AC 2009-2022: INTEGRATING ENGINEERING, MODELING, AND COMPUTATION INTO THE BIOLOGY CLASSROOM: DEVELOPMENT OF MULTIDISCIPLINARY HIGH-SCHOOL NEUROSCIENCE CURRICULA

Tara Gomez, California Institute of Technology

Tara Gomez received her B.S. in Molecular, Cellular and Developmental Biology from the University of California, Los Angeles. She is a Ph.D. Candidate in Biology at the California Institute of Technology. Her research is in the area of Biochemistry and protein degradation. She was the Neuroscience Curriculum Coordinator for the 2008 YESS Program.

Oliver Loson, California Institute of Technology

Oliver received his B.S. in the neurosciences from the University of California, Riverside. He is now in the biology graduate program at the California Institute of Technology, and is working towards earning a doctorate of philosophy. Oliver is investigating the role of mitochondrial genetics in diseases affecting this organelle, and is also trying to develop techniques for manipulating the mitochondrial genome.

Douglas Yung, California Institute of Technology

Douglas Yung earned a Ph.D. in Bioengineering from Caltech, and a B.S. in Electrical Engineering and Mathematics from UCLA. He received the NASA Postdoctoral Fellowship and is currently working at Jet Propulsion Laboratory in California. His research focuses on photonics, biosensor development, microfluidics, molecular & environmental microbiology, as well as astrobiology. He maintains the website and taught biostatistics, network circuitry, and neuronal modeling in the 2008 YESS program.

Sindhuja Kadambi, California Institute of Technology

Sindhuja received her B.S. in Genetics from the Rutgers University. She is currently working on her Ph.D. work at Caltech, studying glutamate gated chloride channels using electrophysiology.

Paul Lee, California Institute of Technology

Paul received his B.S. in Chemistry in 2003 from Dartmouth College. He is currently working on his Ph.D. work at Caltech, studying the response of DNA to oxidative damage.

Luz Rivas, California Institute of Technology

Luz Rivas is Program Manager in the Office for Minority Student Education at the California Institute of Technology. Luz serves as the Director of the YESS Program. She received a Bachelor of Science in Electrical Engineering from the Massachusetts Institute of Technology and a Master of Education degree from the Harvard Graduate School of Education.

Integrating Engineering, Modeling and Computation into the Biology Classroom: Development of a Multi-Disciplinary High School Neuroscience Curricula

Abstract

The YESS program is a three-week summer residential course that brings together extraordinarily talented high school students from underrepresented minority groups to study at the California Institute of Technology. The YESS program is intended for students who exhibit an interest in engineering and science, and wish to engage in collaborative learning. During the three-week program, students take science courses and are exposed to laboratory tours, faculty lectures, and college admissions workshops.

The neuroscience course for the 2008 YESS program was an intensive survey of many different fields, and used lectures, demonstrations and laboratory activities to teach topics such as brain anatomy, *Drosophila melanogaster* pain perception, electrophysiology, recombinant DNA technology, neuronal modeling, the molecular basis of learning and systems neuroscience.

Neuroscience is a branch of biology, yet neuroscientists are typically highly diversified scientists and engineers. Neuroscience spans a wide array of disciplines that include engineering, mathematics, computer science, biophysics and medicine. The diversity found in the neurosciences evolved naturally because of the fields' need for creative problem solving concerning the technical difficulties that plague experimentation with the brain. The California Institute of Technology's neuroscience researchers have synergistic relationships between engineers and scientists of various disciplines, and together, they advance our knowledge in this field. In line with the efforts of our institution, we created a neuroscience curriculum that shows the interplay between engineering and biology, taking care to keep the material accessible for a gifted high school audience.

The creation and implementation of a multi-disciplinary neuroscience curriculum for the YESS program is the focus of this paper. Specifically, we will address how we integrated engineering, mathematical modeling and computation into the curriculum as a tool for communicating intellectually rigorous ideas concerning the neurosciences. We assessed our curriculum using a system of pre- and post-examinations. By combining the results of these assessments with student surveys and feedback, we conclude that the integration of engineering, modeling and computation was an effective way to teach neuroscience.

The modules we describe here, can be adapted by other educators in K-12 advanced science courses as a vehicle for introducing engineering concepts or in an engineering course as demonstratives of engineering applications in the life sciences.

1. Introduction

The increasing interdependence of science and engineering disciplines has led educators to rethink the way science is taught in K-12 grades. The interdisciplinary nature of emerging science and engineering fields requires students to be able to integrate ideas from several subject areas.[1] Recent recommendations for reform have emphasized the need for interdisciplinary approaches to K-12 science education. For example, the American Association for the Advancement of Science's (AAAS) Benchmarks for Science Literacy emphasizes that core studies in K-12 science education should include connections among science, mathematics and technology. [2] In addition, one of the AAAS learning goals for high school students states that students should understand that scientists study problems using information and skills from many disciplines and that disciplines do not have fixed boundaries.

While the need for preparing pre-college students for interdisciplinary fields has been identified, many challenges exist in implementing interdisciplinary curricula in high school science classrooms.[3] For the most part, high school science is taught with strict divisions between disciplines separating the biological and physical sciences. This structure does not easily accommodate integration of disciplines that reformers call for. Additionally, few high school science teachers have had the opportunity to explore interdisciplinary fields or learn engineering concepts.[2] Because of these challenges that exist in formal educational settings, most interdisciplinary K-12 science instruction has been offered at science-rich institutions such as universities and informal science centers. These institutions typically offer workshops or summer programs taught by science researchers. These institutions offer access to resources and science researchers and have more flexibility in offering educational programs in interdisciplinary fields. Programs implemented at universities have included introducing high school students to fields such as nanotechnology and neuroscience. [1,4] Programs offered by universities and other science institutions can have an impact in increasing the science literacy of high school students.

