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A Modular Water Bench and Fountain Design Project for an Undergraduate Fluid Dynamics Laboratory

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Abstract

A laboratory pedagogy that values inquiry-based instruction is under development at the University of Illinois Urbana-Champaign to satisfy ABET Outcome 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions. To do so, there is a need for laboratory equipment that provides flexibility for students to experiment with an array of flow devices such as pipes, elbows, pumps, valves, and measurement devices such as differential pressure transducers and flowmeters.

A modular water bench has been developed with a design project in mind whereby student teams design and build a piping system that draws water from a fixed-head reservoir and splits the flow, sending it to two fountains. Unique performance criteria related to achieving certain flowrates in the two fountains are provided to each team. The water bench is about eight feet in length and three feet wide. The bench includes a sump from which a submersible pump fills a fixed-head overflow reservoir on a rolling tower. The rolling tower has a footprint that takes up two of the eight feet of length of the water bench. Students work on platforms made of perforated stainless steel with square surfaces of three-foot edge length. Therefore, the bench can be converted to arrangements of platform-platform-tower or platform-tower-platform to allow a single student team to work on a 6-foot platform or two teams to work simultaneously on a 3-foot platform, respectively. In addition to the overflow reservoir, the tower features two Coriolis force mass flowmeters and two variable DC power supplies, which can be used to power small DC pumps.

The design project is a four-week, eight-hour activity. The first three weeks are devoted to empirical measurements of major and minor losses, as well as an empirical investigation of fountain-based levitation. Students are provided with sections of clear, rigid PVC tubing, a large suite of push-to-connect fittings, specially made pressure tap fittings, needle valves, and a DC pump. Students are challenged to perform measurements to a degree of quality that can be trusted for application in their final system design.

In the fourth week, students deliver a complete technical report of their measurements, as well as a complete design of their fountain network. No valves are allowed during week four. The students are challenged to perform predictive modeling of the flow resistance through each branch of the fountain network such that the precise ratio of flowrates to the two fountains is achieved. The team builds their system, their teaching assistant tests it, and they write an engineering letter summarizing the success or failure of their system. The perspectives of the teaching assistants are sought to provide some indication of what aspects of the laboratory are effective, which suggest that the design objectives are typically achieved by the most diligent students, but roughly half of the student teams do not attain a successful design. There was a perception that no teams succeeded by luck, but that success came through hard work and effective collaboration.

Introduction

The value of hands-on experimental laboratories for undergraduate engineering students is widely recognized [1–6]. The engineering laboratory has become a focal point for students to connect abstract concepts with hands-on practical investigations. Often, students find hands-on laboratory experiences to be of greater interest than lecture-based learning [2]. Educators observe them to be of critical importance for the development of professional self-identity among engineering students, with calls being made for the development of increasingly innovative laboratory exercises [5]. Accordingly, hands-on laboratories provide great opportunities to satisfy recognized student learning outcomes, such as ABET Outcomes 1, 5, and 6 [7–8]. Laboratory equipment and facilities require investment of time and money, and a competitive market exists to sell engineered laboratory exercises to institutions of higher learning, though some faculty members recognize value in development of their own laboratory facilities [9]. In this paper a case is presented where an innovative laboratory facility is developed with specific aims to inspire and challenge students while putting the onus on them to design good experiments and execute them precisely and accurately.

Course Format and Laboratory Pedagogy

The ME 310: Fundamentals of Fluid Dynamics course is a four credit-hour lecture and lab course that is required by students in the Mechanical Engineering major at the University of Illinois Urbana-Champaign. The lecture meets three times per week for 50 minutes and is taken by a total of approximately 120 students per semester. The students may be enrolled in one of two weekly lecture sections, each taught by a faculty member who is an expert researcher in fluid mechanics. The course covers basic fluid concepts with a math prerequisite of Calculus 2 and a mechanics prerequisite of introductory dynamics. The laboratory portion of the course meets once weekly for 110 minutes in sections comprised of two groups of four students. Each lab section is led by a teaching assistant (TA) who is trained weekly by the faculty laboratory manager. Because all 120 students take both the lecture and laboratory portion of the course, the laboratory is staffed by a team of TAs who lead the 15+ lab sessions over the course of each week.

The lecture and lab portions of the course are weakly coupled in that the laboratory content is not scheduled to coincide with the topics that are taught in the lecture. The laboratory course begins with a series of experiments related to very basic fluid mechanics principles, namely measurements of four fundamental forces in fluid mechanics: fluid inertia, pressure, viscosity, and surface tension. Those same basic topics are also introduced in the lecture portion of the course at the start of the semester.

