

AC 2007-2482: NSF CCLI: A PROBLEM-BASED MICROFLUIDICS LABORATORY COURSE FOR UNDERGRADUATES

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NSF CCLI: A Problem-Based Microfluidics Laboratory Course for Undergraduates

Abstract

In the past decade, microfabrication (MEMS) and behavior of fluids on the microscale (microfluidics) have transformed many areas of engineering and applied sciences. Yet little has been done to transfer the microfluidics research to the undergraduate curricula. To address this need, using support from a NSF CCLI award we are developing a new undergraduate laboratory course at the University of Cincinnati to introduce students to microfluidics and biochip development. The iterative nature of the course directly addresses several components of undergraduate STEM education and follows the cyclic model for knowledge generation and improvement. To assess educational impact of the course, both short-term outcomes, such as individual laboratory experiences, and long-term outcomes, such as increased student knowledge, are used. The initial success of our course is encouraging, and suggests that the developed format can be disseminated to other universities.

Introduction

Microelectromechanical systems (MEMS) miniaturization technologies are important to life sciences because they have a potential of yielding small, cost effective, disposable, rapid sensor systems for point-of-care (POC) medical diagnosis and *in situ* environmental monitoring. For example, microorganisms must be monitored in the environment because they can present a threat to public health (*e.g.*, drinking water quality) or effective biocatalysts for treating pollution (*e.g.*, bioremediation). The main difficulty with such field-based monitoring is that many available tools are lab-based and are not suitable for operations in the field, are cost-prohibitive, or are time-consuming.

Microfluidics is a branch of physics and biotechnology that studies the behavior of fluids at the microscale and the design of MEMS that take advantage of such behavior. The behavior of fluids at these small scales can differ from macroscale fluidic behavior, as factors such as surface tension, energy dissipation, inertia, and electrokinetics begin to dominate. Microfluidics has enabled manipulation and detection of nanoliter and even picoliter fluid samples. The behavior of such systems has been extensively investigated and explored in so-called lab-on-a-chip (LOC) systems.^{1,2}

In the past decade, microfluidics has transformed many areas of the applied sciences, such as medicine, pharmaceutical research, and analytical chemistry. However, little has been done to transfer the microfluidics research to the undergraduate curricula. At the University of Cincinnati we are integrating state-of-the-art research in microfluidics within our undergraduate

and graduate electrical engineering curricula via a laboratory course “ECES678: Micro/Nano Fluidic Biochip Laboratory.”

A unique aspect of the course is that we focus on an extended problem-based learning example of a microfluidic mixer that underlines all course activities. Mixing is of considerable importance in microfluidics and LOC systems because bio/chemical reactions carried out in such devices require on-chip mixing of samples and reagents. A good example is an immunoassay where miniaturization can lead to reduced reagent consumption, faster reactions, fewer byproducts and higher throughput.³⁻⁵ Fully-integrated microfluidic chips performing such reactions require fast homogeneous mixing. Thus, successful development of a micromixer capable of passively mixing in a short distance is an active area of research and is of significant interest to the microfluidics and LOC research communities. Focusing the course on the microfluidic mixer example permitted us to discuss all aspects of microfluidic design cycle, including theory, modeling, fabrication, device characterization, and applications (Figure 1).

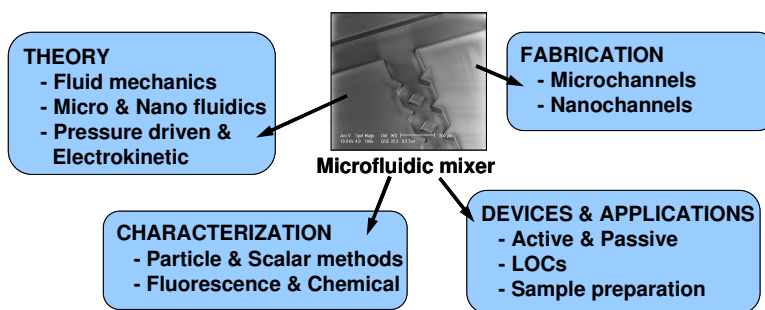


Figure 1. Use of the micromixer to discuss all aspects of microfluidic device design and development.

Details of the NSF CCLI project

Project objective. The objective of our Course, Curriculum, and Laboratory Innovation (CCLI) project is the development and evaluation of proof-of-concept educational materials to introduce undergraduate students in Electrical Engineering to state-of-the-art advances in microfluidics research.

Specific aims. To meet the objective of the project, we are addressing three specific aims. These aims will be iterated three times over the three year NSF CCLI award period, directly reflecting the cyclic model of knowledge production and improvement in undergraduate STEM education. The specific aims (SA) are:

- I. Developing and revising teaching materials and methodology.** Teaching materials were developed for the first offering of the course in the Spring 2006. We are in the process of modifying the course content and the developed teaching materials in response to the student evaluations performed in SA3 for the second iteration of this aim. Course materials will be updated once more in the third iteration of this aim.

