2006-2326: LAB-ON-A-CHIP DESIGN-BUILD PROJECT WITH A NANOTECHNOLOGY COMPONENT IN A FRESHMAN ENGINEERING COURSE

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Lab-on-a-chip Design-Build Project with a Nanotechnology Component in a Freshman Engineering Course

Abstract

A micromanufacturing lab-on-a-chip project with a nanotechnology component was introduced to first-year engineering students as a voluntary alternative within the standard first-year engineering curriculum. The lab project was piloted during Winter and Spring Quarters of 2004, with one section offered in each quarter for a total of 127 students then expanded to 3 sections in 2005 with an enrollment of 190 students. This alternate project is currently being revised and will be fully integrated into the program by Winter and Spring of 2006. In addition, an honors version of the project was offered in Spring 2005 to a single section of 32 students. A revised honors version will also be offered in Spring 2006. A three-pronged approach was employed in developing the project involving on-campus nanotechnology research laboratory tours hosted by faculty and researchers, nanotechnology teaching modules, and hands-on lab activities. The lab activities included a quarter-length design, build, and test problem utilizing project management and team building skills found in the standard lab sections.

The new course offering represents a significant effort to transfer graduate level research findings to a freshman engineering setting. This exposed students to cutting-edge research topics and fostered an early interest in academic and professional careers in new fields such as nanotechnology and biomedical devices. The project also demonstrates a safe method of incorporating more chemical and biological based engineering disciplines into a freshman laboratory course as an alternative to the traditional electro-mechanical emphasis. In fact, the lab-on-a-chip platform provides a very broad multi-disciplinary project that appeals to many interests and this is reflected in the nanotechnology teaching modules contributed by a diverse group of nanotechnology researchers from around campus.

Nanotechnology is introduced in related readings and laboratory tours as well as a nominal experimental component. Pre- and post-tests on nanotechnology concepts helped to gauge increases in student knowledge and understanding of fundamental nanotechnology topics. Pre- and post-surveys indicated the effects of the course on student interest and participation in research and nanotechnology-related issues at an undergraduate, graduate, or professional level. Efforts to expand the initial pilot implementation into a scaled-up regular course offering within the first-year curriculum parallels the recent award of a Nanoscale Science and Engineering Center (NSEC) through which undergraduate research opportunities will be available to students whose interests in nanotechnology and research have been sparked through this course offering. Finally, a longitudinal study is in development to track the involvement of former nanotechnology and micromanufacturing freshmen engineering students in nanotechnology and research as they progress through their academic careers at the university.

Introduction

Government initiative, market-driven, and research-driven forces have drawn international attention to the emerging field of nanotechnology. This initial growth and the projected growth of nanotechnology have fostered a need to provide educational options to prepare future professionals for careers in this new field. The premise for the Nanotechnology and Microfabrication Lab-on-a-Chip course for freshmen engineers complements the findings of many researchers in nanotechnology education. By converting knowledge from local graduate and faculty researchers to a format accessible to freshmen, it is hoped that first-year engineering students acquire the fundamentals of nanotechnology and develop an interest in this and other areas of research. The purpose of this paper is to share the fruits of this effort and provide a high level presentation of the curriculum developed and preliminary research findings.

A component involving a hands-on nanotechnology and micromanufacturing laboratory was developed for inclusion in a required first-year undergraduate engineering course. The Nanotechnology and Microfabrication Lab-on-a-Chip project was intended to provide first-year engineering students exposure to and foster interest in undergraduate research and the field of nanotechnology.

Background

The goals of the First-Year Engineering courses are to provide freshman engineering students with knowledge of engineering fundamentals, knowledge of engineering graphics, engineering communication skills, engineering problem solving skills, team-building experience, knowledge of and an ability to apply the design process, an ability to make measurements, knowledge of how things work, and experiences in a hands-on laboratory.