In this paper, we present the development of an interdisciplinary neuroscience course for a three-week summer residential program for high school students interested in science and engineering. Neuroscience, one of the fastest growing interdisciplinary scientific fields, encompasses the study of the nervous system and its role in regulating behavior. The field spans a wide array of disciplines that include engineering, mathematics, computer science, biophysics and medicine. The curriculum we developed highlights the relationships between engineering and biology by integrating modeling and computation exercises and utilizes the resources (materials, laboratories, and researchers) available at our institution. The course aims to broaden the students' view of science and engineering by demonstrating the interdisciplinary nature of science.

We believe that K-12 educators can adapt our modules to either introduce engineering concepts into advanced Biology courses or to integrate Neuroscience and demonstrate applications into engineering courses.

2. The YESS Program

The YESS (Young Engineering and Science Scholars) program is a three-week summer residential program intended for rising high school juniors and seniors who are underrepresented in science and engineering fields and who wish to broaden their knowledge of science and engineering beyond that offered by their high schools. The YESS program serves as the campus's targeted recruitment/immersion program for highly talented underrepresented high school students interested in pursuing study in science and engineering. The program aims to increase the number of YESS participants who apply to and are admitted by Caltech. Since 2001, 31 YESS participants have been admitted to Caltech with 19 choosing to matriculate.

During the three-week program, students take two intense courses in Neuroscience and Physics. The course curriculum is developed and taught by Caltech postdoctoral scholars and graduate students. Each course is designed to expose students to fundamental ideas by using a combination of laboratory experiments, lecture, laboratory tours and application based homework sets. Both courses end with a group research project, instructors and Caltech community members. In addition to taking courses, participants are also exposed to laboratory tours, attend faculty lectures, and interact directly with Caltech Admission officers through workshops focusing on strengthening college applications.

The neuroscience course was also designed to go beyond teaching students the fundamentals of the advanced topics they are studying. We want our students to begin thinking like scientists and to have an appreciation for the knowledge that is generated about biological systems through hypothesis driven experimentation. We believe that teaching them to think like scientists can have a broad application beyond biology.

2.1 Participant Selection

Each year, the YESS program receives nearly 500 applications and admits 30 students. Applicants must be high-achieving high school juniors or seniors, as well as US Citizens or Permanent Residents. Scholastically, some of the criteria the YESS program evaluates include: PSAT and SAT test scores, high school GPA, exposure to science and math courses, a personal statement, and recommendations from high school teachers.

3. Neuroscience Course Curriculum

Times are changing and there has been an ever-increasing overlap in the interests of the neurosciences, applied mathematics and engineering. It is one of the underlined beliefs of the course to teach fundamental ideas, many of which have mathematic and physical components. A common misconception amongst students about biology and neuroscience is that they are subjects rooted in memorization of facts without much quantitation. Because both these subjects rely heavily on quantitative analysis and many disciplines that have mathematical foundations, the YESS lectures are tailor made to integrate biostatistics, mathematical modeling, basic electrical engineering and neuroscience to communicate the interdisciplinary nature of biological research and to give our students a clear and complete panorama of the neurosciences.

The neuroscience portion of the YESS program is intended to teach participants a few fundamental learning objectives that include:

1) The brain is a processor of environmental stimuli

2) Neurons are integrators and have to process multiple inputs

3) Molecular Biology and Statistical tools can be used in conjunction to understand the nervous system

These particular learning objectives laid a foundation for creating a multidisciplinary course curriculum that would incorporate unifying themes of circuitry, network design, and signal integration. In order to promote our students thinking about neuroscience in these ways, we divided our course into three thematic units: 1) Cells, 2) Tissues and 3) Networks.

Neuroscience is an interdisciplinary science not only because the brain can be thought of as a "super computer" that requires differing disciplines to discover its secrets, but also because of the nature of the tools and instruments used to address research questions regarding this complex organ. For example, some neuroscientists must use sensitive equipment to measure potentials across membranes and the electrical impulses generated by neurons. Other neuroscientists work to create magnetic resonance imaging device technologies used to visualize the brain. In our course, we addressed both the conceptual and the instrumental interdisciplinary nature of neuroscience at every thematic junction. A summary of the topics discussed during each thematic unit, the course goal addressed, and the engineering application of each is presented in Table 1.

The YESS Neuroscience Course aimed to teach our learning objectives by emphasizing hands-on laboratory exercises. The class met for three hours every weekday morning. At the start of each class, students took a 10-minute quiz on preparatory reading assignments they were to read before class. Next, a thirty-minute lecture followed to reinforce the reading topics and the concepts to be learned in the subsequent laboratory procedure. After lecture, the laboratory exercise would generally occupy a majority of the classroom period and was critical for solidifying the lessons taught in the reading and lecture. The lecturer would allow additional time after both the lecture and the laboratory exercise for a class discussion to aid in understanding the core ideas. Classroom discussions were engaging and rewards were given to discussion participants as positive reinforcement.

