Group-Project-Based Development of A Modular Microfluidic Platform: A Case Report on A Hands-on Microfluidics Course

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Abstract

Microfluidic devices manipulate fluids at the micro- or sub-millimeter scale and are used for various applications. Courses on microfluidics offer students an opportunity to learn about microfluidics that may be applicable to their research. Including hands-on experiences in such courses leads to enhanced learning and ability to apply the technology to research and industry settings. In this paper, we introduce a one-semester-long course on microfluidics that integrated in-class lectures with hands-on activities through group-project-based learning. In the first lecture-based half of the course, instead of the traditional class setting where lectures are given by the instructor, students took turns giving lectures on certain chapters of the chosen microfluidics textbook. During this period, students learned about the fundamental theory, various fabrication methods, and current state-of-the-art of microfluidics. The group also developed an idea for their group project under the guidance of the instructor. In the second activity-based half, students received basic training about microfluidic fabrication and experimentation and worked on the group project wherein they solved technical problems together. As the group project, students chose to develop a plug-and-play type modular microfluidic platform for mechanobiological studies. Under the guidance of the instructor, students designed a microfluidic motherboard and microchannel modules with computer aided design (CAD), characterized printing capabilities of the used microfluidic 3D printer, fabricated the parts using 3D printing and soft lithography, and tested the fabricated motherboard and microchannel modules separately and then together. Students found that their prototype was functional but still needed improvement. After the semester, students were each asked to reflect about the course. Altogether, students' reflections show that they perceived that they learned more, were more engaged, and were less stressed in this course than in a traditional lecture-style course. Their learning spanned new knowledge, hands-on skills, research skills, professional skills, and problem-solving skills. While the students were not all able to directly use the knowledge gained through the course in their research, they all reported gaining new skills or knowledge that will be transferrable to their future careers.

Keywords

Project-based learning, plug-and-play motherboard, 3D printing, soft lithography, engineering education

1 Introduction

Microfluidics is a versatile research tool for a wide variety of scientific and engineering disciplines [1,2]. Microfluidic devices manipulate fluids using channels with height or width at a micro- or sub-millimeter scale. One of the most striking and promising applications of microfluidics is to create lab-on-a-chip (LoC) environments in which full laboratory-scale procedures can occur on a footprint smaller than a notecard. LoC devices can be used for detecting and manipulating specific types of cells, creating point-of-care diagnostic devices, and developing drugs [3,4]. The corresponding author of this paper (the instructor hereafter) has also actively employed microfluidics for various projects including cellular mechanobiology and multi-phase flow through porous media [5-11].

Because of the versatility of microfluidics, engineering students, in particular graduate students, often showed interest in learning about microfluidics so that they could use microfluidics for their research with greater understanding. When the instructor talked with such students, they emphasized wanting to have hands-on experiences in making and testing microfluidic devices, which would allow them to gauge the potential usefulness of microfluidics in their research and to inform their discussions with their advisor. In this sense, it was clear that traditional lecture-based teaching, which mainly focuses on theoretical aspects of the technology and lacks hands-on experiences, would not keep students motivated, meet their needs, or lead to enhanced learning.

Pedagogical research in engineering education supports this project-based, student-centered approach to teaching [12]. Student-centered approaches have consistently been found to be equally or more effective than traditional approaches, improving learning outcomes and key competencies like teamwork, critical thinking, and problem solving [12,13]. More specifically, project-based learning has been shown to lead to higher student motivation and better understanding of how to apply learning to realistic problems [14]. Therefore, the instructor designed his microfluidics class in a way that students would learn about fundamental and historical aspects of microfluidics and gain hands-on experiences through working on a common group project on designing, fabricating, testing, and analyzing their own microfluidic devices.

The most conventional fabrication methods for microfluidics are soft lithography and photolithography. In soft lithography, polydimethylsiloxane (PDMS) is cast into a master mold that has microchannel patterns. After curing, the solidified PDMS channel body is separated from the mold and usually bonded to a substrate to form a channel device. The master mold is made by photolithography. Since in photolithography UV light is shed through a high-resolution photomask having the channel pattern to UV-responsive epoxy spin-coated on a silicon wafer, the process is not easily accessible. To circumvent this limitation of photolithography, the instructor used 3D printers to make a plastic master mold [15-17]. In the presented class, students learned and practiced fabricating plastic microfluidic devices and molds using the 3D printing technology, and PDMS microchannel devices using soft lithography.

