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A Hands-On Approach to Teaching K-12 Students About Microfluidic Devices (Work in Progress)

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Abstract

There have been significant advances with microfluidic devices and lab-on-a-chip technology leading to micro total analysis systems (μTAS) capable of analysis and discoveries in the laboratory, the field, and the clinic. Unfortunately, while the academic community is well versed in the utility and application of these devices, the public (especially promising young scientists) is relatively unaware of their existence. Furthermore, several of the underlying chemical and physical principles governing microfluidics have applications in a several STEM disciplines including engineering, chemistry, physics, and biology. Here, we highlight a series of workshops and outreach activities designed to provide elementary, middle, and high school students an opportunity to learn more about microfluidic devices through a hands-on approach. Initially, these workshops were given to high school students from traditionally underrepresented minorities as part of two week-long summer camp offered by the College of Engineering at Louisiana State University entitled REHAMS and XCITE. The demonstrations provided students with an overview of microfluidics including introductions to polymer chemistry and fluid flow dynamics. The students were able to fabricate and test their own devices using a simple microfluidic gradient generator to mix yellow and blue colored water to make green. Expanding upon these initial demonstrations, we have developed a series of outreach activities to be performed at local area elementary, middle, and high schools focusing on the use of microfluidic droplet generators as tools for cancer diagnostics. The presentations and demonstrations were adjusted depending upon the age range, but all session contained several hands-on activities to show the students what could be done in a few millimeters on a microfluidic device. To show the students what was happening in the device, we constructed large-scale version of the devices for the students to use and experiment with (e.g., a table-top microfluidic droplet trap array that uses ping pong instead of picoliter-sized aqueous droplets). Additionally, a key strength of this outreach program is the inclusion of undergraduate students from the Society of Peer Mentors at Louisiana State University as presenters to increase student engagement. As this work is preliminary in nature and no precise quantitative data has been collected about the workshops, informal discussions with student participants have all been positive with many students appearing eager to learn more about this exciting field of science and engineering

Introduction

The development of novel microfluidic devices has made a significant impact on the scientific community. These devices take advantage of their small size, laminar flow, and a low surface-to-volume ratio to achieve an unprecedented degree of control over the physical and chemical environment. This technology was initially confined to the manipulation and mixing of two different chemicals in the form of gradient generators; however several advances and new devices have been developed in recent years that provide numerous applications in the fields of human health, energy, and the environment. Moreover, microfluidic devices offer significant advantages of competing technologies due to reduced reagent costs, ease-of-use, significant reproducibility, compatibility with most types of fluorescent microscopy, and a relative degree of biological inertness [1, 2]. By integrating several different types of microfluidic devices into a single chip, researchers have developed micro total analysis systems (μTAS) that allow for fundamental and applied advances in a number of research fields and STEM disciplines.

Fundamental devices, including organs-on-chip, provide a realistic environment analogous to different types of human tissue including the heart, lungs, kidneys, and the colon. These systems have been used to assess cellular interactions, angiogenesis, drug effectiveness, and graft-versus-host disease [3]. Applied microfluidic technologies are being developed to aid in the fields of personalized medicine and disease diagnostics (both in the clinic and in the field). Yet, even with all of these advances and possibilities, the development and use of this technology is not well disseminated to the general public, especially young scientists. When most K-12 students are asked to come up with a definition for lab-on-a-chip technologies or microfluidic devices, most students think they have something to do with computers and/or smart phones. Moreover, many of these same students are shocked to learn how these technologies, with mostly biological/biomedical applications, are developed by engineers and chemists. The success of microfluidic technology requires the expertise in a number of STEM disciplines including chemical, biomedical, electrical, or mechanical engineering in addition to chemistry, biology, and physics. Many research teams that develop these devices include one or more experts in these fields. This interdisciplinary nature provides a unique outreach opportunity for K-12 students as the students can see applications and learn about core topics in a number of disciplines. Moreover, in the state of Louisiana, chemical engineering is largely associated with the petrochemical industry, thus most K-12 students believe that the only thing that an engineer or chemist can do is to work in the oil & gas industry.

