging, but in the end I feel like I learned a lot.”

“I now believe that I will do much better when I take physics this coming year at my high school.”

The follow-up survey administered in January revealed that 65% strongly agreed that the YESS physics course helped in preparation for their current physics class. The 6% that strongly disagreed corresponded to 1 student who indicated he was currently taking electricity and magnetism, and who believed that the mechanics material from YESS was unrelated. Overall, these results are promising, and will help fulfill the course's goal of building a better physics

foundation in students as well as an increased confidence level in science and engineering as they begin college.

Summary and Recommendations

The 2008 YESS program introduced high-achieving juniors and seniors in high school to a rigorous and challenging Newtonian mechanics curriculum in a three-week summer course. A conceptual learning approach was implemented and the content was taught through a variety of classroom activities as well as an engineering design and analytical research project. The teaching philosophy emphasized a problem-solving technique from fundamental principles, and only simple equations were presented in class lectures to prevent students from a 'plug and chug' style of searching for equations in their class notes. The student's improvement was assessed through a pre and post-test using the Force Concept Inventory (FCI) and demonstrated high gains compared with previously published data from traditional and interactive engagement semester-long introductory physics courses.

The course received good remarks from the students on evaluation surveys, but there is room for improvement in the laboratory exercises. They were designed to complement the mechanics learning process through self-discovery and provide an exercise in the experimental design process. However the guidelines and expectations varied from that of the high school labs many students were accustomed to, and thus led to confusion and disappointment for some. Future recommendations are to give a short lecture-style tutorial on general experimental design, and clearly express the expectations before beginning any laboratory assignments. In addition, renaming the lab activities to mini-research projects may help invoke an investigative spirit in the students, as well as prepare them for the larger research project at the end of the course.

The design and research projects are also reviewed, with specific examples of group dynamics and mentorship from instructors. Difficulties arose when work was delegated and students failed to critique and revise each other's analysis and design. In the future it is recommended that the instructors hold a mentoring workshop before the program begins to talk about potential and past problems with group dynamics, and brainstorm ways to proactively help students collaborate. Another idea is for the instructors to have a brief role-playing skit in front of the students demonstrating how to effectively work together with different personalities.

Research projects allowed the students to investigate an advanced topic under the guidance of an instructor. The major challenge was to show students the difference between a literature survey and the scientific analysis of a particular problem. The final presentations varied widely, but the best groups had a very clear hypothesis and road map predefined by their mentor, were engaged in the subject material, and proactively sought advice. Defining a research project for high school students is challenging, and may be best learned through experience. But general recommendations are to have a very small scope and clear objectives, as students are easily distracted by information, especially given how easily available it is on the internet. Giving students an outline, a set of reliable references, and a list of important questions can help guide them through this process. It is also important to demonstrate the difference between reporting information from a book or article, and critically gathering information to perform an analysis utilizing the mechanics and problem solving skills learned from class.

In summary, student surveys indicate that they are all highly interested in science and engineering careers, and the YESS program helped to further their interest and influenced their current choice in college major. In addition, 91% of the 2008 participants would recommend the program to their friends, and 96% plan to apply to Caltech as one of their top college choices.

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