The group project of the presented class was to make a prototype for a modular microfluidics system with a plug-and-play capability using the 3D printing technology and PDMS-based soft lithography. The aforementioned conventional microfluidic fabrication method has the following limitation. When a part of the channel network is damaged during fabrication or operation, the entire device malfunctions. This limitation becomes more detrimental for complicated LoC devices. To further increase the versatility of microfluidics, the concept of modular microfluidics has been proposed and tested [18].

In this modular approach, multiple microfluidic devices can be connected together through a common motherboard (Figure 1). Such modular approaches have been shown to improve the through-put of biological detection [19], increase the speed of LoC fabrication and prototyping [20,21], and improve their portability [22]. As such, further development of modular microfluidics with plug-and-play capabilities can greatly increase the effectiveness of microfluidic systems. Such motherboards must have leak-free, quick, and reversible sealing methods. The reusability of the motherboard is also essential to its improved function. Additionally, modular microfluidics have the potential to reduce the labor required for operating microfluidic systems.

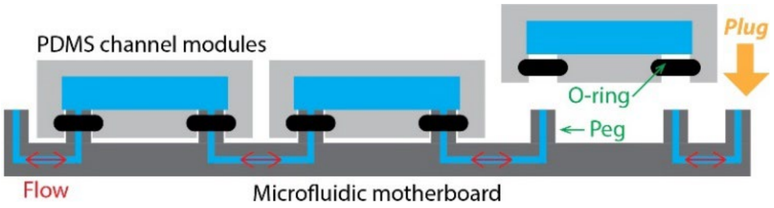

Figure 1: Schematic of modular microfluidics with the plug-and-play capability.

In this paper, we present the course structure, student activities, and outcomes of an independent research course on microfluidics offered in the fall semester of 2022. Five students (first five authors of this paper; the group hereafter) took the course and successfully completed their group project. The group designed and fabricated a motherboard and three simple channel devices, tested several design parameters for optimized 3D printing, and developed design guidelines for 3D printed channel devices. The group also validated their prototype by conducting flow tests to check for leaking and blockages in any part of the assembled setup. The purpose of this paper is twofold: (1) describe how the integration of project-based learning (PBL) enhanced student learning and ability to apply microfluidics to their research, and (2) describe the methodology and results of the project itself.

2 Course Activities

2.1 Student-led lecture

Hands-on experiences and activities were the keystone of the course presented in this paper. Instead of the traditional class setting where lectures are given by the instructor, students took turns giving a lecture on certain chapters of the chosen microfluidics textbook. To ease students' load on lecture preparation, the instructor gave the first lecture at the beginning of the semester to introduce the general aspects of microfluidics and the general structure and scope of the course, and to share expected quality or difficulty level of lectures for the rest of the semester. Students were given a common slide template to use for their lecture and asked to send their lecture handout well before each lecture so that the instructor could give the student lecturer suggestions to improve their material. Lecture slide handouts were shared via online learning management system before each lecture. Each student in the group gave two lectures for the first half of the semester.

The instructor played the following roles in the lecture session. During each lecture, he supplemented the lecture by providing additional explanations on the fundamental and practical aspects of microfluidics and by clarifying murky points in the lecture. Also, he encouraged students to ask questions to the lecturer and to share their related experiences so that the entire group could be engaged. The instructor invited a guest lecturer, who was his visiting graduate student, to present his development and validation of microfluidic devices for pathogen detection.

Therefore, in the first lecture-based half of the course, students learned about the fundamental theory, various fabrication methods, and current state-of-the-art of microfluidics. The guest lecture helped students to envision how they can incorporate their learning in their research. The group also developed an idea for their group project under the guidance of the instructor.

As the group project, the group chose to develop a modular microfluidic platform for mechanobiological studies. Mechanobiological studies of cells often require multiple microchannels with various cell types to be connected. For this purpose, a modular microfluidic platform was developed to further increase the speed and throughput of microfluidic testing. A modular microfluidic platform consists of modular microchannel devices and a microfluidic motherboard to which channel devices can be easily, reversibly, and repeatedly connected (Figure 1). This modular approach allows for high-throughput laboratory experiments while minimizing waste of materials and time. Additionally, a motherboard can enable quick customization of experimental conditions to suit specific needs.