II. Teaching the course. We utilized the course content and materials developed in the first iteration of SA1 to teach the course in the Spring 2006. Following the second iteration of SA1, we plan to utilize the modified course content and teaching materials to teach an updated course in the Spring 2007. The third offering of the course is planned for the Spring 2008.

III. Evaluating the success of the course. We evaluate the success of introducing undergraduate students to micro/nanofluidics research through inquiry-based laboratory exercises and lecture-discussion sessions. We plan to continue to evaluate the success of the course for its second and third iterations. We also plan to determine the appropriate format for local and national dissemination, including continued course development, expansion to include students from disciplines outside electrical engineering, presentations at national meeting of engineering educators, and publications in the archival educational literature.

The “Micro/Nano Fluidic Biochip Laboratory” course

The course was designed to be ten weeks long, two hours of lecture and four hours of lab per week. Laboratory sessions follow the iterative design cycle (illustrated in Figure 2) aimed at teaching students micro/nanofluidic system design. As a 600-level course it was dual-level, intended for the undergraduate seniors and first year graduate students in the Electrical Engineering program.

Students were assigned into laboratory teams with three students per team. The objectives of team assignments included: 1) placing students with previous experiences in computational fluid dynamics into different teams; 2) placing students with previous experiences in microfabrication methods into different teams; 3) placing students with common interests in research topics into the same teams.

In *Module 1: Modeling* (weeks 1-4), students were introduced to the CFD ACE+ (ESI-CFD Inc., Huntsville, AL, www.cfdrc.com) modeling software and learned the basics of microfluidic simulation through step-by-step tutorials we developed as part of SA1. CFD-ACE+ is the most advanced multi-physics software used for accurate analysis of micro/nanofluidic devices. It enables coupled simulations of fluid, thermal, chemical, biological, electrical and mechanical phenomena. CFD-ACE+ is currently used by over 400 major organizations worldwide, including DARPA and NASA. This software package was selected due to its advanced capabilities, rapidly increasing popularity in industry and academia, and easy-to-use graphical user interface. After learning the software, working in teams, students used CFD ACE+ to design and simulate a microfluidic mixer. Each team was given the freedom to develop their own micromixer design.

In *Module 2: Device Fabrication* (weeks 5-8), students designed masks for microfabrication and then fabricated their micromixer designs developed in Module 1. Students used the University of Cincinnati’s state-of-the-art clean room facility to prototype the designed devices in

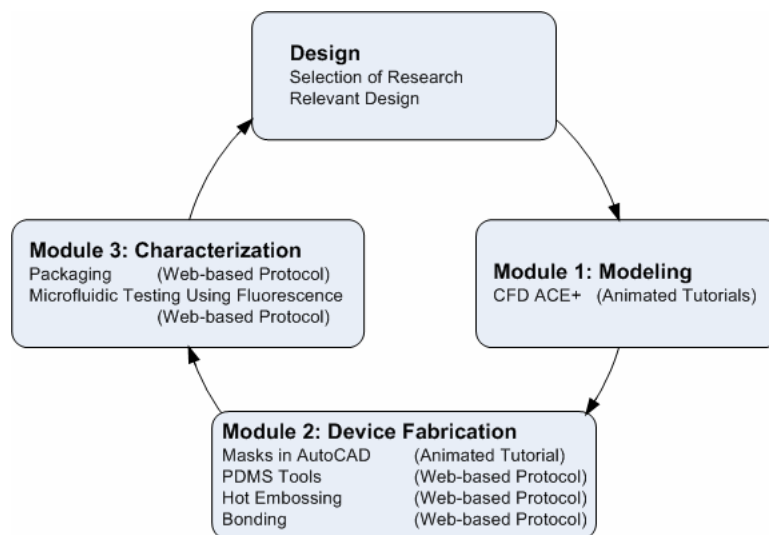


Figure 2. The iterative microsystem design cycle. The process begins with design selection, followed by modeling in CFD-ACE+, mask design in AutoCAD, device fabrication, and fluorescence characterization.

polydimethylsiloxane (PDMS) polymer. At the end of this module, students gained first-hand experience with fabrication of microfluidic systems.

In *Module 3: Characterization* (weeks 9 and 10), students packaged and fluorescently characterized the microfluidic mixers fabricated in Module 2. In this module, students used an inverted epifluorescence microscope (Olympus IX71) with a 12-bit CCD camera (QImaging Retiga EXi) purchased with the NSF CCLI funds.

At the end of each module, each student team gave a 10-min talk and submitted a 3-page report summarizing their findings. At the end of the course, each student team discussed their device design, and compared experimental results with simulations in seminar-style 30-min presentations. Two faculty members of the Department of Electrical and Computer Engineering, experts in the field of microfabrication, served as judges evaluating individual student team designs and presentations.