After the first few weeks of the semester, the laboratory content diverges from the lecture content. Laboratory manuals compensate for this divergence by containing all of the hypotheses and mathematical models to be tested in each laboratory exercise, as well as descriptions of the equipment to be used. The laboratory manuals do not contain recipe-style experimental procedures for the students to replicate; instead, students work in teams to analyze the theoretical derivations and equipment in order to identify the dependent, independent, and control variables pertinent to each investigation. Student teams then design the experimental procedures that they will follow;

after the TA reviews their design of experiment for safety and effectiveness, he or she allows the students to begin conducting the laboratory exercise.

This pedagogy was designed to satisfy ABET Student Outcome 6, specifically, the "ability to develop and conduct appropriate experimentation." [8] Other laboratory exercises include two-week investigations into the performance of centrifugal pumps, measurements of the velocity field of a free jet, and investigations into the wake flow behind a cylinder, and the semester ends with topics related to measuring friction losses in pipes, including both major and minor losses. After each two-week exercise, students prepare individually-written lab reports that are graded on a combination of writing quality and assessment of the technical analysis of the data gathered in the laboratory experiments.

Curation of laboratory exercises

One of the duties of the laboratory manager who trains the laboratory TA staff is to curate the laboratory content with the goal of maximizing the educational outcomes of the laboratory. In general, laboratory exercises are either procured from educational supply companies, who mass-produce equipment designed to be used for a narrow scope of investigations in a particular content area, or the experiments are designed in-house and unique to the department and college where their designer works. Economics dictates that equipment procured from educational supply companies typically costs tens of thousands of dollars per unit, and the recent paper by Earp, et al verifies some of the high unit costs of this equipment from multiple competing manufacturers [6]. While these companies try to design equipment that is robust, it can be difficult to anticipate the rate of wear that the equipment will experience in service, especially when being handled by large numbers of students per year. If this equipment fails, it must be shipped to the manufacturer for repairs. Repairs often come at steep expense both due to labor costs, for which rates are set by the manufacturer, as well as opportunity costs, such as when the repairs delay or prevent students from performing the exercise. Even if the experimental hardware does not break down after many years, data acquisition systems—including both computer hardware and software—may grow obsolete and necessitate the replacement of the entire experimental unit, regardless of how well it was treated over its service life. Additionally, because this equipment is mass produced, it is often used at many universities to perform the same experiments, which may have a fairly limited and perhaps uninteresting scope.

Design objectives for new laboratory exercises

Alternatively, experimental equipment that is designed in-house may be more affordable, easily maintained, and may also have the benefit of being unique, imaginative, and exciting. In this article, the author describes design objectives for a new laboratory exercise that was created with the express intent of replacing a simple, straightforward experiment for measuring major and minor losses. The design objectives for the new laboratory exercise are as follows:

1. The exercise must be *fun and/or inspiring*.
2. Because this is a course for Mechanical Engineers, the exercise should be *based on a design premise uniquely appropriate for their discipline*.

3. The exercise should *reward good practice in experimentation*, such as careful and precise measurements in order to achieve good repeatability.
4. The exercise must teach principles of *major and minor losses in pipe flows*.
5. The exercise must challenge the students' ability to perform *rigorous quantitative analysis*.
6. The students must be able to *assemble the experimental equipment themselves with minimal use of hand tools*.
7. The exercise must use *rudimentary data acquisition*, rather than computer-based recording of digitized data.
8. The exercise must serve *two teams of four students* at a time.
9. The laboratory equipment must be *affordably serviced and/or replaced*, or otherwise designed to be highly robust.

Laboratory Concept: A System of Fountains Design Project

With these design objectives in mind, the notion of inspiration was considered. Throughout human history, fountains have held symbolic significance for the concepts of renewal, refreshment, youthfulness, vigor, health and wealth. Children are amazed by fountains, adults employ fountains in memorials and historical landmarks. To engineers, however, the mechanistic description of a fountain is a jet of liquid (usually water) emitting at a particular flow rate Q, initial diameter d, and angle of inclination θ, flowing steadily into an atmosphere of air with a trajectory determined exclusively by the action of gravity g, giving it a reasonably predictable path. Naturally, a fountain should make excellent inspiration for a new laboratory exercise to both the most- and least-stereotypical engineering students.