2.2 Basic training of microfluidics fabrication

The lecture portion of the course was followed by the hands-on group project in the second half of the semester. Since most students had no experiences in microfluidics, they received basic training about microfluidics fabrication, especially soft lithography and 3D printing, in the instructor's lab. The first author had worked with the instructor on microfluidics fabrication as an undergraduate researcher [16,17]. So, he helped the instructor with training other students.

2.3 Scope and goal of the group project: Preliminary design of a prototype

During the basic training, the group established the scope and goal of their group project and developed a preliminary design of their modular microfluidics prototype under the guidance of the instructor. In this design, a 3D printed microfluidic motherboard would connect three PDMS modules with a straight microchannel (Figure 2). The motherboard was designed to consist of two inlet ports, six connections port for the channel modules, and two outlet ports (Figure 3). The group would print out the motherboard using a microfluidic 3D printer (CADWorks3D) and clear resin (BV-007). Microchannel modules would be fabricated using a 3D printed mold, soft lithography, and PDMS (Sylgard 184, Dow Corning). Finally, the group would prove the concept of plug-and-play type modular microfluidic platform by connecting fabricated motherboard and channel modules and by testing their compatibility. The flow chart shown in Figure 4 summarizes the fabrication process of the group project.

2.4 Characterization of 3D printing capabilities: Final design of the prototype

Before finalizing detailed design of the parts, the printing capabilities of the 3D printer had to be characterized to fully utilize benefits of 3D printing. The design factors for the motherboard were the cross-sectional shape, height, and length of channels embedded in the motherboard, the dimensions of the inlet and outlet ports, and the geometry of connection ports. To find the optimal parameters for the motherboard, several test devices were designed using SolidWorks (Dassault), printed, and tested.

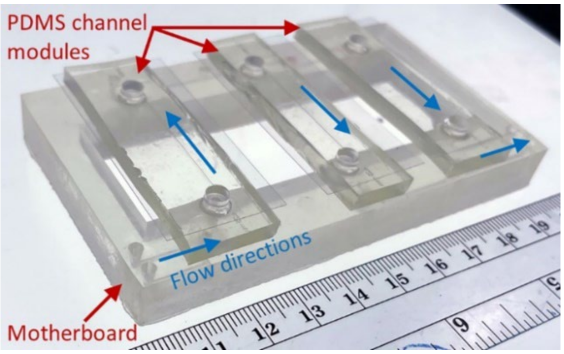

Figure 2: Assembled prototype for a plug-and-play type modular microfluidic system that students completed at the end of the course.

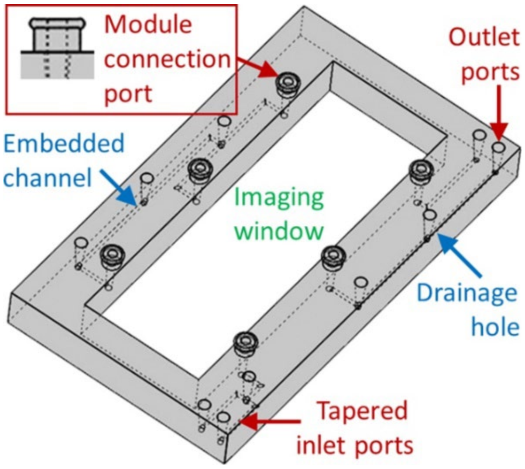

Figure 3: Design of the motherboard. Inset: Magnified view of the module connection port.