The “Micro/Nano Fluidic Biochip Laboratory” course uses a combination of teaching styles and materials in order to maximize learning. At the present time, there is no undergraduate Micro/Nanofluidics textbook. The teaching style includes the use of PowerPoint presentations. Each lecture topic was presented in an interactive lecture-discussion format, with an emphasis on active student participation in the discussion. Given the overwhelmingly positive feedback during teaching of the recently developed *Introduction to Biomedical Microsystems* course,⁶ we supplement these materials with journal articles related to the topics covered in class during that week. The strategy here is to expose students to recent advancements in the microfluidics field.

Overall, the course exposed students to polymer microfabrication technologies that are beginning to dominate microfluidics, as previously discussed. The course lectures complimented the laboratory sessions and included discussions of the microfluidics theory, microfabrication, and the practical issues encountered in the lab. This course provided students with the skill set they will need to pursue graduate work or a career in industry.

Course assessment

Good assessment techniques are critical in both developing and measuring the success of educational activities, such as the course discussed here. The assessment of both short-term outcomes, such as individual laboratory experiences, and long-term outcomes, such as increased student knowledge and enhanced curriculum are all very important. Dr. Cathy Maltbie of the Evaluation Services Center of the University of Cincinnati's College of Education is conducting a comprehensive evaluation of this project. This evaluation focuses on the SA3 goal, evaluating the success of introducing undergraduate students in Electrical Engineering to micro/nanofluidics research through the "Micro/Nano Fluidic Biochip Laboratory" course with both lecture-discussion sessions and laboratory experiences.

The course was offered for the first time in the Spring 2006. It was a considerable success, based on the preliminary results of the evaluation conducted to date. All students enrolled in the course participated in the course evaluation and responded to anonymous questionnaires at the end of each module. Questionnaires used a five-point Likert scale (5 being a Strong Yes and 1 being a Strong No). The preliminary results, summarized in Table 1, show that each module was successful in achieving its objectives. The means range from 4.2 to 4.7, with relatively low standard deviations, indicating highly positive ratings.

Table 1. Summary of Questionnaire Results
(5 is a Strong Yes, 1 is a Strong No; $N = 12$)

Module	Mean	Standard Deviation
1. Modeling (weeks 1-4)	4.5	0.6
2. Device Characterization (weeks 5-8)	4.7	0.6
3. Characterization (weeks 9&10)	4.2	0.7

Another method of assessment was provided by an informal interview of the entire class conducted by Dr. Cathy Maltbie. This provided students with a comfortable forum with a third-party mediator to provide their comments. Students expressed extremely positive comments, such as those below:

- *“This was one of the best classes I ever took, because I was able to see how device would be designed, simulated, fabricated and characterized. You could actually see something you were just reading about earlier.”*
- *“I enjoyed this course very much. I learned a lot without realizing it. I was too busy having fun improving my [micromixer] design...”*
- *“This class helped me visualize microfluidics and physical phenomena... It also gave me a good start at simulation and fabrication/experimental characterization of micromixers. Very good course!”*
- *“This lab taught me so much. I learned how to use CFD and the microscope. I got hands on experience [in] fabrication [of] a microfluidic device and I learned how to characterize using fluorescence.”*

Broader impacts of this teaching initiative

The “Micro/Nano Fluidic Biochip Laboratory” course introduces students to the exciting, rapidly emerging field of micro/nanofluidics. It transfers a hot area of research to undergraduate curriculum to better prepare students to pursue graduate work or to meet the needs of industry and government employers in the micro/nanofabrication area—an area projected to grow tremendously in the next decade.

All of the student comments collected throughout the course in the form of ratings, questionnaires, and informal interviews support the conclusion that the course was a considerable success. In particular, students valued hands-on experience in the laboratory which is not provided to them in other MEMS courses. Specifically, the modeling aspect of the course gave them the opportunity to “learn by doing” as they explored multiple device designs. Hands-on work also allowed for testing the boundaries of possibilities, and therefore resulted in deeper understanding of the material. Some students even suggested splitting the course into two quarters to provide more hands-on experience. Both undergraduate and graduate students indicated that they appreciated the opportunities to see and experience “state-of-the-art” research in the classroom. All three methods of assessment will be used to again evaluate the upcoming offering of the course in the spring of 2007. The initial success of our pilot program is encouraging, and suggests that the format developed in this course could be adapted to introduce engineering students to advanced multidisciplinary research topics.

We anticipate that the diverse instructional approaches of the course will work well to address the different learning styles of students. We also expect to generate educational materials that will be disseminated to the faculty at similar institutions of higher learning who are conducting research in micro/nanofluidics and biomedical microtechnologies. Two future adopters of the course will be involved in the second and third iterations of this course to facilitate an easier transition to their respective institutions in the future. By involving these adopters early, we are creating a scholarly network to promote effective micro/nanofluidics instruction and to support rapid dissemination and adaptation of the generated course materials. The proposed effort directly addresses several components of undergraduate STEM education and follows the cyclic model for knowledge generation and improvement.

Acknowledgements

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