The premise for this laboratory exercise is that a team of Mechanical Engineers have been hired to create a system of fountains for display at an amusement park. They must design a pump-driven pipe network that operates two fountains with distinct performance goals. Fountain A, diagrammed in Figure 1, is nearly vertical and must support a ball at a specific height. This fountain was inspired by a video showed by Soto and Zenit at the 2013 American Physical Society Division of Fluid Dynamics, where they showed that for fixed fountain angle, jet diameter, and

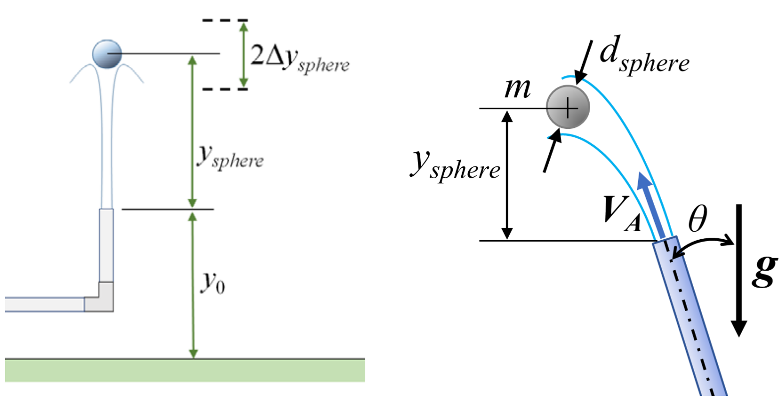

Figure 1. Diagram of Fountain A, the "supporting fountain." Two orthogonal views are shown to indicate how the fountain is gently angled to support the sphere stably.

flow rate, a ball can be stably and predictably elevated to a certain height above the mouth of the outlet pipe [10, 11]. The forces that hold the ball in place stably are not easily modeled. Instead, the students must perform careful experimentation and precise measurements to develop an empirical model for the behavior of this fountain.

By fixing the fountain angle, ball characteristics (size, weight, surface roughness), and pipe size, the empirical function should reduce to the ball height being a direct function of the flow rate Q_A. Students find this fountain fun to play with, and it inspires deep thought about what balances the horizontal forces at play. More importantly, it necessitates that they perform good measurements in order to develop a useful empirical relation for later use.

Fountain B, diagrammed in Figure 2, is an arcing fountain that must pass through a ring of diameter D_{target} placed a set distance and height away from the mouth of its outlet pipe. Unlike Fountain A, Fountain B performs its stated task in a manner that is easily modeled using the Bernoulli equation. Its trajectory is a function of its initial height, velocity, and diameter, assuming that the water emits uniformly from the mouth of the pipe. It follows a parabolic path identical to that which students are familiar with from point-mass dynamics. Indeed, students may find the mathematical description of the path of the arcing fountain more trustworthy than that of a point-mass in motion through a gravitational field, because (1) students often interpret the idea of a point mass to be a spherical ball of finite size, and (2) students are not always comfortable assuming aerodynamic drag on a ball to be negligible; whereas both skin friction and form drag act upon a ball in motion through the air, a steady, smooth, and continuous arcing fountain experiences no form drag.

To summarize, Figure 3 shows the design domain for the students to achieve their performance objectives. They will be provided a flow with controllable input mechanical energy, which must be split into two streams. Each of the two streams must simultaneously carry the precise flowrates Q_A and Q_B needed for fountains A and B to achieve their objective performance goals, respectively, but they must do so *without the use of valves to fine-tune the flow*. The black boxes represent

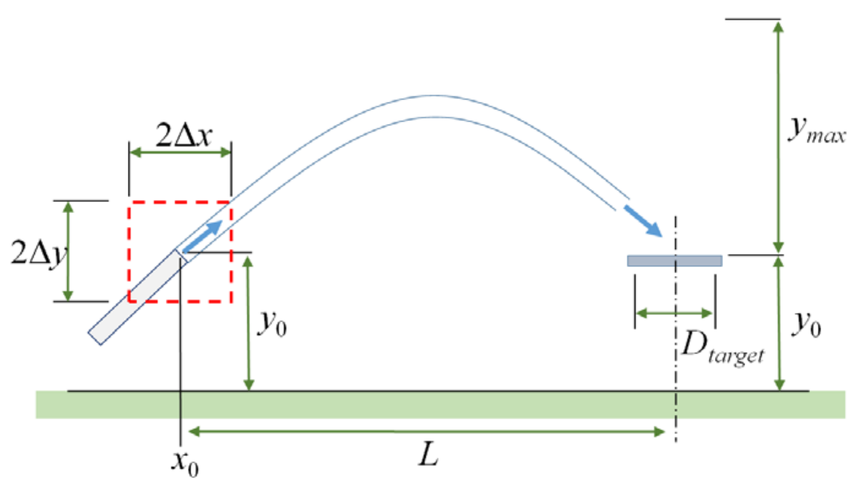

Figure 2. Diagram of Fountain B, the “arcing fountain.”