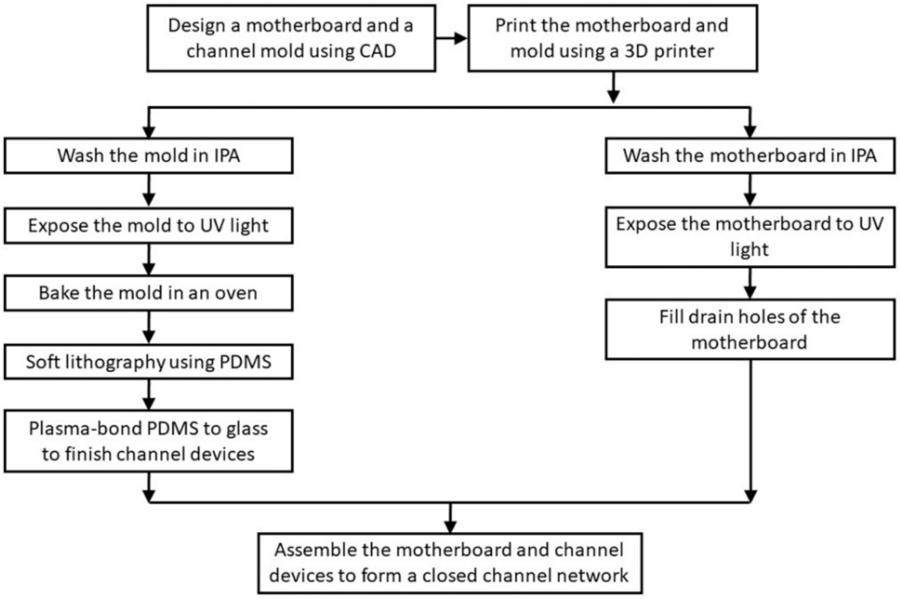

Figure 4: Flow chart of the fabrication process of the project.

The cross-sectional shape, height, and length of a microchannel within the motherboard contributed to whether the 3D printer has the capability to print the device. Channel geometry determines if the 3D printer must print overhanging structures, the orientation of the motherboard on the printer's build plate, and drainage of the channel while printing. Channel height and length determined the drainage of the channel while printing, the effectiveness of the post-processing procedure, and the compatibility of the device with the syringe pump.

The group tested circular, triangular, rectangular, and diamond channels. The group chose these cross-sectional shapes for the following reasons. Circular channels were tested due to their axisymmetric features and the similarity to biological structures such as blood vessels. Triangular channels were tested because microfluidic molds fabricated with most silicone etching techniques produce triangular channels [23]. Rectangular channels were tested because they are the most common channel geometry for microfluidic devices. Diamond channels were tested as a secondary orientation of rectangular channels.

Regarding channel heights, the group chose 120, 240, 480, 760, 1,020 and 1,280 µm for the following reasons. The smaller channel heights were tested because having the smallest dead volume possible for the motherboard is beneficial to biological studies. The larger channel heights were tested because the 3D printer is more compatible with larger channels. All the channel sizes used followed the 30 µm resolution of the 3D printer.

To efficiently test channel geometry and height simultaneously, eight different test devices were designed. Each test device tested printing a single shape with three channel heights. As such, all four shapes were tested with all six heights. Additionally, all the test devices had channels with a length of 10 mm. The group found that the best channel shape and height for the motherboard was circular channels with a height of 1,020 µm. Circular channels were identified as the best due the ability of the printer to print the full length of the channel. This indicated that the channels drained well during printing, and the orientation during printing was acceptable. After printing and processing, other shapes had cured material filling the channel, or the channel had collapsed during printing resulting in channel blockage.

Afterwards the group found the maximum printable length of the channel by creating a test device with the following channel lengths: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, and 55 mm, with the chosen channel shape and height (Figure 5). They found in the printed test device that channels longer than 35 mm had defects and speculated that resin could have not drained well from such long channels. As such, drainage holes were added to the final design of the motherboard to allow for excess material to flow out of the channels while printing. The drainage holes enabled printing of channels longer than 35 mm.

The module connection port design was also investigated. The module connection port was printed such that the port had an O-ring shape at the top of it (Figure 3 inset). The student group and the instructor considered inserting rubber O-rings in PDMS channel modules as shown in Figure 1, but the group chose to incorporate the O-ring shape in the peg for leak-free connections between the motherboard and the channel modules. O-ring cross-section diameters of 250, 500, 750, and 1,000 µm were tested. These diameters were chosen as they are common sizes for O-rings. By plugging and unplugging the printed pegs against the port of the PDMS channel module, the group found that the peg with an O-ring cross-sectional radius of 0.75 mm was best as it was the smallest

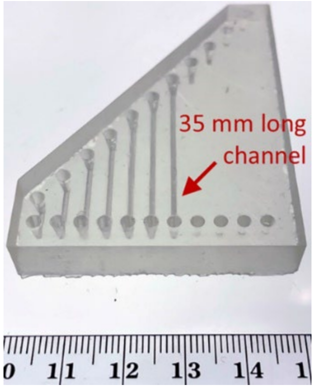

Figure 5: Test device with various channel lengths.

cross-sectional diameter that could lead to tight seals with the straight-channel chips. Also, the O-ring with a 0.75 mm cross-sectional diameter showed the best printability due to small overhanging features and an appropriate thickness between the inner wall and outer wall. As it was the smallest, it also minimized the amount of material needed to print the O-rings.

