AC 2008-1373: INTRODUCING MICROFLUIDICS THROUGH A PROBLEM-BASED LABORATORY COURSE

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Introducing Microfluidics through a Problem-Based Laboratory Course

Abstract

Microfluidics is a multidisciplinary field that deals with the behavior and precise control of microliter and nanoliter volumes of fluids. In the past decade, microfluidics has 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, University of Cincinnati is developing a new undergraduate laboratory course to introduce students to microfluidic device development. A unique aspect of the course is the focus on an extended problem-based learning example that underlines all course activities. Working in teams of three, students use multi-physics modeling software (CFD ACE+ from ESI-CFD Inc.) to design and simulate a microfluidic mixer. Students then use the University of Cincinnati's state-of-the-art clean room facility to prototype the designed devices in polymer and characterize them using fluorescence microscopy. Employing teams of students working together to conduct laboratory assignments allows team members to learn from each other and takes maximal advantage of students teaching students. At the end of the term, in seminar-style presentations, each student group discusses their device design, and compares experimental results with simulations. Following two successful offerings at the University of Cincinnati, we are now offering the course at the University of Illinois at Chicago, with plans of disseminating the course to other Universities across the country.

Introduction

Microfluidics is a multidisciplinary field spanning physics, chemistry, engineering and biotechnology, that studies the behavior of fluids at the microscale and the design of systems to leverage such behavior. The behavior of fluids at the microscale differs from "macrofluidic" behavior in that factors such as surface tension, energy dissipation, and electrokinetics begin to dominate. Microfluidics investigates how these behaviors change, and how they can be exploited for new uses. Integrating microfluidics with sensors, actuators, or other electronics gives new functionalities [1,2,3]. More importantly, the new fluid manipulation principles have enabled manipulation and detection of nanoliter fluid samples.

To address the growing national need, we developed a laboratory course "Microfluidic Biochip Laboratory." The course has been recently described in several publications and presentations [4,5,6]. Briefly, *a unique aspect of the course is the focus on an extended problem-based learning example of a microfluidic mixer that underlines all course activities.* Focusing the course on the microfluidic mixer example permitted us to discuss all aspects of the microfluidic design cycle; including theory, modeling, fabrication, device characterization, and applications which is ideal for this introduction to the field. Working in teams of 3 or 4, students used multi-physics modeling software CFD ACE+ (ESI-CFD Inc., Huntsville, AL) to design and simulate a microfluidic mixer. Students then used the University of Cincinnati's state-of-the-art clean room facility to prototype the designed micromixers in polymer and characterize them using fluorescence microscopy. By employing teams of students working together to conduct laboratory assignments, graduate students were matched up with undergraduate students. This allows team members to learn from each other, and takes maximal advantage of students teaching students. At the end of the term, in their seminar-style presentation, each student group discussed their device design, and compared experimental results with simulations. Each team also prepared a peer-review-quality manuscript as part of their final evaluation. .

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.

Twenty six students enrolled in the course to date (14 in 2006 and 12 in 2007). The course enrollment has grown beyond the instructor's original electrical engineering target audience to include multidisciplinary participation, including both programs within the Department of Electrical and Computer Engineering (namely electrical engineering and computer engineering), Department of Biomedical Engineering, and Department of Chemistry. In both years, enrollment was limited to 12 (four 3-student lab teams) to make it manageable for a single teaching assistant.

Most of the students enrolled in the course each term ($N = 22$) participated in the evaluation and

Table 1. Lecture topics of the "Microfluidic Biochip Laboratory" course.

Week	Lecture Topic
1	Applications of Microfluidics
2	Principles of Microscale Fluid Flows
3	Pressure Driven Flows
4	Electroosmotic Flows
5	Diffusion and Mixing
6	Design of Microfluidic Lab-on-a-Chip (LOC) Systems
7	Fabrication Technologies for Microfluidics: Masters & Embossing
8	Fabrication Technologies for Microfluidics: Nanoimprinting
9	Packaging of Microfluidic Systems
10	Flow Characterization Using Fluorescence

responded to anonymous questionnaires at the end of each three modules. Questionnaires used a five-point Likert scale (5 being a *Strong Yes* and 1 being a *Strong No*). Dr. Cathy Maltbie conducted the informal interview of the entire class at the end of each term. This provided students with a comfortable forum with a third-party mediator to provide their comments.

Overall, the course continues to be a success. Average scores for both course offerings for each module are summarized in Table 2. They show that each module was successful in achieving its objectives. The means range from 4.22 to 4.67, with relatively low standard deviations, indicating highly positive ratings. No substantial changes were observed between the two course offerings.

