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Work in Progress - Group Laboratory Experiment During Lecture in an Undergraduate Fluid Dynamics Class: Increasing Student Learning and Communication Skills

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Abstract: Laboratory classes in engineering often occur toward the end of curriculum, excluding their benefits from the core class while it is being taught. Instead of a full laboratory, presentations and in-class demonstrations are often used to bring the concepts “to life.” This work presents an on-going effort to integrate a simple, group-based laboratory into an undergraduate chemical engineering fluid dynamics course. This implementation method was based on previous work where a brief demo was done in class at the end of the semester in Fall 2016. Student feedback via surveys indicated they needed more time, smaller groups, more preparation, and the lab to be introduced closer to when the topic was learned in class. Those improvements were all made here. The lab occurred during one 75-minute course period. The concept used milli-fluidic devices fabricated in-house with a gravity driven flow. A conical funnel and tubing were used to supply water flow driven via a height difference through the milli-fluidic devices. The devices had various channel designs including a straight channel, one with 14 90^o bends, and one with 22 90^o bends to study the equivalent length (frictional increase) of the bends. Groups of three (from 45 total students) were given a brief write-up in advance of the class period with a schematic of the setup, relating the equipment to the Mechanical Energy Balance, an equation they had learned in the previous weeks. During the course period, the groups had access to the various milli-fluidic devices, tubing, hose-clamps, collection jars, calipers, and a scale. Their task was to find the equivalent length of a 90^o bend, based on their collected experimental data. They designed their own experiment during the class period to accomplish this task. Most tubing was cut to provide a water column (driving force) between 1.5 and 4 ft. Students collected water as it drained while recording the time, and the mass of water was determined with the scale. With this mass flow rate, students could analyze the system for the unknown equivalent lengths. A week after the in-class work, a question based on this experiment was included in Exam 1. Further, a brief report was required of each group 12 days after the in-class activity, worth 5% of the course grade. A survey in the Fall term of 2017 assessed students’ thoughts on this format versus a traditional lecture, and if they believe this helped their understanding. Based on questions asked of the instructor during the laboratory day, it appears many students gained insight by being able to generate numbers via an experiment related to equations previously applied only to textbook-type problems.

Introduction:

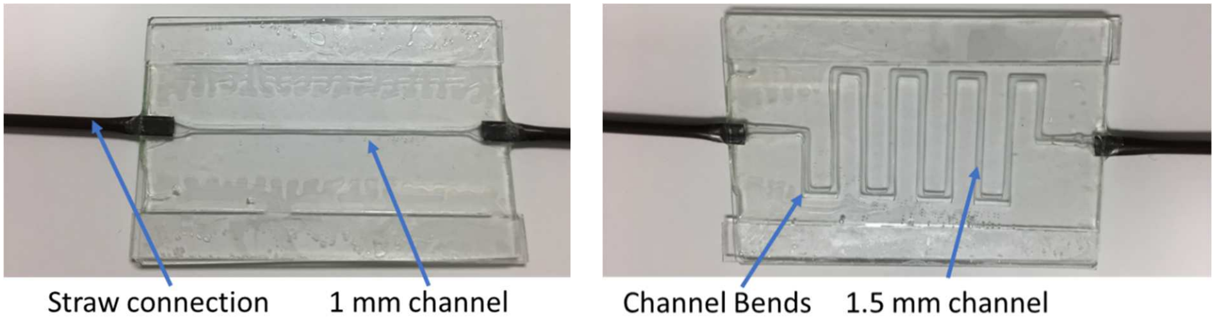
Laboratory experiences are common in engineering curriculum [1], and examples of real engineering tasks [2] and concepts can help student learning [3]. As stated by Feisel and Rosa [4], a typical goal of a laboratory course is to relate theory and practice. They also mention the added benefit of students interacting with physical systems, which can be useful in a successful engineering career where the theory must be applied. If done well, laboratories can assist in hands on skills, problem solving, and analytical thinking [5]. While common in the overall curriculum, it is typical for the laboratory experience to occur as an entire course, as opposed to working a laboratory experience into an individual class where the theory is first being taught. In lieu of a laboratory component of the course, faculty continue to use in class demonstrations, potentially aiding in the connection between theory and practice. For instance, Garrison and Garrison [6] used a demonstration each day (30 demonstrations or videos) in an undergraduate Fluid dynamics class. They point out that a course like Fluid Mechanics has non-intuitive content, and misconceptions can be addressed with their approach. Similarly, Pour et al. [7] addressed the ‘abstract’ concept of thermal boundary layers via a novel visualization technique. Their students noted positive comments about how ‘seeing’ the boundary layer was helpful.