Due to all of these factors, we set out to develop two of outreach activities, specifically geared towards K-12 students interested in STEM disciplines, to educate and engage students on the applications of microfluidics and the underlying chemical, physical, and biological phenomena involved in their design and use. This paper deals with our ongoing efforts to develop this set of outreach activities and hands-on demonstrations, which have initially been met with increased student interest and engagement. The first demonstration was held as part of a week-long engineering camp at Louisiana State University specifically designed to increase enrollment of traditionally underrepresented minorities in STEM disciplines. Based on the initial success of these demos, we next developed a more hands-on, personalized activity to educate K-12 students not only about microfluidic devices, but also their use in the field on cancer diagnostics. This second type of activity (which just debuted in the last week of January 2016) was designed for both large-scale STEM nights as well as small classroom activities. A key strength of all of the outreach programs performed thus far is the involvement of current chemical engineering undergraduate students at our university as mentors and leaders. These students, many of whom perform undergraduate research in the field of microfluidics, provide additional guidance and instruction during the demos and activities. Ultimately, it is our intent for these activities to ignite a passion in the K-12 students to one-day enroll in STEM disciplines and continue to make a significant impact in the scientific community.

Microfluidics 101: How to teach K-12 students about microfluidics in a 90 minute lecture.
The college of engineering at Louisiana State University has three week-long summer camps offered to both middle- and high school students to increase interest and enrollment in STEM majors when the students ultimately decide to attend college. These programs are called REHAMS, XCITE, and Project NJneer and provide the students with a chance to live in a university setting and experience all of the engineering majors offered at Louisiana State University. During the program, students are mentored by counselors (current engineering

undergraduate students), participate in team-building activities, and are able to attend a 90 minutes lecture given by select faculty from each of the engineering disciplines. During the summers of 2014 and 2015, we were asked to give a 90 minute lecture on chemical engineering. Instead of just talking about the petrochemical industry, it was decided to spend more time giving the students an overview of microfluidics as it has applications not only in the petrochemical industry, but also in the fields of human health and the environment. Additionally, the development of the devices require knowledge of several aspects of numerous STEM disciplines. The demonstration was designed to include both lecture and activity components combined with utilizing active learning techniques such as TAPPS and think-pair-share to increase student involvement and retention. Undergraduate chemical engineering students working in the field of microfluidics were asked to participate in the demonstration to assist in the generation of the session materials and to act as helpers during the delivery of the session. This allowed for more direct interaction and instruction of the camp attendees.

The overall goal of the session was to have the students make and test their own microfluidic device. In an attempt to simplify the demonstration, we decided to have the students work with an established microfluidic device called a serpentine gradient generator. This device, which was developed almost two decades ago by Prof. George Whitesides at Harvard University [4], allows for the small-scale mixing of two aqueous streams by length-scale diffusion (Figure 1A). This device requires little in the amount of optimization, can produce an immediate change in output by adjusting the input parameters, and is currently being incorporated into μTAS devices to study numerous biological phenomena including cell migration, drug resistance, and algal biofuels [5, 6]. The length scales necessary for complete mixing of the two inputs are achieved by the continuous mixing and splitting of the channels, which have been patterned in 'switch-back' serpentine channels. The seven resultant channels are merged in a final main outlet channel which results in a linear gradient perpendicular to the direction of flow. The microfluidic device itself consists of fluidic channels imprinted into a flexible polymer [PDMS, poly(dimethyl siloxane)] that is permanently coupled to a glass slide via oxygen plasma. The PDMS replicas are created from a silicon