The motherboard needed inlet ports to be connected with tubing. Tapered inlet ports were designed for ease of insertion and removal of tubing (Figure 3). The inlet ports were designed to have the diameter of the tubing occur at the vertical center of the port. The port's opening was chosen to be twice as large as the tubing diameter. The dimensions of the ports opening and center were used to find a draft angle of 5°.

The group chose to include two inlet and outlet ports in the motherboard for the following reasons. The two inlet ports would allow a biological sample and a biochemical reagent to be injected separately and mixed within the first chip of the device, integrating the initial sample preparation procedure into the chips of the motherboard. The two outlet ports would allow for collecting samples separately from each of the chips, ensuring the excess samples would not mix after passing through the chips of the motherboard.

Also, a viewing window was added to the motherboard to enable better compatibility with microscopy imaging. The viewing window reduced the amount of material required to fabricate the motherboard.

In summary, the group found that the best design parameters for the motherboard were circular channels with a height of 1,020 µm and a maximum length of 35 mm. Inlet ports with a diameter of 2.6 mm and taper of 5° were used, and connection ports with an O-ring cross-sectional radius of 0.75 mm were chosen. Separately, straight-channeled modular devices were designed accordingly. Then, the group fabricated the motherboard using the 3D printer and the channel modules using 3D printed molds, PDMS, and soft lithography.

2.5 Microfluidic 3D printing

The 3D printer was prepared following our previous protocol [16]. The motherboard was printed using clear resin (BV-007) (Figure 6). After it was removed from the build plate, 90% isopropyl alcohol (IPA) was injected into the channels embedded in the motherboard using a 10 mL syringe.

The injected IPA removed excess uncured material from the channels. Next, the motherboard was submerged in 90% IPA to remove uncured resin from its surface. After IPA rinsing, the motherboard was placed into a UV oven (Creative CADWorks LED Light Cure Box). The motherboard was exposed to three, 10-second-long cycles, for a total exposure time of 30 seconds. The motherboard was allowed to rest for 60 seconds between each cycle. The UV exposure finished the solidification of the resin. Finally, the drainage holes in the motherboard were filled with epoxy (Gorilla Epoxy). After epoxy was applied to the motherboard, tape was applied over the holes and the board was flipped upside down to prevent the epoxy from flowing into and blocking the channels. The epoxy was allowed to cure overnight.

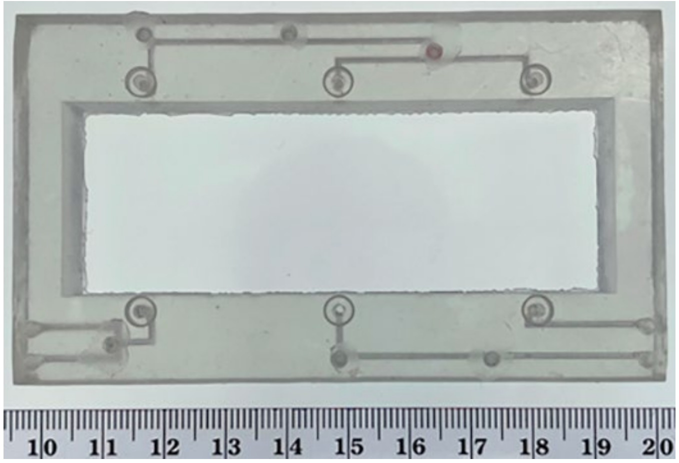

Figure 6: 3D printed motherboard.

For the microchannel modules, a mold was printed using master mold resin (CADWorks3D) and the 3D printer (Figure 7A). Once printed, the mold was washed and cured as done previously in Ref. [16]. The mold was washed in 99% IPA for a total of 50 minutes. During washing, the mold was shaken on a digital shaker at 160 rpm. Additionally, it was removed from the IPA and blown off with compressed air every 10 minutes. This helped to remove the excess resin. Once washed, the mold was placed into the UV oven to finalize the resin solidification. It was exposed to UV light for four cycles, totaling 40 minutes. Finally, the mold was placed into a conventional oven overnight at 130°C. This finalized any chemical reactions occurring within the resin, allowing for PDMS to cure on the interface of the mold and PDMS.