At Montana State University, the Chemical and Biological engineering department has approximately 600 students with laboratory experiences occurring in the freshman year and then both semesters of the senior year. The goal of this work is to report on the implementation and an initial assessment of a brief laboratory-like experience in a Fluid Mechanics course. This iteration substantially improves upon a previous exploration focused on a single-day in-class experiment [8]. This course is a good test-bed as it is a “fundamental” course common in chemical and biological engineering curricula. It was hoped by pushing this activity closer to a laboratory-like experience, students would learn more than from an instructor-led demonstration [1]. The first iteration (Fall 2016) occurred during the final exam review and focused on friction losses in piping systems. Milli-fluidic devices developed at the university were fabricated with a straight channel and with several bends. Using a funnel and tubing, a fixed driven force could be set for a gravity driven flow through the devices. By collecting and weighing the water, the students could determine a mass flow rate and relate this back to friction effects in the system (e.g. major and minor losses in the systems). Students worked in large groups (~8 people per group) to set this experiment up and collect data in approximately 15 minutes. This approach accommodated five groups in the 75-minute class period. The instructor verbalized instructions to each group as they worked. While survey results showed self-reported increases in student learning, the additional survey results and open-ended responses echoed several improvement areas: smaller groups, clearer instructions, more structure, and better timing relative to course content. These issues were in-part due to the timing of the device fabrication and are consistent with problems that can occur in a problem-based learning environment [9].

This paper presents a similar approach in the same course during Fall 2017 with these improvements taken into account. Enough equipment (tubing, funnels, etc.) and milli-fluidic devices were procured so three students per group (n = 45 students) could complete the exercise in an entire 75-minute class period. The lab occurred in the classroom where lecture was held during the regularly scheduled time. The activity occurred soon after the topic (Mechanical Energy balance) was first taught instead of during the final exam review day. Lastly, written instructions were provided to all students in advance of the in-class laboratory day so they could arrive with questions and ideas about how to proceed. The students were asked to use their collected data to determine the equivalent length of the 90^{o} bends in some of the channels. This paper details the chip fabrication methods in brief (based on previous work [8]), the new implementation, results from a survey, and additional instructor perspectives.

Chip Fabrication:

Microfluidic devices were made with two glass slides and UV-curable epoxy, similar to methods from [10,11]. The inexpensive chip design and fabrications efforts are explained in detail in our previous work [8], and as such as only included in brief here. The procedure manufactures 'close-faced' milli-fluidic devices. The UV epoxy is poured onto a glass slide that contains spacers to define the channel height. A second slide is placed over this epoxy, 'closing' the device. A mask, a printed design channel pattern on a transparency, is then affixed above the slide-epoxy-slide. This chip is exposed to UV light, curing the epoxy through the clear transparency, leaving the epoxy in fluid form underneath the printed designed channel. This remaining epoxy is flushed with solvents and deionized water. Straws are inserted into the chip inlet and outlet ports and further cured into the system, allowing the devices to be connected to standard syringe barrels for use in the experiments. Two examples of devices are shown in Figure 1.



a) b)

Figure 1 a) Straight channel used to determine friction associated with the straws and syringe connection b) Multi-bend channel used to determine the equivalent length of each bend

Fifteen straight channel devices were fabricated, along with different designs with bends. The variations focused on channel width and number of bends, allowing the students more choices in designing their own experiment.

Equipment for Student-Designed In-Class Laboratory

Table 1 highlights the key purchases needed to develop a microfluidic chip laboratory based on the approach described in the previous section. In total, the cost is approximately $1,100, with the majority of it being one-time purchases. The UV lamp and UV curable epoxy are the largest expenses, with the one-time cost of the lamp being nearly one third of the price. The supplies to make 15 gravity-driven funnel system is approximately $300, and much of the equipment remains available for future implementations (non-consumable).