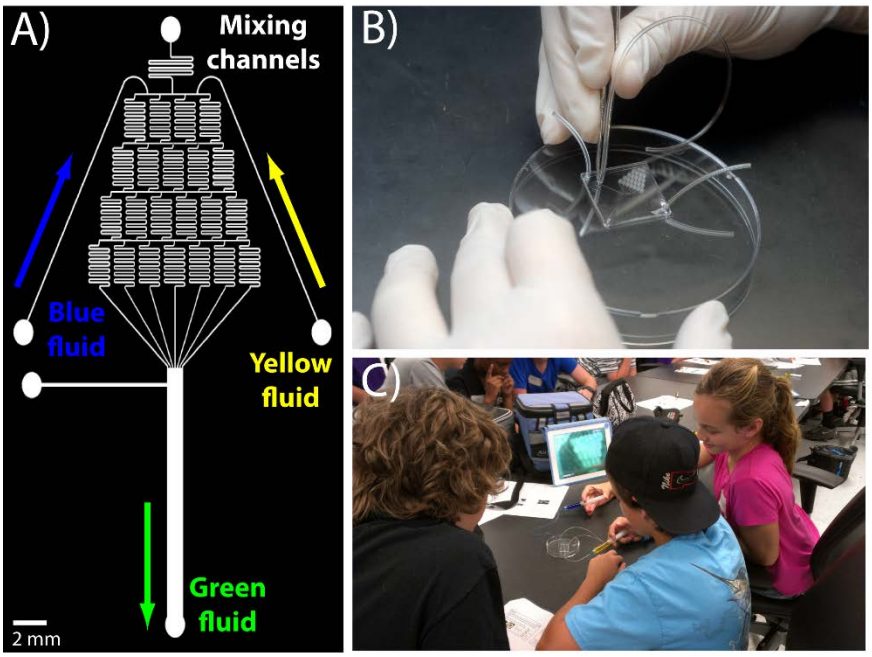

Figure 1. Design, fabrication, and use of a microfluidic gradient generator. (A) Schematic of the serpentine gradient generator used in the microfluidics 101 demo that used the device to mix blue and yellow fluids to produce a green fluid. (B) Image of the assembled and plumbed microfluidic device. (C) Students from one of the COE summer camps using the microfluidic device.

master wafer, which is generated using established soft lithography and replication techniques [7], resulting in the ability to make several PDMS devices from a single silicon master. Flow is introduced into the device by connecting two inlet ports to two syringes containing the blue and yellow fluids via Tygon tubing (Figure 1B). The use of the colored fluids (which consist of dH_2O spiked with blue or yellow food coloring) eliminated the need for fluorescent microscopy and allowed for the students to easily visual the mixing phenomena that occurs in the device. As for fabricating the devices, as discussed above, this requires a multi-step process, some of which are performed by the students with others being performed by the undergraduate student helpers.

The fabrication and use of microfluidics requires an understanding of several STEM topics, thus the demonstration required the students to learn about polymers (and polymer chemistry), mass transfer, chemical reactions, and teamwork. This was accomplished by a combination of lecture and hands-on demonstrations. First, the students were split into groups of 2-4 (depending on the size of the group) and tasked with coming up with (1) a definition of chemical engineering and (2) career options for chemical engineers. This initial activity helped to break the ice and get the students involved in the session in addition to getting them to think about what exactly a chemical engineer does. Next, the students were introduced to the topic of polymers, which included questions like “what is a polymer?” and “how is a polymer made?”. Since PDMS is a polymer consisting of a binding and curing agent, it was important to teach the students how two component liquids could ultimately result in a flexible, imprintable solid. To achieve this, the students were given their first hands-on activity: Polymer Slime. This established outreach activity involves the mixing of 10 mL of a 4% polyvinyl alcohol (PVA) solution with 1 mL of a 4% solution of borax ($Na_2B_4O_7•10H_2O$) resulting in a 10:1 dilution ratio of the two components of the polymer slime. Student thoroughly enjoyed the opportunity to make their own slime mixtures and the chance to put on gloves and safety googles to feel like ‘real’ scientists (Figure 2). As part of the activity, students were instructed to investigate how changing the dilution ratio would affect the stiffness of the polymer slime (e.g., adding more PVA or borax solutions). This gave students their first opportunity for performing an engineering analysis in addition to providing a visual foundation for the underlying polymer chemistry and reaction involved in the fabrication of a PDMS replica.

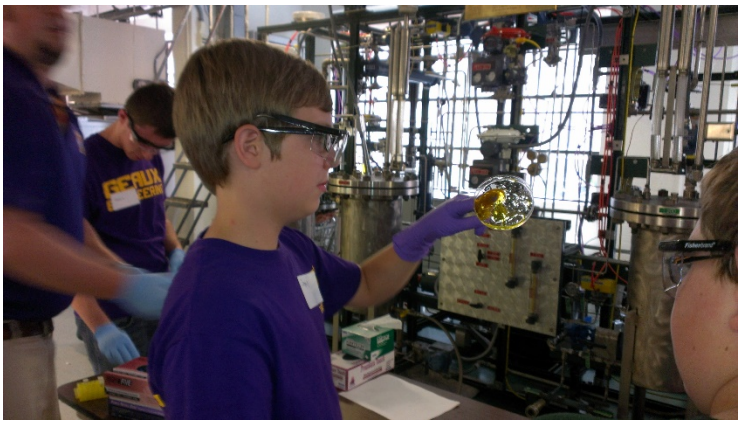

Figure 2. Synthesis and testing of polymer slime.