The First-Year Engineering Program is a sequence of two courses, ENG 181 and ENG 183. Each course is composed of two major parts: a Basics segment for 3 hours per week and a Lab segment for 2 hours per week. In the second portion of the sequence, ENG 183 labs provide a quarter-long design, fabrication, and implementation project upon which student teams of four collaborate. Students are expected to tend to such issues as initial research, brainstorming, designing, building, testing, and implementation. They are also expected to exercise project management skills, project economics, and teamwork as they work on the project. Throughout the project, lab memos are assigned on a regular basis and an oral presentation is given at the conclusion of the quarter. Previously implemented ENG 183 design projects include traditional electro-mechanical projects such as designing and building a conveyor that sorts objects of various dimensions and material properties, and designing and building a model roller coaster that meets specified design and performance criteria. A nanotechnology and micromanufacturing lab-on-a-chip project was developed as a third design project option with a greater chemical and biological focus. This project is comprised of three phases: hands-on design-build lab activities, nanotechnology teaching modules, and nanotechnology research laboratory tours.

Lab Activities

The lab project was piloted during Winter and Spring Quarters of 2004, with one section offered in each quarter. Activities included a quarter-length design, build, and test problem utilizing project management skills found in the standard lab sections. Major revisions were made to the curriculum materials, lab activities and equipment during Summer Quarter 2005. This resulted in a streamlined and relatively typo- and bug-free final offering, now with systematic continuous improvement practiced. After piloting, the components deemed essential to student education and satisfaction upon project completion were refined. Those items deemed less consequential were de-emphasized or omitted. What follows is a high level description of the resulting curriculum and student lab activities.

The overall design objective given to the students is to design, fabricate, and operate a lab-on-a-chip made from polydimethylsiloxane (PDMS) capable of optically detecting the presence and quantity of an agent via detection of emissions from a fluorescent tracer using an electronic detection device built by the students. Students are introduced to current and future applications of micro- and nanotechnology and the relative length scales of macro-, micro-, and nano-systems via multimedia presentation. This is intended to help the students to connect to the project on the first day of class.

Students spend the first four weeks benchmarking a generic chip design with experiments to determine performance on various features. They also use this period of time to design their own chip by using knowledge gained from the benchmarking activities to produce a chip that will outperform the generic design. Figure 1 shows the currently used generic chip design. The deadline for the student teams to submit designs for external photolithography processing is the fourth lab session.