Table 1. Costs to fabricate milli-fluidic devices and the gravity driven funnel system

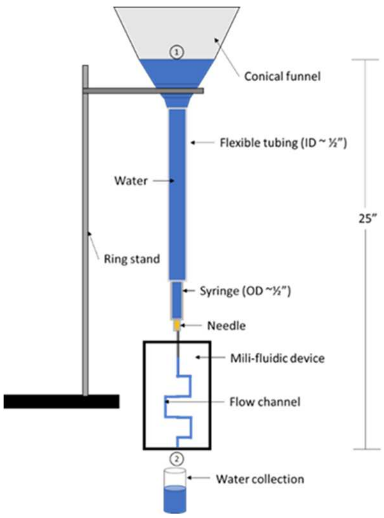
Items	Description	Approximate Total Cost ($)
	Gravity driven funnel system	
Funnels (x15)	McMaster- 16 oz. Plastic Funnel with Vapor-Lock Resistant Ridges	37
Hose Clamps (4x Boxes)	McMaster - Worm-Drive Clamps for Soft Hose and Tube, 201 Stainless Steel, 1/2" to 7/8" Clamp ID Range, Packs of 10	45
Tubing (4x)	McMaster - PVC Tubing for Food, Beverage, and Dairy, 1/2" ID, 5/8" OD, 25 ft. Length	69
Syringes (1x)	Plastic Syringe with Luer Lock Tip, 0.2 oz. Capacity, 20 per pack. Modified	12
Tape Measure and Stop Watches	Available to borrow from lab	--
Calipers	General UltraTech	25
Scale to weigh collected water	EBAY - SAGA Digital Scale 2000g x 0.1g	25
Water containers (1x/size)	Semi-Clear HDPE Plastic Vial 1oz and 2 oz (10 per pack)	60
	Milli-fluidic Chips	
UV Lamp	Spectronics XX-15A	368
Collimator	Custom; see [8]	18
UV Curable Epoxy	Norland NOA 83H 1lb bottle	382
UV Glasses	UVP UVC-303	30
Glass Slides	Package of 100	30
Transparencies	$1/sheet	10

Implementation in Class, Survey, and Report Guidelines:

The activity can be broadly viewed as two components: how the activity was structured and implemented during the 75-minute class period, and how the activity was assessed via the survey questions and subsequent lab report.

In-class Implementation:

The students received a lecture on the Mechanical Energy Balance and equivalent lengths as they relate to piping systems on Sept 21, 2017 (Lecture 8). Lectures 9 and 10 were on piping systems and involved textbook type calculations related to friction, pump work, pressure drop, etc. These lectures focused on students solving problems during class with the instructor answering questions and providing information as needed. The in-class laboratory occurred during Lecture 11 (10-03-17). This meant the laboratory experience occurred much closer to when the content was first learned vs. during the final exam review as was done in Fall 2016. Four days before class, students were given the following information in a handout along with a schematic:



> As we have learned in this class, friction in flow systems can come from the channel walls and from additional fittings, such as valves, bends, expansions, and contractions. It is critical to understand these concepts in order to effectively design piping systems.
>
> This in-class laboratory experiment asks you to determine the equivalent length of 90^o bends in milli-fluidic channels (this means channels on the order of 1 mm x 1 mm). These bends serve as an analogy to the frictional losses in large systems (the same logic applies here, regardless of the scale).
>
> The experiment is based on flow driven through the device via a height difference (potential energy). For a schematic, refer to the figure. The device has a secure connection allowing it to be connected to a syringe barrel. Available tubing can fit around the syringe barrel and the exit of a conical funnel. A conical funnel allows one to make the assumption that "the tank area is much greater than the discharge area", an assumption you will confirm or disconfirm. Available to you are multiple channel designs, including a straight channel with no bends.
>
> Your group's task is to devise and then execute an experiment to determine the equivalent lengths of the 90^o bends. Based on the experimental data you collect as a team in class, you will analyze the data and present a memo/report detailing your findings.
>
> Items to consider before class and then in your experimental design: What equations govern this experiment, and how can it be used to inform your design; How many trials/repeats for one chip system; Will you use multiple chips with the same design to check for manufacturing consistency; How will you analyze the effect of the narrow connections (straws) to the device; What height should you set the water to; Will you set the same height in each trial; Do the Frictional losses in the funnel, tubing, or syringe barrel matter