Once the students had an understanding on polymers, they were next introduced to microfluidic devices. This included an overview of the chemical reaction needed to make the PDMS replicas and the numerous applications of the technology (as described above). This overview was followed by two hands-on activities: (1) the fabrication of the PDMS replicas and (2) the testing of the microfluidic gradient generator. The fabrication of the PDMS replicas strongly resembled the protocol for the generation of the polymer slime, except here the students were split into groups of 2-4 depending on total size of the group. While it would have been optimal for each

student to get their own silicon master, our limited number of silicon masters required the students working in groups. However, this gave students the chance to work on their teamwork and communication skills. Once split into groups, the students were given pre-aliquoted volumes of PDMS base and curing agent and then told to mix them up in weigh boats. Once thoroughly mixed, each group poured their liquid PDMS onto a silicon wafer contained in a petri dish, taking care to ensure complete coverage of the wafer. These wafers were then taken to the lab and cooked on a hot plate overnight at 65°C. After the demonstration, the student leaders then detached and cut PDMS replicas (each silicon master contained the mold for four separate device) for the camp attendees to take home with them. Thus students not only performed the chemical reaction, but also were given their own microfluidic device to take home as a reminder of their first chemical engineering experience.

The final activity of the session was for the students to use an assembled microfluidic gradient generator. Each group of students was given a pre-fabricated device with the tubing and syringes hooked up (again previously assembled by the undergraduate student leaders). Pre-fabrication of the devices was done to eliminate the sharps hazard associated with the syringes and to eliminate the lag time associated with device assembly due to the time being a potential limiting factor for the 90 minutes demonstration. The students were first instructed on the fundamentals of the device (e.g., blue fluid plus yellow fluid equals green fluid) and then told to make green fluid. To accommodate the numbers of students, each group was encouraged to have one members use the syringe containing the blue fluid while another member used the yellow fluid-containing syringe. This was done to increase student involvement and teach students about teamwork (e.g., if one student over-pressurized their syringe then mixing could not occur). To enhance visibility, students were given “microscopes-on-a-rope” to see a zoomed image of the device, which was broadcast onto iPads the students were using (Figure 1C). For the most part, the students greatly enjoyed working with the devices with roughly 50% of the students producing a successful green color exiting the device. Of the students that could not get the device to work, the main problem was the students over-pressurizing the syringes and causing the tubing to detach from the device or form leaks between the PDMS and glass substrate. In an attempt to overcome this issue, we provided additional back-up devices to reduce the number of students left without a working device. A few of the more successful groups were able to work together to rapidly alter the color of the green fluid from a light green to a dark green simply by adjusting the pressure on the two inlet syringes. This demonstrated to students how subtle manipulations could affect an experimental output. At the end of the session, the students were instructed to written down three things they learned and one thing they wanted to learn more about. Most students were excited by the concept of miniaturized technology and were eager to learn more about how these devices could be used in different STEM disciplines. This demonstration was so highly received among the students and the camp organizers, that it was highlighted in the PBS-sponsored American Graduate Day during the fall of 2015 (http://video.lpb.org/video/2365577270/). Although we considered these demonstrations to be successful, one significant drawback to the session is the lack of any quantitative metrics highlighting what the students learned or the overall impact of the session. We are currently exploring methods to obtain more quantitative data.

Microfluidics 201: How to make a hands-on activity based on an 8 cm device

One limitation of the microfluidic demonstration offered to the COE summer camps is that students could not directly observe what was happening within the micro channels. Even with

the use of handheld microscope-on-a-ropes and iPads, the students still had a difficult time processing what was happening within the device without seeing it. Additionally, we found that many students wanted to learn more about specific applications of the technology. To address both of these issues, it was decided to develop a larger-scale, more specific demonstration that could be performed in individual K-12 classroom or at K-12 STEM nights. We decided to switch from using the microfluidic gradient generator to a microfluidic droplet generator coupled with a micro droplet trapping array. The underlying principle behind this device is the rapid generation (e.g., 10-100 droplets per second) of monodisperse, picoliter-sized aqueous droplets (often containing single cells) in a continual oil phase (Figure 3). These types of devices offer several applications including single cell analysis, dynamic measurement of intracellular activity, high-throughput screening, and isolation of rare cells [7, 8]. Another reason why this type of device was selected is that it is currently being developed in our lab in tandem with fluorescent, peptide-based reporters to perform high-throughput single cell analysis of *ex vivo* patient samples from individuals suffering from cancer. As such, the outreach activity we developed not only provided students with a hands-on opportunity to work with microfluidics, but also address a significant challenge in the field of human health. The design of the device is included in Figure 3 and shows the rapid generation of aqueous droplets followed by the subsequent trapping of the droplet in chambers imprinted into the PDMS above the fluidic channels (Figure 3i-iii). The aqueous droplets containing 0-4 cancer cells are isolated and trapped from the continuous oil phase to the relative difference densities between the aqueous droplets and oil phase (Figure 3iv).