There was a daily problem set assignment that reflected the ideas discussed in the lab. This homework assignment was generally due on the following day. Additionally, daily homework also included a 30-minute pre-reading assignment that prepared the students for the laboratory to be performed the next day.

Laboratory exercises were completed in the teaching laboratory spaces found on the Caltech campus. These rooms generally had most of the physical equipment and many resources required to execute our laboratory-based curriculum. The laboratories were completed in groups of five, and the ratio between instructors and students was 1:5. With this small ratio, one instructor could work with each group and better mediate understanding and comprehension of the activity.

The remainder of the paper is dedicated to detailing the specifics of some of our key laboratory exercises and the assessment of our curriculum as a whole.

Table 1. The YESS 2008 Course Design and Learning Objectives

Thematic Unit	Laboratory Exercise	Learning Objective[1]	Engineering, Math &/or Physics Concepts[2]	Engineering, Math &/or Physics Tools Used[3]
Cells	Brain Dissection	1	✓	
	Brain Visualization using Staining	1	✓	
	Pain Perception in Flies	1, 2 and 3	✓	✓
	Brain Visualization using Fluorescent Proteins	3		
Tissues	Statistics in Neuroscience	3	✓	
	Neural Communication	1	✓	✓
	Measuring Action Potentials in Worms	2	✓	✓
	Measuring Action Potentials in Coachroaches	2	✓	✓
Networks	Neuronal Modeling	1 and 2	✓	✓
	Protein Synthesis and Learning	1 and 2		
	Brain Visualization and Network Circuitry	1 and 2	✓	✓

[1] The learning objectives outlined in the chart, correspond to those listed in section 3
[2] If engineering concepts were used to teach the laboratory, a check appears in this column
[3] If special equipment/instruments with engineering applications were used to complete the laboratory procedure, a check appears in this column

Table 2. Typical YESS Neuroscience Weekly Schedule of Activities & Assignments

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
9 – 9:10 AM **Pre-Reading Quiz**	Course Introduction and Pretest	Quiz	Quiz	Quiz	Quiz
9:10-9:40 **Lecture and Post Lecture Discussion**	Lecture on Brain Dissections	Lecture on Nissl Staining of Brain slices	Lecture on DNA, Genetic Screening and Mutations	Lecture on DNA, homology and conservation	Lecture on protein expression and fluorescence
9:40-11:40 **Laboratory Exercise**	Brain Dissection	Nissl brain staining and brain slice observations	Pain Perception Screening Lab I	Pain Perception Screening Lab II	Protein purification Lab
11:40 – 12 PM **Post Laboratory Discussion**	Discussion	Discussion	Discussion	Discussion	Discussion
HOMEWORK	Problem Set on today's lab and a Pre-Reading Assignment	Problem Set on today's lab and a Pre-Reading Assignment	Problem Set on today's lab and a Pre-Reading Assignment	Problem Set on today's lab and a Pre-Reading Assignment	Problem Set on today's lab and a Pre-Reading Assignment
HOMEWORK DUE TODAY:	NONE	Monday's Problem Set	Tuesday's Problem Set	Wednesday's Problem Set	Thursday's Problem Set

3.1 Integration of Computer Computation: Fish Scale Experiment

Increasingly, biologists are becoming experts in computer applications and the hardware interfaces that computers can have with equipment. This is especially true for the neurobiologist because of his/her heavy use of microscopy and electrophysiology, which are two techniques that strongly rely on computers to control these experimental tools and collect data. Moreover, to enhance such tools for better application in the studies they perform, neurobiologists are collaborating with physicists and engineers to help them achieve such technical goals, and others are themselves trained physicists or engineers who now study neurobiology.

Our students were challenged to optimize their use of toy microscopes that interface with computer software. The task for students was to image the change in size and color of single cells found within the isolated scale of a betta fish. Their first challenge was to engineer a chamber for not only imaging the scale under a microscope, but also for enabling them to stimulate the tissue with a pharmacological agent. This type of challenge is almost a daily task for a neurobiologist, who has to develop ingenious ways to perform experiments with an organ encased in bone and not easily accessible. Secondly, the students were asked to document the effect of stimulation. To do so, they had to formulate an imaging protocol that would serve this purpose. By taking images at a defined interval (i.e. time-lapse microscopy) and combining those images into a short movie, the students discovered that they could observe gradual changes in the size and color of the relevant cells over ran elapsed time.

The collection of data is only one component of experimentation. To understand the data, the appropriate analysis must be performed to discover quantitative information. Again, computers and their software are invaluable to neurobiologists in accomplishing the quantification of data. Furthermore, a scientist must know how the quantization should be interpreted in the context of his/her hypothesis. For the fish scale experiment, students first learned how to measure the change in area of the cells they imaged using image analysis software, and then had to interpret the results they obtained for several types of pharmacological stimulations. Specifically, they were tasked to interpret which agent caused the cells to change size and color, and to conclude what molecular mechanism was responsible for this change.

3.2 Integration of Biostatistics: Problem Solving

This unit introduces basic statistics with application in neuroscience experimental design and analysis. Statistics is a form of mathematics that allows one to properly collect, interpret and present data in a rigorous format. Inclusion of basic statistics in high school curriculum is uncommon. However, the essence of statistics hinges on its application on real-life examples. The lecture began with clear statements of pertinent definitions, theorems and principles together with illustrative materials. Topics included the analysis of frequency distribution and the associated measures of central tendency, dispersion, skewness and kurtosis. This led quite naturally to a discussion of elementary probability theory and its applications, which paved the way for a study of sampling theory. Techniques of large sampling theory involving the normal distribution, applications of statistical estimation, tests of hypotheses and significance using Student's t distribution were also introduced.