On the day of the laboratory, students self-selected into groups of 3-4 students. The instructor gave a brief overview of one example system fully assembled and how to connect the milli-fluidic devices to the tubing system. The equipment listed in Table 1 was made available and the students had to devise their own experiment. This included choosing how much tubing to use (i.e. how tall the device would be and thus what driving force was available for flow) and which milli-fluidic devices to choose. All students were told to use a straight channel device as a baseline, and then they could choose additional devices with varying numbers of bends and diameters. They could also choose the number of repeats, if any, and if they wanted to do multiple trials with different devices containing the same design. Students shared one scale to weigh the collected water. The instructor monitored students throughout the activity, fielding a range of questions from theory on the topic, to experimental design, to how to set the systems up. After class, the devices and equipment were made available in a common room the students could access in case they wanted to collect additional data. The instructor was also available in office hours or via email appointment to help groups structure an algorithm to analyze their data.

Survey and Report:

Thirteen survey questions were distributed to the students twelve days after the report was graded and returned. The questions are presented in Table 2. Q1-Q13 were Likert scale questions from "Strongly Agree" to "Strongly Disagree" with a neutral position of "Neither" included.

Table 2 Likert style survey questions Q1-Q13 and three additional open-ended questions

Q1-7:	Q8-13:
Q1 - The demonstration helped me learn core content related to Fluid Mechanics.	Q8 - I would prefer someone leading the demonstration while I watched.
Q2 - I enjoyed working in a group.	Q9 - I learn more by doing ‘hands on’ activities.
Q3 - I liked designing the experiment as a group.	Q10 - I would recommend doing this demonstration in future ECHM 321 courses.
Q4 - I better understood the Mechanical Energy Balance because of this demonstration.	Q11 - This single demonstration should be used multiple times throughout the course to highlight different topics.
Q5 - More small labs/demonstrations during the course would be helpful to my learning.	Q12 - I would use a “maker-space” area dedicated to designing my own “fluid dynamics” experiments.
Q6 - The demonstration helped me prepare for the first exam.	Q13 - The report writing helped me learn the material after completing the experiment.
Q7 - The open-ended nature of the demonstration confused me.	
Open-ended questions:	
Did this demonstration help you prepare for the exam? If so, how? If not, why not?	
How effective was your group at collaborating? Explain. (Or, How would you describe your group’s collaboration?)	
Given the opportunity to do this again, what would you change?	

The report was worth 5% of their course grade. Grading was generous due to the relative vagueness of the report guidelines and the students’ relative lack of experience in writing reports, though that was not articulated to the students in advance of the report. The guidelines (somewhat reduced here for clarity) were given on the day of the in-class laboratory exercise:

> In class, you collected experimental data related to the flow rate of water through milli-fluidic devices. In this report, you will present analyzed data to determine the equivalent length of the 90^{o} bends in those channels. Deliverables: The written report must be less than 3 pages, including a title and team names on the first page. Use 11 pt font with 1.15 line spacing. In the report:
>
> - Introduction: What problem are you solving and why?
> - Methods: Describe the experiments you performed, including your own schematic, relevant lengths, how data was collected, and the analysis procedure. Be clear about assumptions.
> - Results and Discussion: Focus on what values you calculate for the equivalent lengths of the 90^{o} bends. Show the flow rates obtained. Be clear about assumptions. In your discussion, mention key sources of error either in the experiment or what our device fabricators could do differently next time.
> - Conclusions: Concisely describe the overall aim, the approach taken, and key results. No new information is here.
> - References (If applicable)
> - An Appendix can be included with relevant tables in Excel and sample calculations by hand if needed.

Results and Discussions:

Results are presented from the survey questions and the open-ended responses. Survey results are presented in terms of percentages, and the total number of student responses to each question varied from 23 to 27 students. These survey results in aggregate show that the overall implementation was successful.

Likert Scale Results:

The results in Figure 2 relate to self-reported student learning, including if they believed it helped their learning in the course, the use of demonstrations, and the efficacy of the report writing. Overall, the students report that the laboratory in class helped them learn content central to the class, more labs would also be advantageous, and the report writing, where they had to analyze the data, was beneficial.