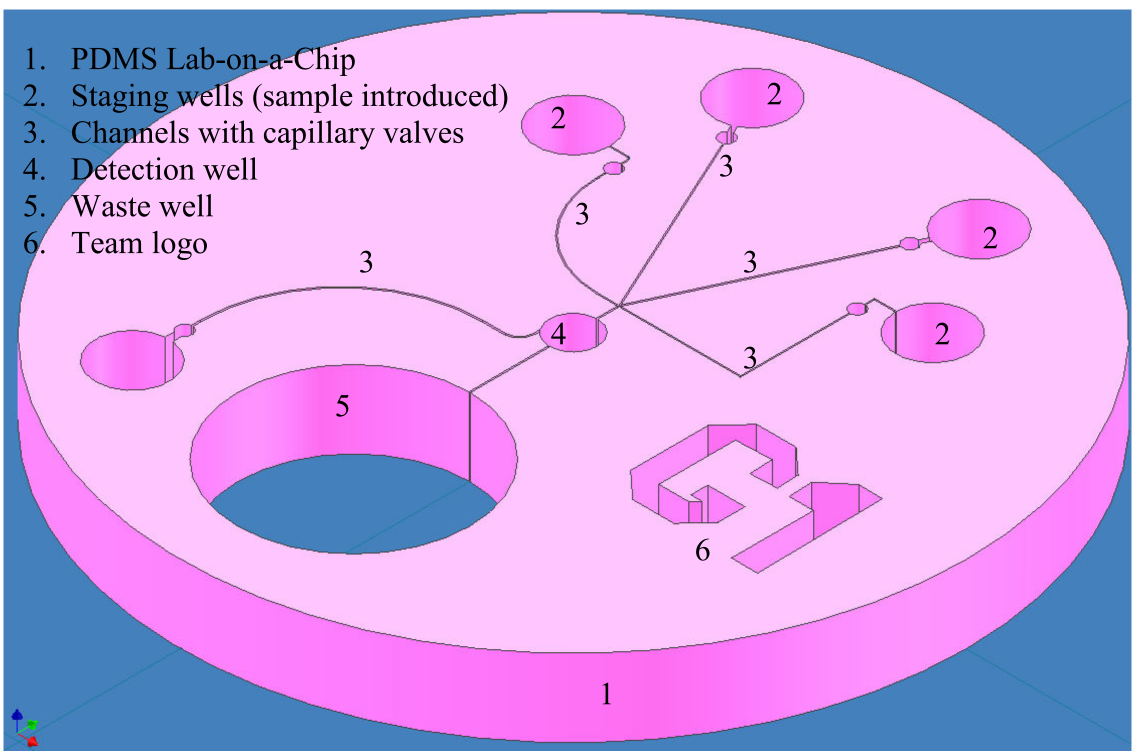

Figure 1. Generic chip design.

During the fourth and fifth lab sessions, the students build and calibrate their electronic optical detection devices. Figure 2 is a prototype of the electronic detection device setup with the chip and agent plumbed into the chip. Figure 3 is the circuit schematic of the detection device. The calibration is important as it is used during final testing where student teams are graded on how well their device can determine the unknown quantity of agent in a limited number of trials.