The lecture was followed by in class problem assignments, which in many instances, used data drawn from actual statistical situations associated with neuroscience. For instance, students were to calculate a p-value for the pain response of wild type and mutant painless fruit flies using various statistical tests, and then analyze these results. This exercise highlighted the importance of statistical tools in the presentation of experimental results. This exercise was valuable because it prefaced a similar analysis needed for the forthcoming poster presentation, where students were to design a primer and evaluate its effectiveness in amplifying and detecting a particular gene. Without explicitly mentioning the need of statistical analysis, most students formulated hypotheses, tested them with the appropriate statistical tests, and drew conclusions. In general, they demonstrated skills in qualifying the significance of their data, the relationship between correlated or unrelated phenomena, and even predicted what may happen in the future

3.3 Integration of Mathematical Modeling: Modeling the membrane of a neuron using circuits

This unit introduced basic circuit analysis and mathematical modeling in neuroscience. It can be argued that of all the biological sciences, neuroscience is the one in which mathematics has played the greatest role. From the work of Helmholtz and Frank in the last century through to that of Hodgkin, Huxley, and many others in this century, neuroscientists have repeatedly used mathematical methods and models to help their understanding of physiological processes.

A classic example of mathematics application in the understanding of the neuron is the use of differential equations and asymptotic theory to model the diffusion phenomena responsible for the travel of electrical impulses throughout the neuron. Often times, the application of mathematics to a process that can be rather abstract can be challenging for high school students to understand. Thus, this makes teaching about the diffusional forces involved in the generation of membrane potentials in the neuron difficult. For this reason, we have specially prepared examples and models in which the only mathematical background needed for understanding the properties of the neural impulse is one in arithmetic and basic algebra.

A model is a set of instructions designed by scientists to generate data resembling those of the real system. These instructions may merely describe the data, or they may embody our concept of what causes the behavior. Comparison of the two sources of data (measured and generated) can help in evaluating how compatible the parameters of the model are with those experimentally observed, and whether the model needs further development. Before tackling the modeling of physiological systems, the instructors gave a brief background for several neurological systems, which included those of vision, audition and emotion. To help students in understanding the importance that models serve in understanding such systems, the instructors described ways in which mathematical modeling might be used to give insight into these various physiological systems, and how models help neuroscientists in developing hypotheses for testing unknowns about them.

The electrical characteristics of dendrites, axons, and synapses are all quite different. The spread of electrical current in a dendritic network is mostly a passive process that can be described by the diffusion of electricity along a leaky cable. The axon, on the other hand, has an excitable membrane and thus can propagate an electrical signal actively. At the synapse, the membrane is specialized for the release or reception of chemical neurotransmitters, and the transformation of these chemical messages into electrical ones. We discussed the flow of electricity in neurons using theories common in electrical engineering, and by deriving the mathematical bases of these phenomena, we taught the students why the flow of electricity differs in these different structures.

One way in which we approached modeling the electrical character of a neuron in a hands on and experimental fashion was to divide it into a large number of small pieces, or compartments, each of which is assumed to be isopotential. Within each compartment, the properties of the neuronal membrane were specified, and thus some compartments had excitable kinetics, while others were purely passive. The compartments were then connected by an axial resistance, resulting in a large system of coupled ordinary differential equations, with the voltage specified at discrete places along the neuron. Using basic circuit components used in nearly every electrical device, students were instructed to build simple circuits comprised of a power source (membrane potential), resistance (membrane resistance), capacitors and inductors to simulate the propagation of potential (synaptic and potential) along the different portions of a neuron's membrane. Students were to also calculate the voltage and current present in the circuit they assembled using equations as well as computer software. In addition to this modeling exercise and in an effort to show students how modeling can be used in a more physiological example, we also challenged them to calculate the signal amplification in the auditory system based on the physics of leverage. Through these exercises, they are expected to learn the concept of mathematical modeling and reductionism in science. Furthermore, this learning unit is also designed to teach students to use controlled observations or experiments to rationally build conceptual models from ones' imagination, experience and learning.

Neurons are among the most important and interesting cell type in the body. They are the fundamental building blocks of the central nervous system and hence, are responsible for motor control, cognition, perception, and memory, among other things. Emotion was used as a concluding theme to stress the significance of interactions between neurons in the nervous system, and also to summarize the entire course from nucleotides and cell physiology, to more high-level manifestations of behaviors like emotions, cognition and consciousness.

Figure 1. YESS 2008 students performing a brain dissection (A), and building models of neurons, as discussed in section 3.3, (B).

3.4 Integration of Engineering Tools: Electrophysiology

Electrophysiology experiments are the golden standard for investigation in neuroscience research. These experiments have been made possible by scientists combining an understanding of basic processes within a neuron and a background in engineering to detect and amplify electrical signals within a neuron. Giant leaps in the field have enabled the recording of electric currents from single channels of a neuron, and of a collection of neurons within a living and conscious mammalian organism. The basic principles behind electrophysiological experiments however, have not changed. Understanding these basic principles and an introduction to the engineering of tools involved in using electrophysiological equipment was the aim of this lab.