Table 2. Summary of Questionnaire Results (5 is a *Strong Yes*, 1 is a *Strong No*; *N* = 22)

	2006		**2007**	
	Mean	SD	Mean	SD
Module 1 (Modeling)	**4.55**	**0.63**	**4.59**	**0.56**
Where the modeling tutorials sufficiently detailed?	4.58	0.52	4.56	0.53
Where the modeling tutorials relevant?	4.83	0.39	4.67	0.50
Did you have sufficient time to complete the tutorials?	4.58	0.52	4.78	0.44
Did tutorials provide enough background to allow you to work independently on your design?	4.42	0.79	4.67	0.50
Did you have enough time to model your design?	4.50	0.67	4.00	1.00
Was software available to you in the lab outside class hours?	4.58	0.90	4.67	0.50
What is your comfort level with this module?	4.33	0.65	4.78	0.44
Module 2 (Fabrication)	**4.67**	**0.50**	**4.57**	**0.61**
Did the fabrication protocols provide sufficient process detail?	4.77	0.44	4.67	0.50
Were the fabrication protocols relevant?	4.69	0.48	4.67	0.50
Do you understand the mask design process?	4.92	0.28	4.40	1.00
Did you have sufficient time to complete the mask design?	4.77	0.44	4.56	0.73
What is your comfort level with this module?	4.62	0.51	4.78	0.44
Do you feel sufficiently trained now to carry out the fabrication process by yourself?	4.23	0.83	4.33	0.50
Module 3 (Characterization)	**4.22**	**0.73**	**4.65**	**0.61**
Was the microscope demonstration sufficiently detailed?	4.33	0.65	4.78	0.44
Was the microscope demonstration clear?	4.33	0.65	4.78	0.44
Did you have enough time on the microscope to perform your device characterization?	4.17	0.72	4.56	0.53
Was the data analysis tutorial sufficiently detailed?	4.00	0.85	4.44	1.01
Was the data analysis tutorial clear?	4.17	0.84	4.67	0.71
What is your comfort level with this module?	4.33	0.65	4.67	0.50

In the focus group, 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.*

Pilot Dissemination at UIC

In fall 2007, we conducted a pilot dissemination of the microfluidics lab course at University of Illinois at Chicago (UIC). The course at UIC, *BioE494:Microfludics Biochip Lab*, was taught by Dr. David Eddington, Bioengineering. The core materials developed at UC were modified from a 10-week quarter term to a 15-week semester term. The number and the subject of the laboratory sessions remained the same, while the introductory materials were expanded to include fundamentals of microfabrication, as this course is the first time the students were exposed to MEMS. Thus the course had *no prerequisites*.

The course dissemination was evaluated through questionnaires and a focus group, using the assessment materials developed at UC. All students enrolled in the course ($N = 16$) participated in the evaluation. Overall, the average scores for each module were slightly lower than those for the courses at UC, ranging from 3.9 to 4.5 (Table 3), but quite comparable to the scores from UC (Table 2).

Table 3. UIC Results ($N = 16$)

	Mean	SD
Module 1	4.38	0.72
Module 2	4.47	0.77
Module 3	3.91	0.87

These scores do not necessary indicate a less successful course. Quality of student presentations and work was just as high as at UC. We believe differences in the UIC course are likely the result of differences in engineering disciplines, student population demographics, instructor pedagogic styles, and students' learning styles.

Dr. Cathy Maltbie conducted the end-term focus group at UIC. Similar to UC students, UIC students expressed extremely positive comments, such as those below:

- *Lab was the best part. Doing something new is exciting. Getting the results and comparison with what was expected increases curiosity.*
- *I liked how we had complete control over our project throughout the entire process. It was very open-ended.*
- *The combination of the experimental part with the computer simulation.*

Broader impacts of this teaching initiative

As we enter the early 21st century, microfluidics and lab-on-a-chip technologies are still developing. However, nanotechnology is knocking on the door. Scaling down to nanometer dimensions of the channels for fluid transport opened a new window for fundamental and applied studies of *nanofluidics*—studies of the characteristics of flow in nanoscale systems. It has been recently shown that nanofluidics has advantages in biological sciences, biophysical sciences (*e.g.,* DNA analysis) and chemistry. Yet current nanotechnology research and education are focused mostly on studies of nanomaterials, such as nanoparticles and carbon nanotubes, and their preparation and properties. Little has been done to transfer the micro/nanofluidics research to the undergraduate curricula.

The laboratory experience described in this paper introduces students to the exciting, rapidly emerging field of microfluidics. The students will be better prepared to pursue graduate work or to meet the needs of industry and government employers in the micro/nanofabrication area, which is projected to grow tremendously in the next decade. The problem-based learning approach in this highly specialized field will also teach students how to approach real-world engineering problems spanning all engineering disciplines. Thus, regardless of their future career path, students will gain experience of working as part of a team to solve a real engineering problem.

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.

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