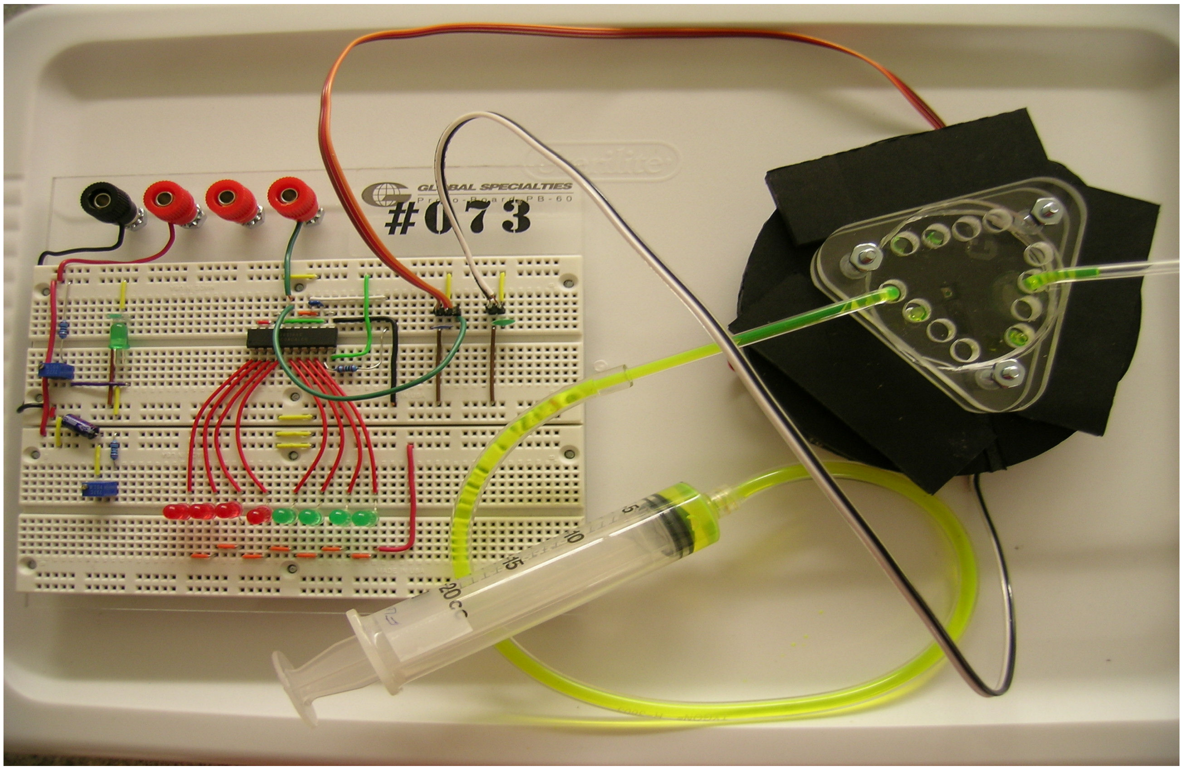

Figure 2. Detection and calibration setup (prototype).

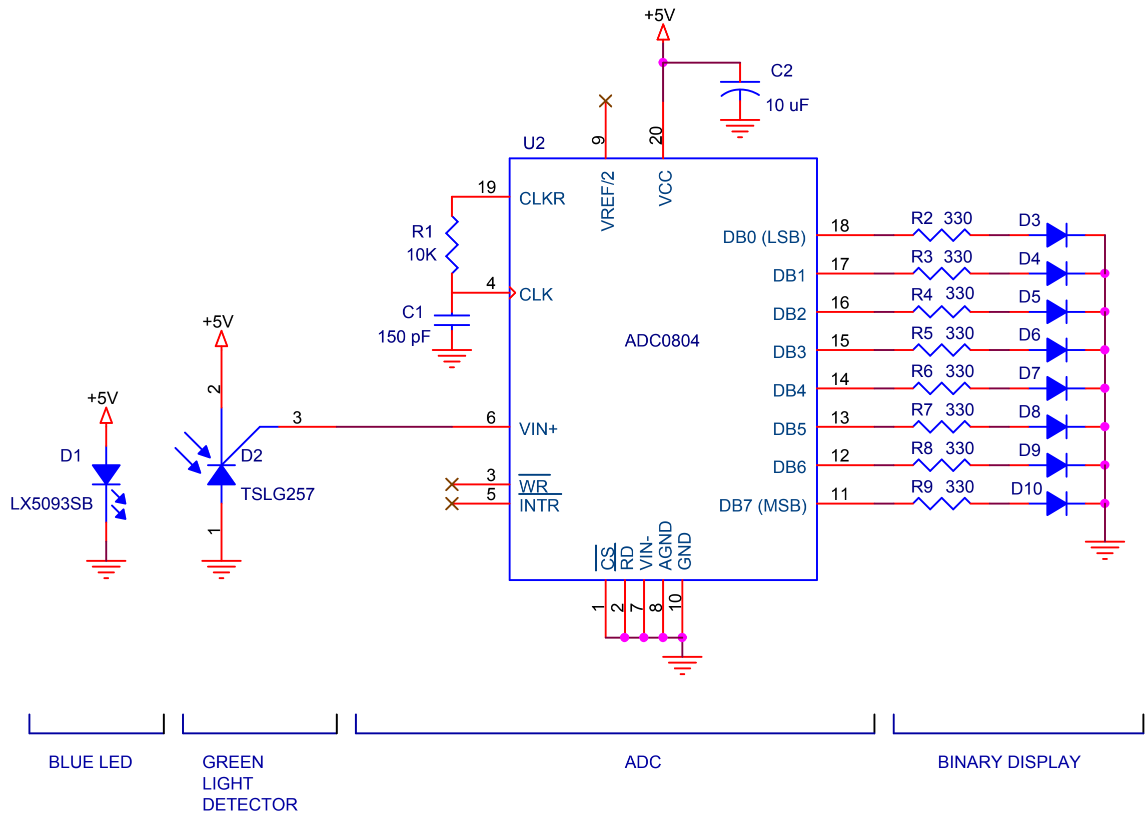

Figure 3. Detection circuit schematic.