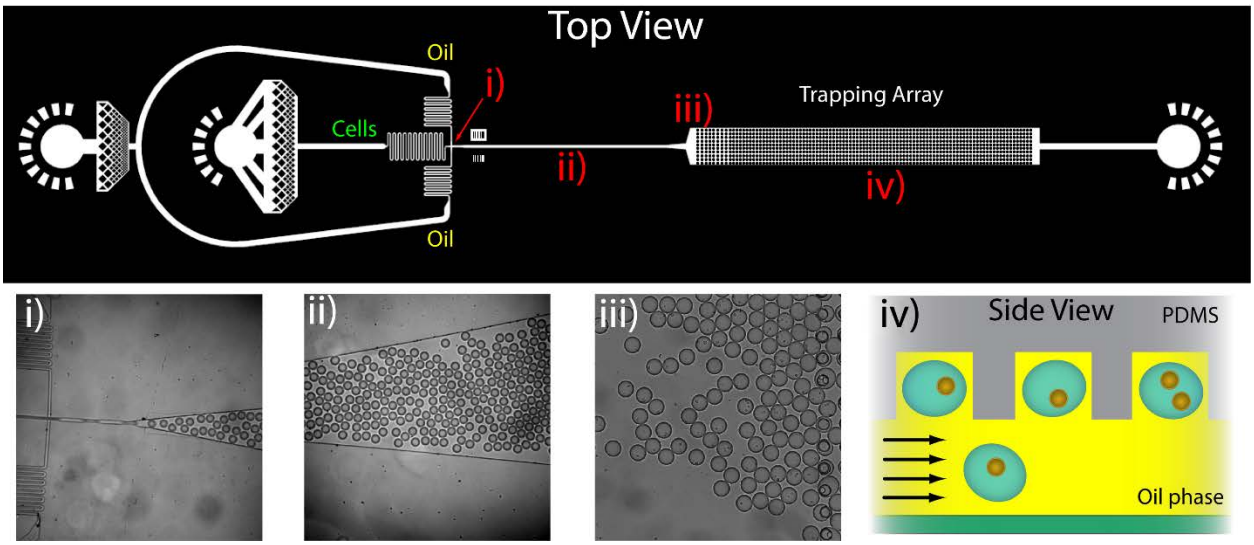

Figure 3. Overview of the droplet microfluidic trapping array. (i)-(ii) Generation of monodisperse aqueous droplets containing single cancer cells. (iii) Trapping of aqueous droplets in an array fabricated on top of the microfluidic channel in the PDMS. (iv) Cartoon schematic of the droplet trapping observed from the side.

The first challenge in developing this new outreach activity was how to present the device and its applications to younger scientists without completely diluting the message. To accomplish this objective, we reached out to the Society of Peer Mentors at Louisiana State University – a student-lead organization that focuses on leadership and outreach to K-12 schools in the Baton Rouge area. We assembled a team of seven students (all majoring in chemical or biological engineering) and tasked them with crafting a demonstration. While the student leaders were not initially well-versed in biotechnology or microfluidics, they easily took to the project and came

Figure 4. Images of the first outreach activity using the large scale microfluidic droplet trapping array. (A) Student leaders teaching students about different types of cells in the body. (B) Isolation and trapping of mock cancer cells (ping pong balls) in the large scale device. (C) Diagnosis/counting of cancer cells using a black light.