In this section, students were taught to think about the processes of the brain in their simplest form: the action potential. Neuronal membranes generate energy potentials, and when cued to activate, the neuron produces an electrical signal (i.e. the action potential) that propagates throughout the neuron and eventually transmits a signal to a receiving neuron. Both the potential energy and kinetic energy is a direct result of ions moving through ion channels because of chemical and electrical gradients. Understanding the action potential requires the integration of concepts ranging from chemistry to physics, and their application to biology. To give students a hands-on experience with the tools engineered for studying neurons and their action potentials, the laboratory included the dissection of earthworms and visualization of action potentials from the worm giant axon generated using mechanical stimulation. Such a hands-on experience with this most rudimentary unit of information transfer in the nervous system, the students were shown how the brain works as an electrical circuit and how engineering has allowed us to visualize this process.

This laboratory can be enhanced by introducing experiments where drugs that modulate action potentials are used. By first learning the particular effects that these individual drugs have at a the molecular level, students can be challenged to contemplate what effects each of these drugs will have on the action potential, and then directly test the effects of the drugs. Aside from such hypothesis driven experimentation, the lab was designed to get the students to think about how they would go about recording a phenomenon, such as an action potential, and what it was that they were really visualizing on the monitor when they saw the traces on an oscilloscope.

This type of experiment necessitates the calibration of many parameters in order to accurately visualize action potentials. The tissue needs to be immersed in a solution of certain osmolarity and pH, and the solution needs to contain certain ions not only for the tissue to survive, but to also conduct electricity. Students needed to understand that the extracellular space content is important because when measuring voltage, we are measuring the potential difference across a membrane. For this lab, students used the electrical equipment that is typical of any electrophysiology experiment. By learning how the recording equipment is set up, the students were able to comprehend that neuronal recordings are performed by establishing a circuit with the neurons, and that the electrode in the tissue is used to pick up ionic changes in the extracellular space. Also, they learned that like any electrical circuit, they had to establish a reference point for measuring the voltage potential of the giant axon, and used a ground electrode to accomplish this. Because an action potential is generally in the range of a few microvolts to a few millivolts, an amplifier is a vital component of these recordings, and by removing the amplifier from their set-up, the students quickly learned how difficult it is to detect small electrical events without this hardware.

This experiment proved to be difficult for the students particularly because the recordings are difficult to do in live tissue. First, the nerves had to be picked up by the electrodes, and as the students discovered, the nerves had to be isolated away from the body without detaching them completely. Not doing so dilutes the responses observed and increases the noise seen on the oscilloscope. Students quickly learned to determine which changes observed on the oscilloscope were real and which were artifacts of movements of the electrodes or improper isolation of the axon from the worm's other tissues. The lab gave them a feel for how equipment designed to do biological experiments requires careful calibration and preparation, and also demonstrated the importance of filtering noise to determine valid signals.

3.4 Integration of Engineering Tools: Painless fly experiment

The *painless* Drosophila experiment asked students to postulate a reason for a behavioral phenotype observed in fruit fly larvae given their knowledge of the molecular biology they had learned in classroom lectures and experiments done in the laboratory. The project was divided into two days and culminated in a poster presentation. On the first day, students were asked to observe the difference in behavior between two groups of fruit flies in response to a heat stimulus. The data for the entire class was compiled, and in order to collect information on the genetic cause for the discrepancy they observed between the two larvae groups, students were asked to set up polymerase chain reaction samples (PCR), which is a methodology used to amplify particular DNA sequences. For the second day, students created agarose gels commonly used in molecular biology to visualize DNA, and they then ran their DNA products from their PCR assays through these gels. Students were also introduced to web-based sequence alignment tools, such as BLAST, to study gene conservation, variation, and mutation, which they then applied to their fly larvae experiment in an effort to interpret the results of their PCR experiment. Finally, students were asked to design a poster presentation summarizing their results and proposed hypotheses.

Students learned engineering concepts in both a large scale and molecular framework. The equipment used for the behavioral tests was fashioned from a soldering iron outfitted with a variable voltage dial, which was necessary for the fine control of temperature used in the experiments. Students were exposed to the fundamental principal behind gel electrophoresis: that charged molecules migrate when placed in an electric field. An unplanned complication of this experiment was when the agarose used in the gels was dissolved in water instead of buffer and melted when being run. We used the opportunity to have the students postulate on why this had occurred, and most were able to realize that the gels, lacking salts, would have a high resistance, and that heat would build up faster than it could dissipate, leading to melting.

In addition to learning large scale engineering concepts, students learned the basics of biomolecular engineering. They were taught the fundamentals of how researchers study genes and biomolecular systems. The students were taught about polymerase chain reaction (PCR), and how researchers are able to exploit the unique properties of a DNA polymerase, an enzyme that synthesizes DNA, isolated from a thermophilic organism for biological research.

In addition, for the YESS 2009 year, we plan to extend the engineering applications in the laboratory by allowing students to make the soldering iron-variable voltage dial devices used.

4. Assessment

The neuroscience curriculum was designed to expose students to the multidisciplinary nature of neuroscience using a hands-on laboratory based instruction. The course proved to be a challenging and exciting experience for many of our students.

Despite the quantitative nature of neuroscience, many neuroscientists seek only verbal descriptions, naming and learning the functions of an incredibly complicated array of components; often the complexity of the problem appears to preclude a mathematical description. The goal to break this communication barrier between disciplines appeared to have been successful in the YESS 2008 program. Instructors noted that students actively sought mathematical modeling and statistical analysis throughout their final presentation. For instance, one of the student groups presented neuronal circuit models of the causes and mechanisms and various eating disorders and the interactions between different neurotransmitters and hormones.