The student teams mold and de-mold their devices with PDMS during the sixth and seventh lab sessions. From the remainder of the seventh lab through the open eighth lab, the student teams are expected to refine their chip operations and prepare for the final test which is held in the ninth lab. A finished PDMS lab-on-a-chip under blacklight is shown in Figure 4. Oral presentations on their projects and lab tours are given in the tenth and final lab. A significant portion of the lab grade is based on chip performance and functionality in this final segment. Table 1 summarizes the lab activities.

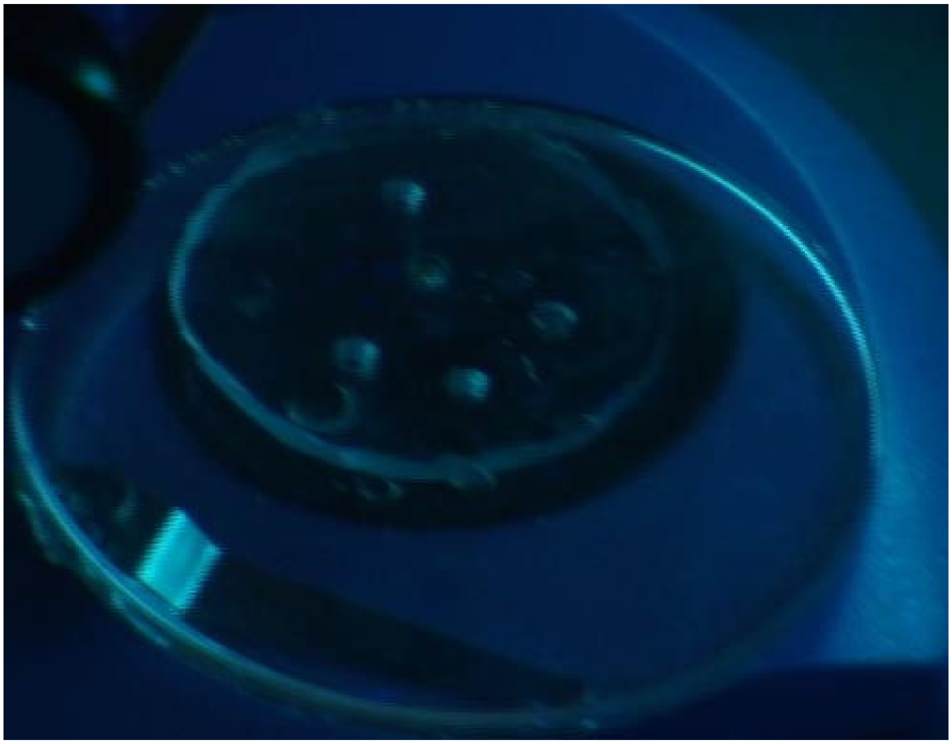

Figure 4. PDMS lab-on-a-chip under blacklight.

Lab Session	Topics / Activities
1	Introduction: Nanoscale Definitions, Techniques, Devices Hands-on experimentation and benchmarking.
2	Fluid mechanics, capillary flow, clean room practices. Advanced capabilities testing. Begin design.
3	Lab Tours or Sensor Circuit Design I Paper chip design, operational design, calculations due.
4	Lab Tours or Sensor Circuit Design I Final CAD design in Inventor, operational design, calculations due.
5	Sensor Circuit Design II Dilution of concentrations and detection device calibration.
6	PDMS Chip Molding, Prototype Chip, Sketch Designs, Manufacturing Principles 2 chips per team.
7	Chip Demolding & Assembly, Production, Economics Initial testing.
8	Chip Fluidics Test, History of IC Talk & Relevance to Micro- & Nanotechology
9	Final Chip Test Determine unknown concentration based on calibration; competition.
10	Oral Presentation

Table 1. Revised lab topics and activities.