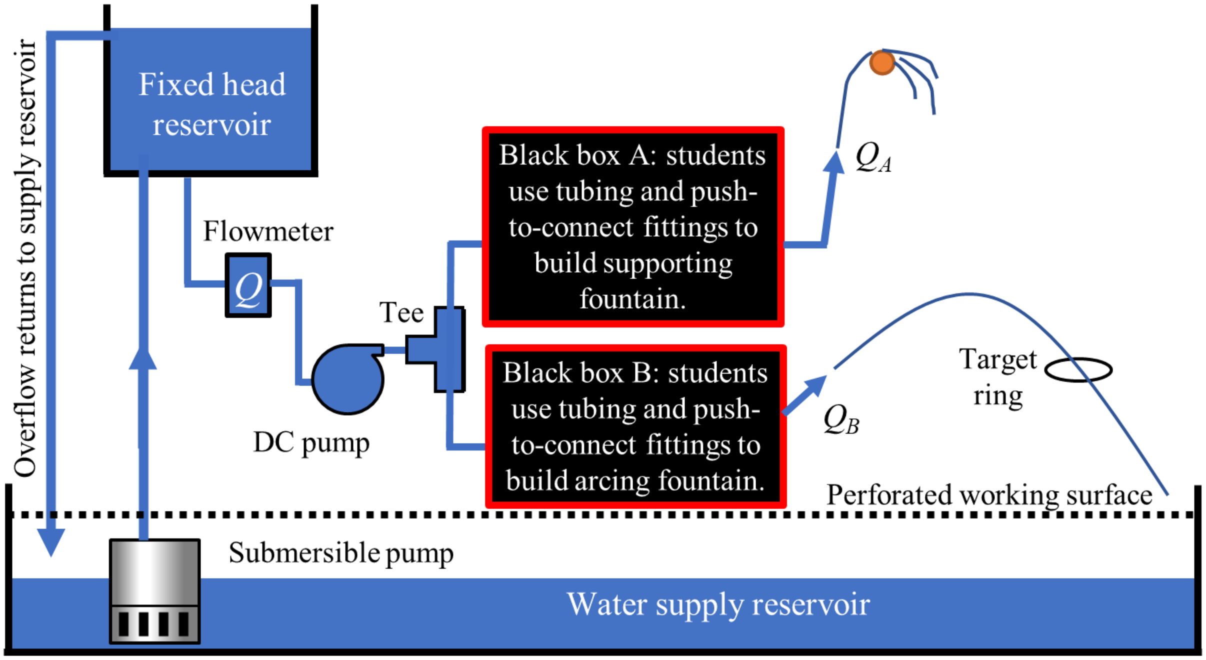

Figure 3. Design domain for fountain prototype objectives. Black boxes represent domains where students must specify combinations of tubing and components to achieve the desired ratio of flowrates. Note that only one DC pump is allowed and no valves are allowed.

where the students must assemble flow components with careful intention in order to achieve the proper balance of flowrates Q_A and Q_B.

In an electrical circuit analogy, this problem would be akin to tuning the current through parallel legs of a circuit by adding just the right combination of discreet resistors to each of the legs. Fluid mechanics, of course, is more complicated than a simple electrical circuit in that the resistance of each component is a function of the "current" flowing through it. Here, the divided flow must encounter precisely the correct total resistance through accurate prediction and summation of the major and minor losses in each path. By taking the conservation of energy from the stagnation point inside of the tee to the outlet of each fountain, the following expressions are obtained:

$$\frac{p_{tee}}{\gamma} + \frac{V_{tee}^2}{2g} + y_{tee} = \frac{p_A}{\gamma} + \frac{V_A^2}{2g} + y_0 + \left[\sum h_{major} + \sum h_{minor}\right]_{tee-A} \tag{1.a}$$

$$\frac{p_{tee}}{\gamma} + \frac{V_{tee}^2}{2g} + y_{tee} = \frac{p_B}{\gamma} + \frac{V_B^2}{2g} + y_0 + \left[\sum h_{major} + \sum h_{minor}\right]_{tee-B} \tag{1.b}$$

These equations can be simplified by assuming $V_{tee} = 0$ at the stagnation point, $p_A = p_B = 0$ (gage), and then equating the right-hand sides to get:

$$\frac{V_A^2}{2g} + \left[\sum h_{major} + \sum h_{minor}\right]_{tee-A} = \frac{V_B^2}{2g} + \left[\sum h_{major} + \sum h_{minor}\right]_{tee-B} \tag{2}$$