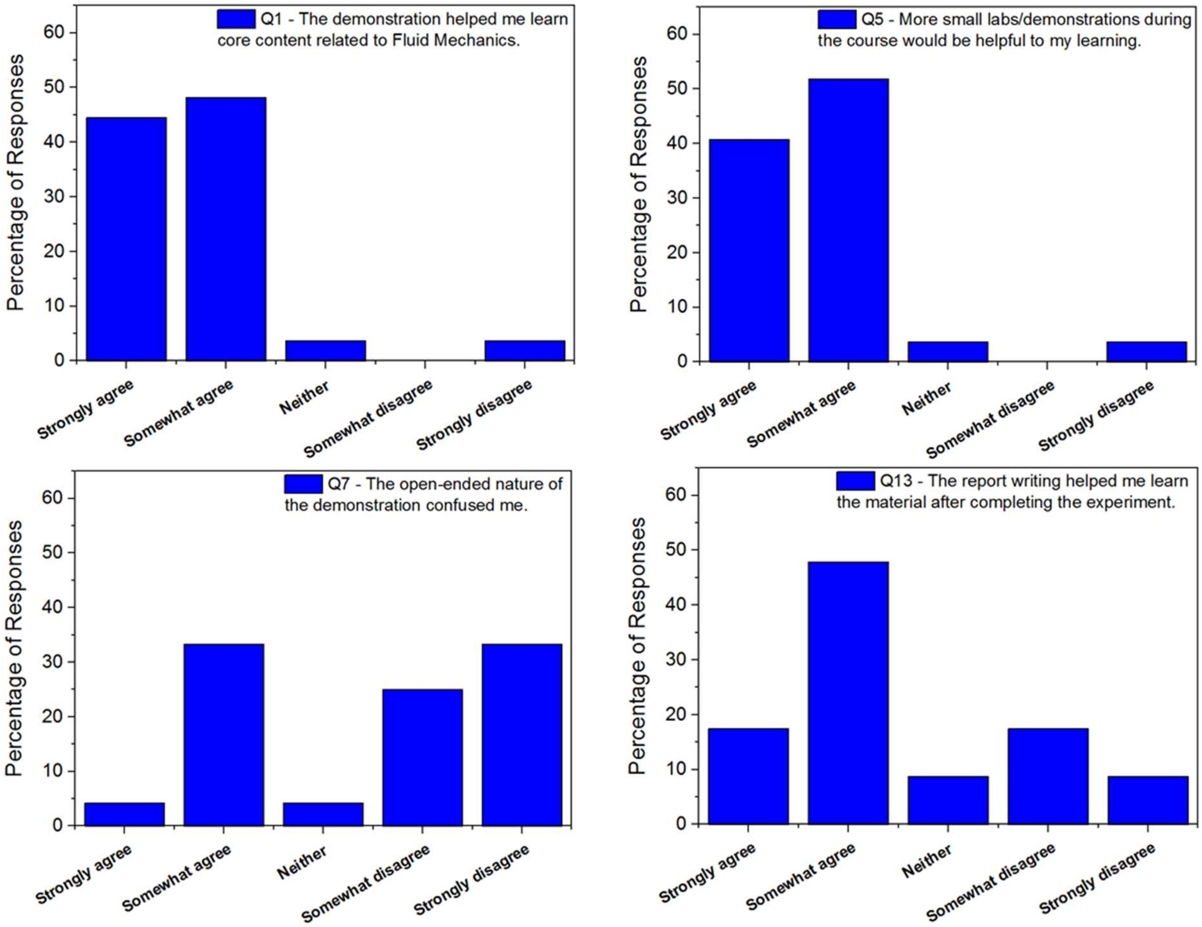


Figure 2. Q1, Q5, Q7, and Q13 survey results focusing on overall themes of self-reported student learning

Results in Figure 3 focus on the group experience. Overall, students reported enjoying working in their group (self-selected), designing the experiment, and would prefer not to watch someone else do the lab for them (i.e., a demonstration by the instructor). They also indicated they would use a space dedicated to designing their own labs.