The hands-on activities expose the students to the design process, in which after significant benchmarking and analysis, they design, revise, and build a prototype based on the lessons learned earlier in the quarter with a generic design. They also experience firsthand the importance of proper calibration of a detection and measurement device and use their calibration data to derive a curve and function that is employed in testing and determining the concentration of an unknown sample. Because the student teams are exposed to important engineering topics like analysis, design, synthesis, calibration, and testing with a microfabrication and nanotechnology focus, the hands-on activities represent the most important focus of the aforementioned three phases of this lab.

To emphasize to the students the significance of the lab activities they are performing, a video of a university promotional commercial seen on television during football games is shown. The commercial features a top university researcher in a cleanroom coverall, describing his top-down nanoscale fabrication techniques while speaking with an array of technical jargon. Many students recognize the commercial, upon which they are told by the instructional staff that they will be utilizing nearly all the procedural steps described by the researcher in their own lab activities.

Nanotechnology Teaching Modules

Most of the lab activities were not truly nanoscale due to the lack of access to the major research instrumentation required (e.g., electron beam lithography) and the associated costs. However, because the project made use of microscale analogs (e.g., photolithography), the students were provided with six teaching modules of approximately six pages in length each to discuss and explore nanotechnology issues related to the hands-on activities they were performing in the lab. Table 2 lists these modules by topic, author, the respective affiliation of the author, and a brief synopsis of each.

Module	Topic	Author	Affiliation	Summary
1	Top- Down vs. Bottom- Up Nanomanufacturing	Derek J. Hansford	Biomedical Engineering Program; Department of Materials Science & Engineering	Methods, strengths, and limitations of fabricating nanometer-scale structures using Top-down methods (lithography and patterning) compared to bottom-up methods (self-assembly and selective growth) ; current uses of both nanomanufacturing techniques.
2	Molecular Self-Assembly	James F. Rathman	Department of Chemical and Biomolecular Engineering	Role of intermolecular forces in molecular self-assembly of amphiphilic molecules; formation of 3-D structures by self-assembly in solution; surface tension and the formation of 2-D structures by self-assembly at interfaces.
3	Nano-Structured Ceramics for	Sheikh A.. Akbar	Department of Materials Science & Engineering	The emerging field of nano-ceramics and nano-technology; some potential

	Chemical Sensing			applications with an emphasis on chemical sensors; the challenges and opportunities in this evolving area.
4	Polymer Processing at the Nanoscale	L. James Lee	Department of Chemical and Biomolecular Engineering	The emerging field of nanoscale manufacturing of polymeric materials; state-of-the-art mold (master) making and replication techniques; challenges and opportunities in this evolving area.
5	Nanofluidics	A. Terrence Conlisk	Department of Mechanical Engineering	How nanofluidics differs from traditional fluid mechanics, with emphasis on fluid flow in a tube or channel.
6	Nanotechnology for Drug Delivery	Derek J. Hansford	Biomedical Engineering Program; Department of Materials Science & Engineering	Concepts in drug delivery, including tissue targeting, biomolecular markers, and reasons to use controlled release; basic concepts of nanoparticles and why they are useful for drug delivery; understanding the differences of classes of nanoparticles.

Table 2. Nanotechnology teaching modules, authors, and affiliations.

Lab Tours

Lab tours were conducted by faculty members who were specifically recruited to demonstrate their nanotechnology research facilities to the freshman students. There were nine tours rescheduled over a two week period, allowing one lab section to work on the "Circuits I" lab while the other section toured research facilities. These tours enhanced the students' overall experience and provided direct exposure to ongoing nanotechnology research. Each team toured a different facility, and developed an oral report. A summary of the facilities toured and the corresponding topics covered in the tours is provided in Table 3.