In order to more quantitatively assess the effectiveness of our newly designed curriculum, we used several assessment tools that included: a diagnostic pre and post examination, student performance evaluations, and student surveys.

4.1 Diagnostic Exam

Pre and post examinations were used as one way to assess the effectiveness of our course. The pre examination was administered on the first day of class before any instruction began. The exams remained ungraded until the end of the course. On the last day of the course, the same exam was administered to the students. Once all exams had been collected, both the pre and post examinations were graded together blindly to eliminate any bias.

The bar graph shows the results of this assessment. The average number of correct responses increased from 19.5 ± 6.9 to 27.9 ± 5.2 from the pre examination to the post examination, respectively. The two-tailed p-value for this data set is 2.2×10^{-6}. The average improvement in correct responses/student was 8.4 ± 3.9 points. A graphical representation of this assessment can be found in Figure 2.

To quantify our student's learning, we calculated the average gain per student to be 0.41 ± 0.13. Gain is an accepted measure commonly used as a learning metric in physical science courses.[5] We calculated this value by computing: (Post Exam Score % – Pre-Exam Score %)/(100% - Post Exam Score %). A gain value can vary from 0-1 with numbers closer to 1 meaning more has been learned. We believe that our gain value shows that our students were successful in learning much of the material presented during the three-week course.

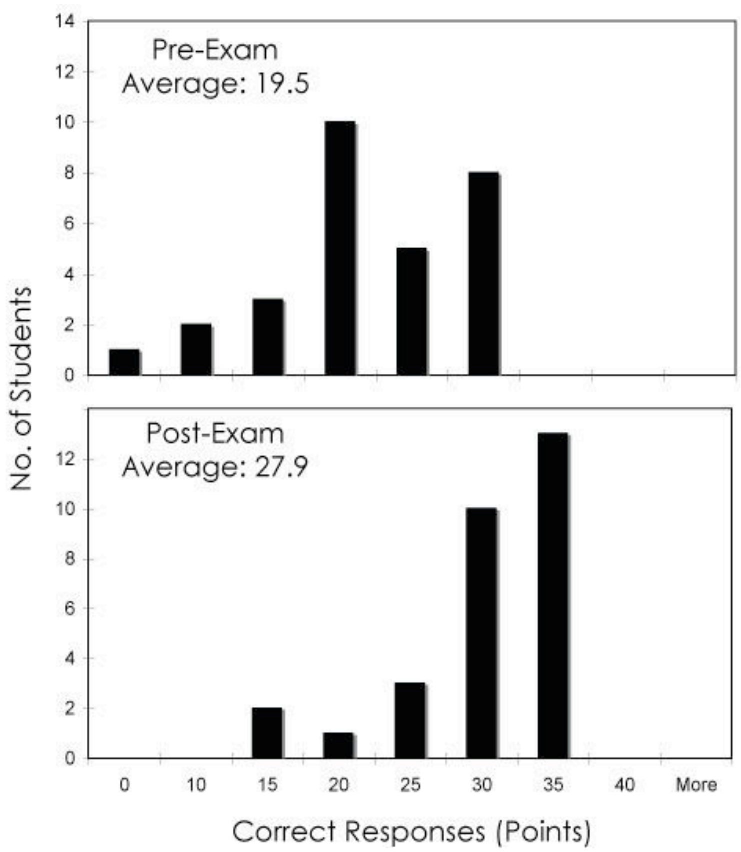

Figure 2. Comparison of performance histograms generated from the pre and post examination.

4.2 Student Course Surveys

Data collection of prior YESS students is an on going effort. Student surveys distributed shortly after the conclusion of the YESS program give us a snapshot of how the students felt about the curriculum. The surveys ask very specific questions and allow students to rank their response to the remark. From this data set, several exciting observations were seen. Some of these are highlighted in Figure 3 and below:

<u>Students enjoyed the class overall</u>. A majority of students (86.4%) strongly and somewhat agreed that the class maintained their interest. For example, one student said, "[It] was a very interesting class and had extremely fun labs." Another student enthusiastically noted that the class was "Quite wonderful, the material was fascinating." Other comments include: "It was an interesting, engaging and well-taught course."

<u>Students enjoy laboratory-based courses:</u> 90.9% of students who took the course either strongly agree or somewhat agree that the laboratories were interesting. Students expressed their pleasure with hands-on learning through many of their feedback comments. One student said, "The labs were the best part of this course. They solidified what we learned in the class through hands-on activities, and they were extremely interesting."

<u>Student's increased their interest in the subject matter:</u> Of the 22 student respondents, 72.7% of students strongly or somewhat agreed that the YESS 2008 Neuroscience course increased their interest in the subject matter. A student noted "the class in neuroscience made me more interested in the topics as well as other biological topics!" There were also some positive comments that demonstrated students' enjoyment of the interdisciplinary nature of the course and that this in itself helped nurture their interest in the subject. For instance, one student said: "this was a great course—we were able to actually learn and apply the material in many circumstances. The research aspect was greatly emphasized—I believe that I learned more about the research at Caltech through this class." Another student commented: "the most interesting aspects of the program was the ability to learn science and engineering concepts in a different way then presented in school..."