up with some great ideas. The first idea was the development of a large-scale replica of the microfluidic droplet trapping array. To give students a more hands-on approach, it was decided to use ping pong balls to represent the cancer cell containing aqueous droplets. Multi-color ping pong were selected to represent the different types of cells often found in a tumor biopsy (e.g., yellow balls were immune cells, while pink balls were red blood cells) (Figure 4A). To give the appearance of cancer cells and healthy cells, half of the population of ping pong balls were painted with glow-in-the-dark paint to represent the cancer cells. The rationale behind this was related to the overall goal of the technology being developed by engineers. Doctors cannot visually distinguish between healthy cells and cancer cells, so researchers are developing metrics to 'tag' the cancer cells for more accurate diagnostics, typically using fluorescence. The large-scale microfluidic trapping array was fabricated out of two layers of clear and black Plexiglas with an array of cups fabricated into the top layer to allow for easy trapping of the ping pong balls (Figure 4B). The large-scale device was fabricated on an incline to allow for gravity-driven 'flow' of the 'cells' to facilitate trapping. Finally, a black light was used to identify the 'cancer cells' from the 'healthy cells' that have been trapped in the array (Figure 4C).

Once the equipment had been designed, the final step was developing the presentation itself. We developed a ~5-10 minute interactive lecture that provide instruction on cancer, the need for diagnostics, how engineers can help doctors, and how to use the device to trap the cancer cells. This activity was called "Counting Cancer Cells" and has been presented one time so far at a STEAM night at a local magnet elementary school. As part of the demonstration, we

would select two students to act as the ‘engineer’ and the ‘doctor’. The ‘engineer’ would be responsible for sorting and trapping the ping pong balls (Figure 4B), while the ‘doctor’ would hold the black light and diagnose/count the cancer cells (Figure 4C). These students were dressed up in lab coats and safety goggles and really felt like actual practicing scientists. Other students present during the demonstration would encourage to assist in the counting and active discussions about cancer and microfluidics. The student leaders directed the demonstration, which included asking questions like “what is cancer?”, “what is a tumor?”, “how can doctors treat cancer?”, and “what can engineers do to help?” We also brought along PDMS replicas and actual microfluidic devices for the students to pass around and see how engineers are able to trap and study single cells on a device that is barely 8 cm long. We have received excellent informal feedback from the first STEAM night and have since arranged three more outreach activities at local elementary, middle, and high schools. It is our intent to continue to modify/enhance the outreach activity to further engage the students and provide more hands-on opportunities with microfluidics.

Preliminary conclusions and future directions

Our intent with this paper is to demonstrate how to teach K-12 student about the fabrication and use of microfluidic devices. Traditionally, it has been difficult to instruct students on micro-scale technologies that are difficult to visual and somewhat difficult to fabricate without some degree of scientific training. During the first outreach session, we were able to have the students perform stepwise experimentation with actual microfluidics devices that generated an observable output. The advantages of this session are the use of several hands-on activities coupled with an interactive lecture to teach students about the underlying chemistry and physics involved with microfluidics. The disadvantages of this session is the relative short time period to accomplish all of the objectives (~90 minutes), the significant amount of prep work that is required by the undergraduate student leaders to get all of the devices made for the session, and the lack of any quantitative deliverables. As this outreach session was part of a larger camp, we could not perform any entry or exit surveys, beyond a five minutes discussion of what students have learned at the end of the session. We are currently working with COE counselors in an attempt to devise a method to get more feedback from the students to find a way to improve the 90 minutes demos. Additionally, the use of large-scale devices could also increase student interest and engagement.

The goal of the second outreach demonstration was to generate a large scale version of a microfluidic droplet generator so that students could get a more hands-on experience with the technology. Using the same principles that guide single cell trapping in the microfluidic device, we generated a ‘rig’ that could effective trap mock cancer cells that would allow students to count/diagnose the cancer. As this outreach activity was just deployed, we are still optimizing the presentation style to maximize student engagement. The inclusion of students from the Society of Peer Mentors at Louisiana State University was a key strength as they helped to craft a message and design an activity that was easily understood by the K-12 students. Moving forward, we intend to continue to offer the outreach activity at local area elementary, middle, and high school in both individual class rooms and STEM nights. Additionally, we are in the process of developing metrics to quantify the success of the outreach activity. Proposed metrics include surveys and post-demonstration activities to gauge student interest and retention and provide a more quantitative assessment of outreach effectiveness. Finally, we are exploring additional

activities to give students even more hands-on experience with microfluidic devices. An optimal outreach activity would allow individual students to work with/optimize mock devices made from PDMS that replicate the physics of the microfluidics, but that were also more robust and less likely to get damaged by the students.

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