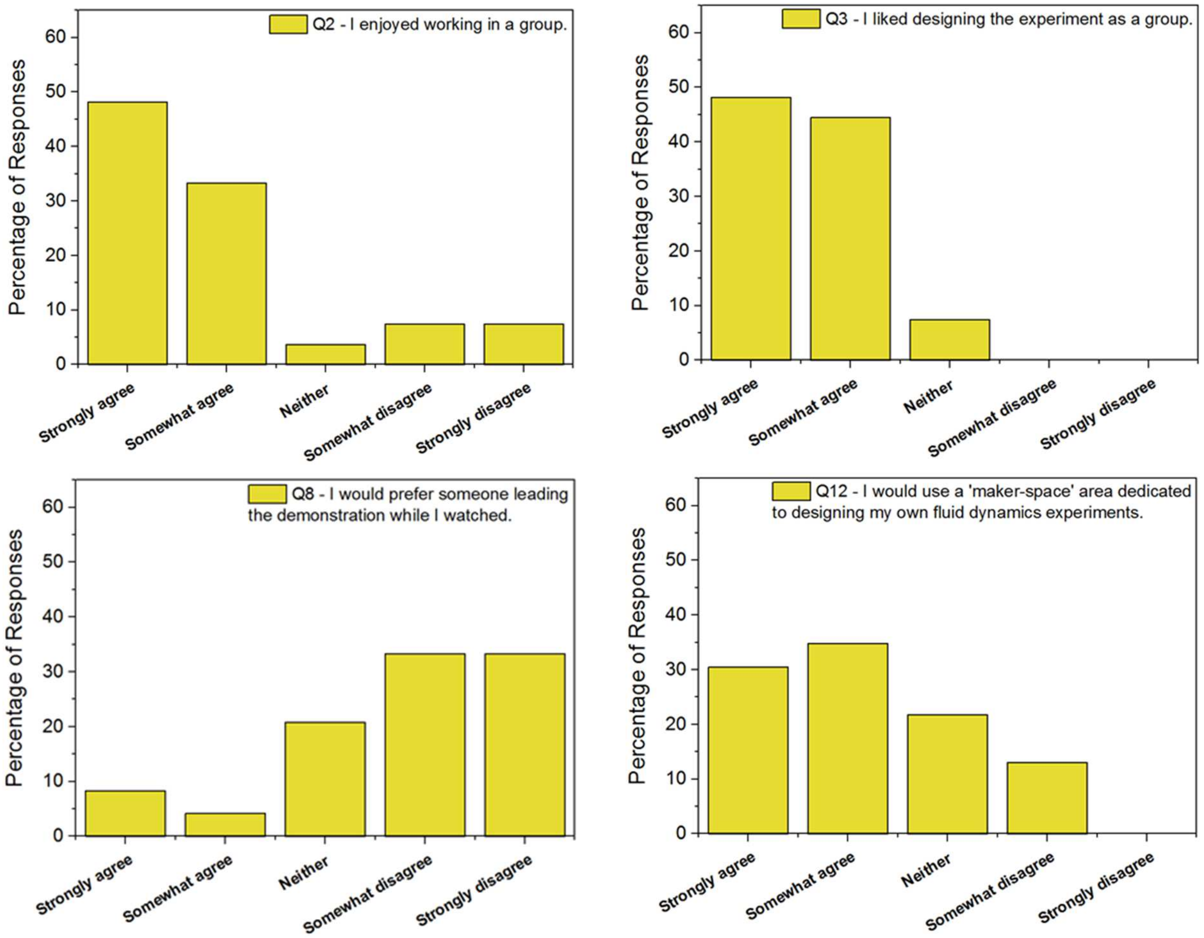


Figure 3 Q2, Q3, Q8, and Q12 survey results focusing on the group and experimental experience

Table 3 highlights the percentage responses for the remaining survey questions. The laboratory topic specifically related to the mechanical energy balance, and 78% of the students somewhat or strongly agreed that it helped them understand that concept better.

Table 3. Percentage responses from remaining survey questions, highlighting understanding and recommendations for future use

	Q4 - I better understood the Mechanical Energy Balance because of this demonstration.	Q6 - The demonstration helped me prepare for the first exam.	Q9 - I learn more by doing hands-on activities.	Q10 - I would recommend doing this demonstration in future ECHM 321 courses.	Q11 - This demonstration should be used throughout the course…
Strongly agree	59%	38%	38%	71%	9%
Somewhat agree	19%	38%	46%	21%	57%
Neither agree nor disagree	15%	13%	8%	0%	22%
Somewhat disagree	4%	8%	8%	4%	9%
Strongly disagree	4%	4%	0%	4%	4%

They also self-report that they learn better via more hands-on activities and recommend implementation in future courses. A majority of students also agree the topic could be revisited throughout the semester.