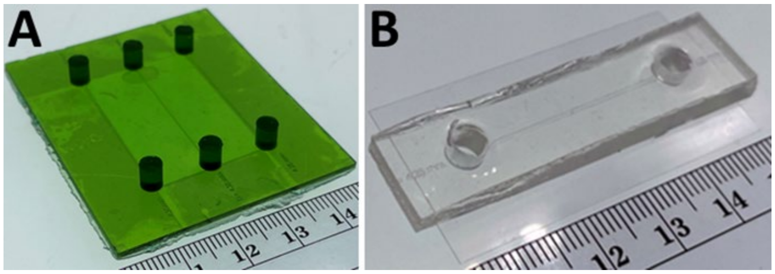

Figure 7: (A) 3D-printed plastic master mold for the channel modules. (B) Fabricated PDMS channel module.

2.6 Soft lithography

Soft lithography was used to make the microchannel modules (Figure 7B). Before pouring PDMS, the mold was coated with tridecafluoro-octylreichlorosilane (T2492, UCT Special Ties) to prevent the PDMS from sticking to the mold. The mold was placed into a vacuum chamber with 250 µL of T2492 suspended in mineral oil. Negative pressure was applied for two minutes to aerosolize the T2492. The chamber was turned off and allowed to sit overnight.

Next, 30 grams of PDMS was mixed at a base-to-agent ratio of 10:1. The PDMS was poured into the mold. Care was taken to ensure the PDMS did not submerge the pegs on the mold so that the channel modules could connect with the motherboard. Then, the mold and PDMS were placed into a vacuum chamber for 1.5 hours to remove air entrapped within the PDMS. After degassing, remaining bubbles were popped using a syringe needle. The PDMS and mold were placed into an oven at 60°C for 8 hours. Once the PDMS was solidified, it was carefully peeled from the mold. Finally, plasma treatment was applied to the PDMS and a glass slide (25 mm □ 75 mm) for plasma bonding. The combined PDMS and glass slide was placed at 80°C overnight for permanent bonding.

2.7 Motherboard and module testing

The motherboard and microchannel modules were first tested independently and then together. For both, red-dyed water was injected into the channel using a syringe. During the flow test, the devices were inspected for leaking and blockages. Once separately confirmed operational, the motherboard and the channel modules were connected with a press-fitted seal. A flow test through the assembly device was conducted using tubing (Tygon, outer diameter: 0.06 inch), which was connected to the inlet and outlet ports of the motherboard, a syringe, and a syringe pump. Slight leaking at the inlet and outlet ports was found if the tubing was not cut perpendicular to its cross-section. Overall, at a volume flowrate of 0.1 mL/min, 5 of the 6 connections between the motherboard and the microfluidic chips were leak-free. The connection was also shown to be effective under repeatable disconnecting and reconnecting.

3 Results And Discussion

Students could successfully fabricate a prototype for a plug-and-play type modular microfluidics platform, consisting of a plastic motherboard, which was directly printed from the microfluidic 3D printer. Students also successfully fabricated three PDMS-based microchannel modules, which were fabricated using 3D printed plastic molds and soft lithography, based on what they learned in the class and their project-based collaboration. For successful design and fabrication of the parts, the group developed a design protocol for 3D printing microfluidic devices as follows.

The ideal channel geometry for the motherboard was a circular channel because the circular cross-section eliminated the need for specific printing orientation, as well as reduced the angle of overhanging features.

Channel height of 1,020 µm enabled excess resin to flow out of the channel during printing. It also reduced the probability of channel blockages and the effect of the printer's tolerance on the printed device. This channel height improved the success rate of printing for all channel geometries. Smaller and larger channel heights were found to be less successful. It is thought that smaller channels are less successful because the scattering of UV light solidified the resin within the desired channel blocking the channel. Additionally, smaller channels have a higher potential to entrap resin during the printing process.

Channel length was also found to play a critical role in successful channel printing. Longer channels showed a greater probability to entrap resin during the printing process. As such, a maximum channel length of 35 mm enabled proper printing of the motherboard. For channel sections that were longer than 35 mm, drainage holes were included to prevent entrapment of resin. These holes were sealed using epoxy after printing.

The geometry and size of inlet ports for tubing played a role in the functionality of the motherboard. The inlet ports were designed such that 0.06-inch diameter tubing could be easily inserted for a leak free connection. To achieve this, the inlet port begins at a diameter of 0.12 inches, and tapers down to a diameter of 0.03 inches. A taper angle of 5° was found to be easily printed and hold the tubing appropriately.