<u>The curriculum successfully taught students that neuroscience is a multidisciplinary field:</u> In addition to the follow-up surveys that were sent out a few weeks after the conclusion of the program, an additional survey was sent out 6 months after the program's conclusion to YESS 2008 participants. This survey asked additional focused questions about the multidisciplinary nature of the course. Of the 17 students that responded to the follow-up survey, 88.2% of students strongly or somewhat agreed that the course taught them that neuroscience was a multidisciplinary subject. 94.2% of students strongly or somewhat agreed that the laboratories conducted over the class period contained computer, physics and engineering skills. These responses are outlined in the chart below (Table 3):

4.3 Evaluation of Student Performance

Students were evaluated throughout the course. These evaluations included daily homework and quiz scores, written feedback on a student poster presentation, and a written evaluation on their overall performance at the conclusion of the course.

Table 3. YESS 2008 Neuroscience Survey Responses (distributed 6 months after program conclusion)

Question	Strongly agree	Somewhat agree	Neither disagree nor agree	Somewhat disagree	Strongly disagree
The YESS Neuroscience course taught me that neuroscience is a multidisciplinary science involving biology and engineering	52.9%	35.3%	11.8%	0%	0%
The YESS Neuroscience labs had computer, physics, and engineering examples	47.1%	47.1%	0%	5.9%	0%

4.4 Feedback Based Adaptations from the YESS 2007 Course

The YESS 2007 course contributed a basic curriculum mold for the YESS 2008 course. However, there were many aspects that changed in the new YESS 2008 course due to responses from student feedback. Some of these changes and their assessment follow.

The YESS 2007 course was a broad survey of the many different neuroscience disciplines, including: cognitive neuroscience, molecular and cellular neuroscience, psychology, behavior and computational neuroscience. The course was mostly lecture based and consisted of only 4 major laboratory periods during the three-week course. It appeared that many students appreciated the diversity of topics, however, we also received feedback that it was hard for students to grasp important concepts. For example, one student said: "It covered a really broad amount of information and seemed to be in a random order which was somewhat confusing. It was really interesting information though, and I enjoyed the labs a lot."

Based on the feedback the YESS 2007 course received, the YESS 2008 staff of instructors built a curriculum that focused on molecular and cellular neuroscience, and the course was taught in three thematic units that followed a logical progression: Cells, Tissues and Systems. Furthermore, because many YESS students are typically interested in math and engineering, we decided to ensure that the course incorporated interdisciplinary concepts and methods (as outlined above in section 3). This goal was in line with recommendations from the National Research Council (NRC) that states that biology curriculum should contain an emphasis on math, statistics, and should be interdisciplinary.[6] In addition to these changes, the YESS 2008 instructors also created a course manual that included all pre-reading assignments, laboratory protocols, homework assignments, a course syllabus, a course schedule and a glossary. These curriculum changes appear to have had positive effects on the students' perception and interest in the course. Figure 3 contains information collected in the student survey distributed at the completion of both the YESS 2007 and 2008 years. We acknowledge that there are many other variables that could also attribute to these differences, including the change in the instructor staff and differences in the interest of the students. Assessment of the YESS program is ongoing, and by collecting more information from past students, we hope to elucidate if other factors contribute to the positive difference we see in comparing the revised YESS 2008 course to the YESS 2007 course.