Facility Toured	**Tour Topic**
Ohio MicroMD Laboratory Cleanroom Facility	Medical and biomedical applications; silicon, polymer, characterization, photolithography, biohybrid processing.
Micro/Nanoscale Welding Laboratories	Nanoindenter, Nd:YAG laser micromachining.
Nanoscale Metrology and Measurement Lab	Laser-guided magnetic suspension stage; dynamic modeling with ATM tip-cantilever system.
Microfabrication Laboratory	Replication of microstructures for microfluidics, sensing, tissue engineering, and drug delivery; structural testing; microfluidic testing; fluorescence testing with microscope.
Atomic Force Microscopy Lab	Use of Atomic Force Microscopy for surface topography at the atomic length scale.

Electronics Cleanroom Manufacturing Facility	Silicon processing;;photolithography equipment and methods; mask aligners ; spinner; thermal evaporator.
Nanoelectronics and Optoelectonics Lab	Dielectric deposition, hydrogen processing, and etching; electron beam evaporation; filament evaporation; ellipsometer; photolithography; annealing, oxidation and diffusion furnaces; pulsed laser deposition.
Semiconductor Epitaxy and Analysis Laboratory	Applications in optoelectronics, photovoltaics, electronics, and integrated systems.

Table 3. Nanotechnology research facility tours.

Interdisciplinary Contributions

Nanotechnology Teaching Modules were contributed by selected faculty researchers in various departments and were edited as necessary for a freshmen audience. Questions were written based on the content of the modules for the freshmen to discuss in their lab reports and quizzes.

Lab tours required a considerable donation of time, resources, and expertise by researchers on campus to accommodate the 18 different teams. Each of nine laboratories hosted 2 groups on separate visits. Many tour guides provided handouts and access to other information as well as visual aids for use by the student teams in their oral presentations at the end of the quarter.

Although the design and fabrication techniques employed by the students represent the state of microscale research from as recently as the mid- to late-1990's, it is important to show the students how their work in microfabrication and design is analogous to current nanotechnology research. Both the lab tours and Nanotechnology Teaching Modules provide a bridge from the students' hands-on lab activities and their associated assignments to the current research and pioneering efforts in the field of nanotechnology. In the absence of components in either the lab tours or Nanotechnology Teaching Modules, one type can be used to supplement an area in which the other is lacking, however a balance between them is recommended.

Research Studies

Aside from preliminary and informal findings from the initial pilot offering in 2004, there are several studies underway that will be discussed in a later publication. Data are currently being collected for a Winter and Spring 2006 study described below. A longitudinal study is also running in the background to track the involvement of former nanotechnology and micromanufacturing freshmen engineering students in nanotechnology and research as they progress through their academic careers at the university. Below, some preliminary studies from the initial pilot offering are discussed, followed by descriptions of ongoing and future studies.

To gauge how students in the initial pilot offering performed relative to their peers in the standard first-year course, preliminary findings from data collected in the pilot course students' demographics, feedback, and performance were recorded and compared to non-pilot students in the initial 2004 offering. Student profiles and performance in common engineering fundamentals areas were similar to the general freshman engineering student population. Specifically, program-wide results on identical midterms were recorded for Winter and Spring 2004. Midterms from all sections had common graders uninvolved in the development or administration of the pilot course, where each grader was assigned a problem to grade on all midterms from all sections. A comparison of the mean scores of students in the pilot course versus the remainder of the population in the standard course yielded statistically insignificant differences, suggesting students taking the nanotechnology and micromanufacturing lab segment were able to perform as well as their peers in metrics gauging general engineering fundamentals. Midterm results were statistically similar, with nanotechnology pilot and non-pilot students scoring an average of 83.2 and 81.9, respectively. A two-sample t-test showed statistical insignificance ($p>.10$). Table 4 provides a summary for the Winter and Spring 2004 comparisons of pilot class versus standard class performance on this measure of common engineering fundamentals skills. These preliminary findings suggest that substituting a non-traditional design-build lab project for the existing electro-mechanical design-build project may not adversely affect the students' learning of engineering fundamentals.