Regarding the plug-and-play type connection between the motherboard and PDMS channel modules, the connection ports on the motherboard were printed with a diameter of 4.75 mm. The O-ring geometry on the connection port had a cross-sectional diameter of 0.75 mm. This O-ring size was chosen as it was easily printed while using less material. Additionally, the smaller O-ring size reduced the strain on the PDMS of the microfluidic chips while it was connected to the motherboard. For the channel modules, inlet diameters of 4.25 mm showed to be the best size for connection to the motherboard. Inlet diameters smaller than 4.25 mm would not fit onto the motherboard while larger diameters would leak.

Once the motherboard and channel modules were fabricated, they were combined and subjected to a flow test. As Figure 8 shows, the assembled prototype had a total of six connection sites between the motherboard and channel modules. Red dyed water was injected into the setup using a syringe pump. Flowrates higher than 0.5 mL/min caused leaking between the tubing and the inlets of the motherboard. Flowrates between 0.15 and 0.5 mL/min caused leaking at the connection of the motherboard and the channel module. It was found that at a flowrate of 0.1 mL/min, only one of the connections leaked. Therefore, flowrates below 0.1 mL/min were found to be successful.

To prevent leakage when operating the motherboard, multiple different solutions could be enacted. First, lowering the flowrate through the device helps prevent leaking due to a decrease of applied pressure on the device and its connections. Second, clearing the connection port on the PDMS channel device of debris using compressed air helps to create a tighter seal between the device and the motherboard. Third, decreasing the size of the connection port on the PDMS device would also create a tighter seal.

After the flow test, the group discussed how to improve their prototype as follows. The motherboard could be improved by modifying the design such that it has the capability to change the ordering of flow through the channel modules. This could be achieved by adding valves to the motherboard channels that can be open or closed as desired. Additionally, reducing the dead volume on the device would be beneficial for saving the amount of sample used for biological studies. The straight channel modules could be improved by developing more complex microfluidic chips for specific functions. Further testing of the setup could be done by performing flow tests with biological samples. Not only would this further check for leaking, it would also test the biocompatibility of the devices. Additionally, cleaning and reusability of the motherboard could be investigated after performing tests with biological samples.

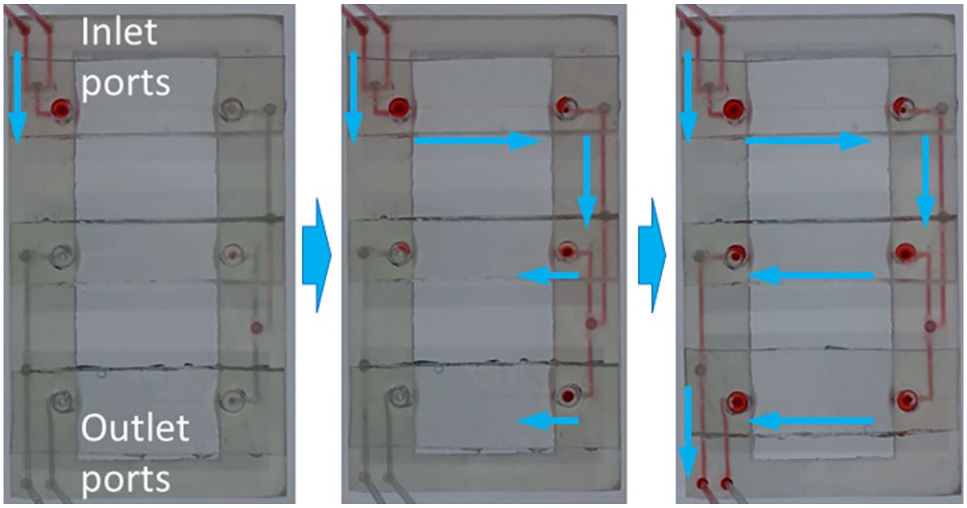

Figure 8: Chronological images showing the flow of the red dyed water through the assembled prototype. Cyan arrows show how the injected dyed water flowed through the motherboard.

4 Self-Reflection Of Students

The students who participated in the course, and who are co-authors on this paper, were each asked to reflect on the questions in Table 1. Students emailed written reflections to the course instructor, and their reflections were analyzed using thematic analysis by co-author Jessica Deters. The major themes that emerged from this analysis are discussed below.