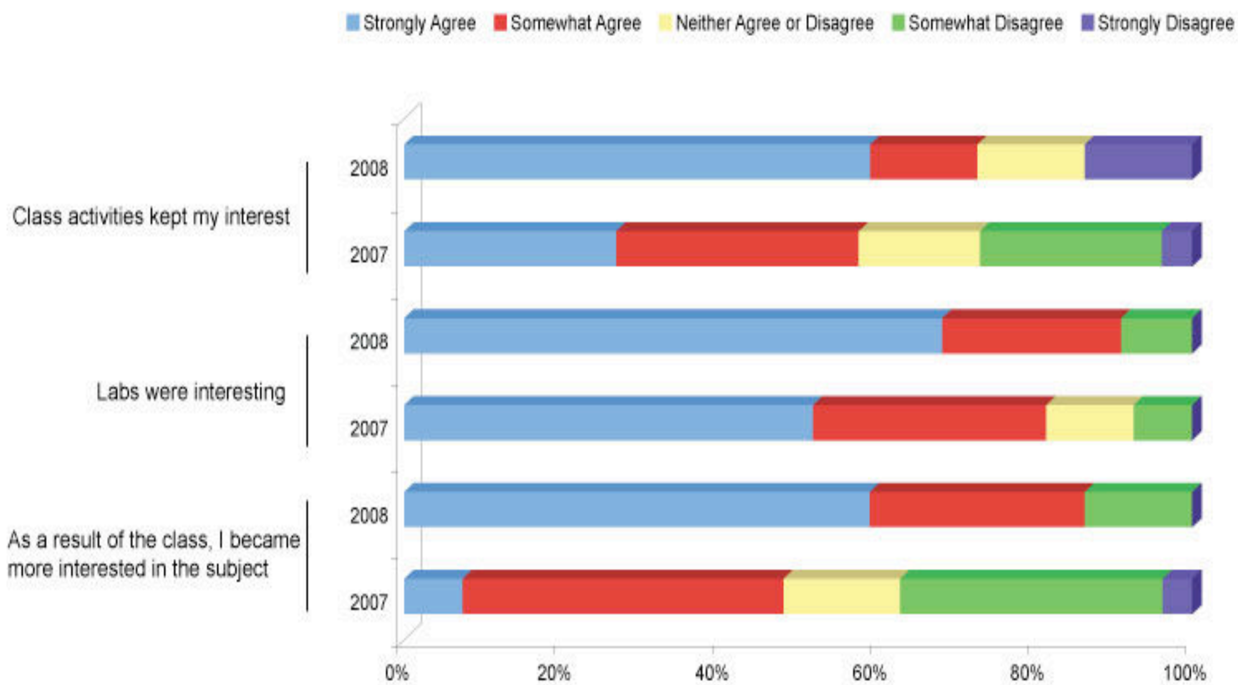

Figure 3. Survey Results from YESS 2008 and YESS 2007 Neuroscience Courses. The 2007 survey results were tallied from 27 student respondents, and the 2008 survey from a total of 22 respondents.

5. Conclusions and Recommendations

The neurosciences cover a wide spectrum of sciences and makes teaching a three-week course about them difficult. Thus, our efforts were focused on developing a course that was founded on basic principles that guide scientists and their work throughout this field. At the center of our curriculum was our emphasis on the interdisciplinary nature of the experimentation used to study the nervous system, and how non-biological sciences are invaluable in helping us understand this incredibly complicated biological system. We also made it a priority to create a curriculum in which students learn by stimulating their creativity and problem solving skills through experimentation commonly practiced in the neurosciences.

The daily laboratories performed by students offered a unique opportunity for discovering that pursuing the answer to many biological questions requires experimentation that is a combination of non-biological sciences. Because the laboratories required the use of sophisticated electronics, computers and hardware, the students were exposed to the great resourcefulness and creativity that is necessary for a biologist to develop as a means to acquiring knowledge about a living organism. With our focus on laboratory experiments, we hoped to instill this type of ideology in our students' thinking and perception of the neurosciences.

Teaching a three-week course focused on a particular type of science to young students presents a broad array of challenges that range from grabbing their attention and curiosity to communicating difficult and complex information effectively. The YESS Neuroscience course curriculum changed dramatically in response to the comments and suggestions collected from the 2007 program participants. These evaluations guided us in re-working our curriculum to better engage and excite students about the subject matter. We were careful to create laboratories with the primary goal of complimenting and extending the material the students were learning, but also geared towards helping to capture and keep their attention. Our success was made evident by the excitement that students showed for the laboratories. From the 2008 program evaluations, we found that implementing exercises that involved hands-on learning through experimentation enabled the course material to be better understood, and also better appreciated. We believe that feedback about our course will help to continue to refine our pedagogical strategy, and will enhance the way in which challenging and advanced science can be taught to young persons.

With the emergence of fields that integrate engineering with other disciplines, it is becoming increasingly important for the engineering education community to develop multidisciplinary courses. The curriculum we presented provides an example of the role of engineering in the study of biology. This type of curriculum introduces students to interdisciplinary fields while engaging them in engineering concepts. For precollege students, this provides educators another approach to introducing engineering into their K-12 curriculum. For instance, an advanced biology or chemistry class can introduce computer computation using the fish scale experiment described here. A K-12 science class can use the Biostatics module to integrate math into their course. Conversely, the units we designed can also be used in engineering courses to teach specific concepts and applications. For example, the neuronal modeling activity can be used to teach electrical circuit theory. The electrophysiology lab module can be used to demonstrate an electronics application.

Laboratory courses can be expensive and logistically difficult. We found it particularly helpful to have a team of instructors to help students mitigate each laboratory. Allowing students to work in groups minimized the cost of the course.

In summary, the multidisciplinary Neuroscience curriculum we developed engaged our students and increased their interest in the subject. These lessons can be adapted by K-12 educators to demonstrate the interplay between engineering and the life sciences.

6. Acknowledgments

The authors would like to acknowledge the Gordon and Betty Moore Foundation for funding the YESS program and the Caltech Minority Student Education office for all of their support in designing our course. We also acknowledge the Biology Division at Caltech for support. We thank Caltech faculty and personnel, Dr. Erin Schuman, Dr. Gilles Laurent and Dr. Elizabeth Bertani for allowing the YESS to use their classroom facilities and William Lease and Tim Heitzman for equipment support.

7. References

[1] Stevens S, Shin N, Delgado C, Cahill C, Yunker M and Krajcik, J. "Fostering Students' Understanding of Interdisciplinary Science in a Summer Science Camp" Paper presented at the annual meeting of the National Association of Research in Science Teaching, April 2007, New Orleans, LA.

[2] American Association for the Advancement of Science "Benchmarks for Science Literacy" available at www.project2061.org

[3] Hulse, R "Preparing K-12 Students for the New Interdisciplinary World of Science" *Experimental Biology and Medicine* 231:1192-1196, 2006

[4] Dormett EJ, Westwell MS, and Greenfield SA "A Multifaceted Approach to Neuroscience Outreach: Meeting the Challenges" *The Neuroscientist* 13:447-453, 2007

[5] Metz, A. Teaching Statistics in Biology: Using inquiry-based learning to strengthen understanding of statistical analysis in biology laboratory courses. CBE—Life Sciences Education.7:317-326, 2008

[6] National Research Council. BIO2010, Transforming undergraduate education for future research biologists. Committee on undergraduate education to prepare research scientists for the 21st century, Washington DC. National Academies Press, 2003