Open-Ended Student Responses:

The responses to the open-ended questions give further insight into the laboratory experience. Select results are shown in Table 4-Table 6, focusing on exam preparation, group collaboration, and suggestions for improvements.

Table 4. Did this demonstration help you prepare for the exam? If so, how? If not, why not?

Yes, as it required us to analyze an entire system using the mechanical energy balance, which was probably the most important subject to master for this section off the course
No, it was confusing as you were thrown into it without understanding what you are dealing with. Needs to be more clear about the goals of the experiment, and why you trying to achieve that.
This material was useful. Having to calculate multiple times the friction factor in both the straight channel and the bends channel was good practice for the exam as it helped e memorize the Mech Bal Eqn. It also made the concept of friction quite clear as far as how it affects flow, especially on the micro scale.
it was good to talk through the math and how it worked with my group members and explain the math to them.
I would have preferred if the report was due before the exam, so we all get a chance to really think and analyze the process. The math would be good practice for the exam as well.
The demonstration was confusing at first, but I feel like struggling my way through it really helped me understand the concepts.
It was helpful to be required to solve these equations and calculate actual values. It was, however, do to inconsistent data, unhelpful to get values that were no reflective of reality.
Yes, the hands on nature of directly seeing the effects of the energy balance helped me understand the equation visually and mentally.
It helped me in setting up a problem to solve for the friction of the system. I believe I could have done this without the experiment but it made the process easier.

The practice received by repeated calculation is a benefit of this approach. Even if students input the calculations into Excel, they had to be sure to account for the effect of the channel bends and input all relevant parameters (channel length and width, mass flow rate, height of water etc.) This practice could further solidify concepts seen throughout the class. It was also noted the group focus forced students to talk about the concepts, likely increasing the learning of those participating. Some confusion was also noted, but the frequency of that type of comment was down compared to the first iteration in Fall 2016. Unfortunately, the exam was returned to the students before the instructor analyzed that specific question for inclusion in this paper.

Table 5. How effective was your group at collaborating? Explain. (Or, How would you describe your group's collaboration?)

Group collaboration was easy and not problematic. There were no communication issues
Very effective, everyone helped and when I needed help understanding a concept my group mates were happy to help me.
During the experiment, we had great synergy putting together the necessary parts and gathering measurements. It was the after, that threw us. While we each had promised to write a section of the lab report, it did not get done in a timely manner, leaving a single member (myself) in charge of completing it.
Pretty good. i knew how to do the math and one of the other group members was confident enough to check my math and they were much better at the write up portion so they focused on rewriting my explanations into a good lab write up. Unfotunatly we didn't collaborate far enough in advanced so we ended up writing it the night before and the morning of. But their working pre-med students. what can you do?
meh.

We worked well and met a handful of times as well as collaborated on a google document to get the report written.
Group collaboration was a little frustrating. Out of three people, two of us did everything. It would be nice to include some peer evaluation of group mates.
Not very good, we didn't know each other.
It was very effective.

A range of comments are noted in terms of how the group functioned. Somewhat to the instructor's surprise, many noted a relatively functional group environment even though they were not coached on group dynamics and had relatively little time to work together. This may have been due to students self-selecting teammates and thus selecting friends/acquaintances. It was noted that not all members participated. With relatively little experience in group environments before the course, the students may not be used to dealing with this issue, and the group is not together long enough to fix these issues. Future implementations may need to consider a way to increase individual accountability.

Table 6 Given the opportunity to do this again, what would you change? [Semicolons added by authors to save space]

Allow for more than one class period to conduct the experiment
More measuring, though it sounds like such a simple thing many groups seemed to be waiting to move onto the next part because there were only a few measuring devices.
Clearer instructions, make sure everyone understands what they are doing as some were confused.
Assign groups instead of choosing. Especially since it was the beginning of the year. Even though it is my second year in the program, I did not know many people in the class that well. While picking your own group might be very good towards the end of the semester, it did not work out so well for me closer to the start.
It'd be nice get some feedback on how we could have improved the write up. And if the piping was in better condition that would be nice but i understand not necessarily possible.
better scale and more time for data collection; more sample replicates.; More trials; Nothing; Microfluidic devices that did not leak.
Give more directions and time. Time was a major key in trying to finish this
Making sure the micro fluid channels were all working well. Our's were far too slow.
A little more direction would have been nice, but the biggest problem was that there was not much time to actually collect data
The microfluidic devises not leaking and using an accurate scale.
More instruction on writing the report.