Table 1: Student Reflection Questions

Reflection Questions
• What did you learn from this course? ○ How does what you learned in this course compare to what you've learned in courses with a traditional format (i.e., lectures and exams)? ○ What challenges did you face during the course? How did you overcome those challenges? • Have you been able to apply what you learned to your research? If so, how? If not, can you foresee applications in the future? • Did the course impact your perspective about how engineering graduate courses should be taught? If so, how? If not, why not? • Has this course impacted your future career plans and/or your preparation for your future career plans? If so, how?

Across the reflection questions, students reflected on the role of themselves, their peers, and their instructor in the learning process. First, students learned by taking an active role in the course, through preparing a lecture, managing a piece of the project, and collaborating with their peers. One student reflected on their development of project management skills through the hands-on part of the course:

> “The hands-on portion of the course helped me develop my **skills as a project manager**. I was in charge of leading the class through the required steps to complete the modular motherboard. I decided which tasks were most critical and was able to identify potential obstacles to completing the project on time. Additionally, I was able to see the way other students tackled similar problems that I had faced, which gave me a new perspective on some of my own personal obstacles. [emphasis added]”

Second, students reflected on the role of their peers in their learning process. Each student prepared and delivered a lecture and collaborated on the course project. While one student reported learning more through their own lecture than others’, another student wrote:

> “**I found myself very engaged when learning from other students**, most likely to make them feel more comfortable, which aided in my learning. Interjections from students and especially the professor was very insightful. Extra information about the history of the lab, project, technology or technique used was engaging. [emphasis added]”

Moreover, students reflected that the collaborative nature of the project let them build on each members’ strengths while learning new skills. One student wrote:

> “Practicing **overcoming design challenges as a team** is always beneficial. We were able to work together and bring out the strengths of each member. From CAD design, fabrication expertise, and experience in cell research, **each member brought something useful to the table**. [emphasis added]”

The students were able to identify the strengths of each team member and assign tasks that aligned with those strengths. Another student reflected on this delegation in terms of interest and motivation:

> “A secondary challenge with the class was the different levels of interest and motivation. Some students were highly motivated to complete as much as possible within the course, while others were focused on other objectives. **Giving each student tasks that they enjoyed and could learn from** was critical to overcoming this obstacle. [emphasis added]”

In addition to the reflections about the student’s and their peers’ role in their learning, one student provided an astute reflection on the professor’s role in the course:

> “The **professor’s involvement in the lab sessions was perfectly balanced**; guidance in the beginning and end to keep us on track in the long-term, which only he could do with his experience, and no involvement afterwards. His lack of involvement was imperative, allowing the students to depend on one another to solve the problem at hand. I believe if Dr. Ryu was more involved, the students would value his opinion more than other students’, leading us to think that there is a “right answer” to our design. [emphasis added]”

Students reflected on their learning in this course as compared to courses taught with a traditional lecture and exam format. Overall, students believed that they learned more, were less stressed, and had a more enjoyable experience through this project-based course. Students reported learning from each other, hands-on work, and through preparing a lecture. One student reflected on the long-lasting learning spurred by this course:

> "This course has definitely impacted the way I believe engineering courses should be taught. Classroom styles classes for upper-level engineering students are a way of the past. Far less material is learned and remembered over a long period of time. **Hands-on courses enforce long-lasting learning**. [emphasis added]"

Altogether, students' reflections show that they perceived that they learned more, were more engaged, and were less stressed in this course than in a traditional lecture-style course. Their learning spanned new knowledge, hands-on skills, research skills, professional skills, and problem-solving skills. While the students were not all able to directly use the knowledge gained through the course in their research, they all reported gaining new skills or knowledge that will be transferrable to their future careers. Regarding self-reflection question, a numerical grading rubric could be distributed to the students. This numerical metric could complement their qualitative reflections and better reflect the students' sentiments and evaluation of the course, but was beyond the scope of this study.

5 Conclusions

A prototype for a plug-and-play type modular microfluidic platform was developed as a part of a microfluidics course with an alternative course structure emphasizing hands-on experiences and group work. All aspects and activities of the course were led and performed by students under the guidance of the course instructor. This course went beyond the theory-focused and lecture-based aspects of typical courses and gave students an opportunity to actively participate in the course and engage themselves in active learning. Through the course, students gained experience in preparing and giving lectures, fabrication and testing microfluidics, and prepared a conference level paper. By incorporating project-based, student-centered learning practices, students gained valuable hands-on experiences that will be helpful for their future careers. Students' self-reflections show that they perceived that they were more engaged and learned more in this course than in a traditional lecture-style course.

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