Winter 2004
t-Test: Two-Sample Assuming Equal Variances

	non-Nano	*Nano*
Mean	90.70	92.25
Variance	66.52	42.42
Observations	272	69
Pooled Variance	61.69	
Hypothesized Mean Difference	0	
df	339	
t Stat	-1.46	
P(T<=t) two-tail	0.15	
t Critical two-tail	1.97	

Spring 2004
t-Test: Two-Sample Assuming Equal Variances

	non-Nano	*Nano*
Mean	81.92	83.16
Variance	90.62	97.48
Observations	439	58
Pooled Variance	91.41	
Hypothesized Mean Difference	0	
df	495	
t Stat	-0.93	
P(T<=t) two-tail	0.35	
t Critical two-tail	1.96	

Table 7. Statistical comparison of standard and nanotechnology pilot students' midterm grades for Winter and Spring 2004.

Although a baseline comparison was not available, many students in the Spring 2004 pilot offering also expressed interest in nanotechnology and/or research. In a survey conducted towards the end of that quarter, one third indicated an interest in research. All but one student felt research is important for science, technology, and the economy. A majority showed interest in attending graduate school and nearly half showed interest in participating in undergraduate research. In contrast, only two students indicated current involvement in undergraduate research. Albeit informal, this may point to the benefits of providing undergraduate research opportunities and spurred the current study for which data are being collected in the Winter and Spring 2006 Nanotechnology and Micromanufacturing Lab-on-a-Chip course offerings.

Concurrent to the Nanotechnology and Microfabrication Lab-on-a-Chip course offering, an ongoing research study is being conducted to examine several effects of this alternate course relative to the standard offering. One goal of the study is to determine the type of response in attitudes and interest towards research and nanotechnology by students in a first-year engineering course of this nature. Another aspect of the study examines team-building attitudes of these students. Both portions of the study involve pre- and post-course surveys between demographically matched populations where the experimental group, the Nanotechnology and Micromanufacturing Lab-on-a-Chip students, are compared to the control group, those students taking the traditional lab offering. Changes in attitudes as indicated by identical surveys given at the beginning and after the course concludes of each, the experimental and control group, will be gauged and compared.

The multiyear longitudinal study tracks the involvement of former nanotechnology and micromanufacturing freshmen engineering students in nanotechnology and research during their undergraduate, graduate, and at the inception of their professional careers. Data on their involvement in research and nanotechnology will be gathered to assess the impact of the new course on their careers and interests.

Conclusion

The successful implementation and standardization of the Nanotechnology and Micromanufacturing Lab-on-a-Chip course for first-year engineering students is promising in that it shows that traditional boundaries of electro-mechanical design-build projects can be expanded to include new and cutting edge technologies only recently trickled down from the graduate research arena to the undergraduate classroom. It is important to expose new engineering students early to these new technologies as there is a projected need for researchers and professionals in the burgeoning field of nanotechnology. It has yet to be seen, but this early exposure can hopefully foster student interests in careers in nanotechnology to fulfill future demand for qualified scholars and professionals. The standardization, after revisions, and expansion of this offering to more course sections illustrates that the importance of nanotechnology in research and education can be addressed at the early undergraduate level.

Afterword

An single-section honors version of the nanotechnology and micromanufacturing Lab-on-a-Chip course was piloted in Spring Quarter 2005. It is currently being revised and will be offered again in Spring Quarter 2006. It is similar in that its use of equipment and concepts are generally common to the non-honors version, except the lab hours are longer and the expected research efforts outside the classroom are greater. In addition, rather than dealing with the electronic optical detection of an agent, it investigates the pressure-driven flow and shear forces necessary to shear incubated yeast cells from the PDMS channel walls inside the chip.

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