Leaking devices and more scales to weigh the water were common suggestions. With the number of devices fabricated, the instructor did not test each one. Also, the repeated connect-disconnect of the device to the column of water led to some devices breaking at the connection. Future devices will be more secure via additional epoxy on the straw connection where it affixes to the milli-fluidic device. While time was noted, the students did have access to the equipment outside of class before the report was due. Not accessing the equipment may relate to the aforementioned dysfunction in some groups. Though more instruction is noted in the comments, many students seemed to fully engage in the experiment in class and asked the instructor questions throughout.

Instructor's Perspective:

The instructor enjoyed operating class in this fashion. Though chaotic at times with ~40 students, most of the students were engaged. Many students asked questions (many more than ever asked questions during a lecture), allowing for more focused explanations from the instructor. It was encouraging to see students suddenly "get it" as their question was answered.

The variability in the chips and straw connectors also meant the experiment was not "perfect" in terms of highly accurate and reproducible data. While this could be frustrating, the instructor liked that the students had to make reasonable assumptions. One such assumption was to calculate friction in the straw from data in the straight channels, and then use that friction value in the other devices. While not a perfect assumption, the instructor's own calculations indicated it was acceptable for this experiment. This ambiguity seems helpful earlier in the curriculum to prepare students more for Capstone Design, which is very open-ended. Some students have difficulty adjusting to that type of course or problem compared to traditional homework problems with a solution that is neatly "boxed" each time.

The instructor is also intrigued by the results in Q11, which indicated 66% of students somewhat or strongly agree that the "demonstration" should be revisited throughout the semester. One approach would be to make teams that would be together throughout the semester. The equipment could be handed out early in the course so students could make the apparatus, even if the concepts are not clear yet. When hydrostatics are introduced, the vertical tubing could be plugged at the exit and hydrostatic pressure measured and calculated at various points. When re-visiting mass balances, new chips could be fabricated with changing width/depth dimensions so the students could calculate the velocity at several locations. A more viscous fluid could be used to highlight the "resistive" nature of viscosity. Finally, the COMSOL Multiphysics project could be to model a microfluidic device and compared the numerical data to the experimental data. Two reports could then be written- one on the CFD project and the other on the project described here to find the equivalent lengths based on experimental data.

The report writing experience could also be improved. As this was a first iteration, the grading was kept relatively easy and it was only worth 5% of the course grade. The instructor did note though that all of the reports could use improvement in terms of data presentation, content, and overall writing. Considering the scope of the course already, it is unclear if more iterations in writing are possible or if this initial report writing is beneficial in future reports. At minimum though, it seemed to force the students to think about the concept in depth and gain more understanding, which was the main motivation of this effort.

Considering the experience took one class period, content had to be re-arranged later in the semester. However, the end of the semester is arranged so the last four to five lectures are on advanced topics in fluid dynamics so the content reduction was easily accommodated. These topics vary from year to year, and have included survey/overview style lectures on compressible flows, boundary layers, turbulence, multiphase flows, etc. These topics are not included on exams. To account for this "extra" laboratory day, one of these topics was simply removed. The instructor thinks this is beneficial as the most important topics in the course (such as the mechanical energy balance) receive more attention.

Conclusions:

This paper presents an in-class laboratory that can be accomplished by groups of students in a 75-minute class period. Students used milli-fluidic devices fabricated in-house to study friction effects caused by channel bends. By connecting the devices to a water column, the flow rate of draining water could be determined in a device with one straight channel and in devices with several bends. Students could use this data to calculate an equivalent length of the bend, and the results were presented in a report. Survey data indicates the students believed they better learned the course material and that the report helped solidify this understanding. They also report in general that they enjoyed working a group and liked designing the scope of their own experiment within the framework of the milli-fluidic device / draining column of water system. Future implementations may be able to use the same groups and equipment throughout the semester to show several concepts with the same equipment.

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