By invoking the conservation of mass for incompressible flow $Q = Q_A + Q_B$, or, alternatively, $Q_B = Q - Q_A$, and using the inner tube diameters to relate the velocities V_A and V_B to the volumetric flowrates Q_A and Q_B, Equation 2 can be reduced to a single flowrate value of the student's choosing. The matter of predicting the major and minor losses must come down to conducting careful empirical measurements. Finally, one simplifying assumption is suggested to the students: to assume that the minor loss associated with the flow passing from the stagnation point inside the tee to the outlet of each branch of the tee is negligibly different for each branch. At that point, the students should be able to solve this equation for various arrangements of flow components in each branch. The following section describes the hardware and accessories provided for the students to conduct their investigations and design their system.

Water Bench Facility

A two-sided water bench facility, shown in Figure 4, was designed to provide a fixed-head reservoir, as well as flowrate measurements and a power supply for use with a DC pump. The water bench consists of a large, heavy-duty fiberglass tank with inner dimensions 96 in long×32 in wide×36 in deep. The tank can hold a large supply of water, though it need only be deep enough to prime a submersible pump that is used to fill a constant-head overflow tank mounted on a rolling gantry. The overflow tank can be moved to either the middle of the bench or to one end, allowing students access to a constant-head water supply from which to run their experiments. Worktop platforms made of perforated stainless steel allow the students to set up their experiments over the water bench such that spilled water returns to the reservoir. Splash booths are placed at each end of the bench when the gantry is in the middle position. Drain tubes at the bottom of the reservoir

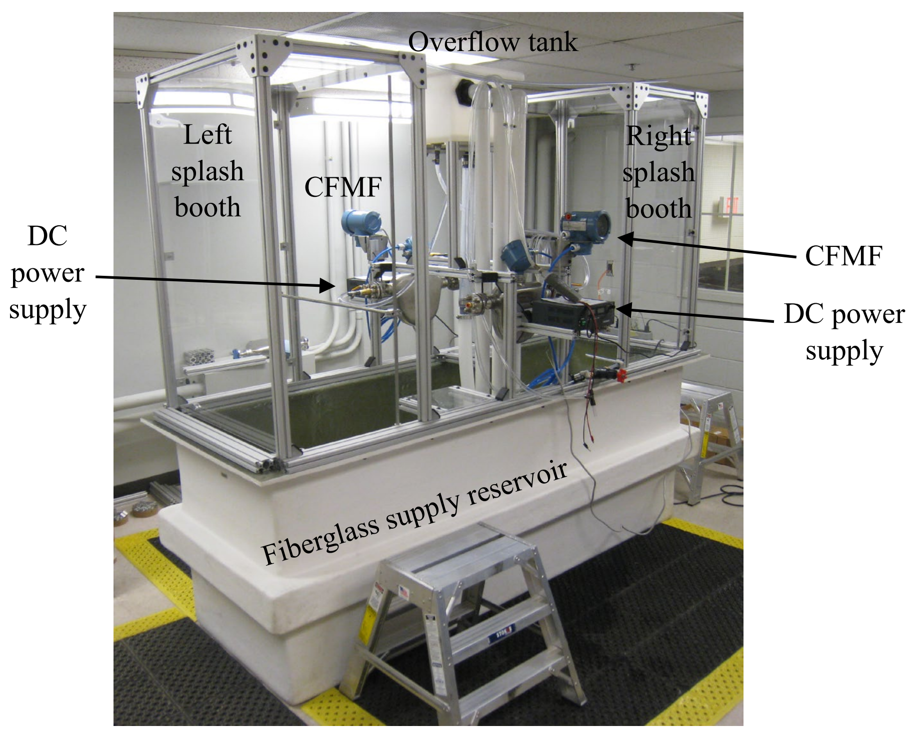

Figure 4. The water bench facility. Here, splash booths are set at opposite ends and the overflow tank is set in the middle of the bench. The perforated steel work platforms are not shown in this image.

flow to two Coriolis force mass flow meters (CFMF), one on each side of the gantry. Two variable 3–15 VDC power supplies are provided, one on each side of the gantry, for the students to power a small centrifugal pump. The centrifugal pump affords each group of students a single degree of freedom for controlling the mechanical energy of the flow as it enters their pipe network. This symmetric arrangement allows two student groups to use the water bench at a time, each from opposite sides of the water bench.

Students are furnished with clear, rigid PVC tubing in four sizes (outer diameters of 1/2 in, 3/8 in, 5/16 in, and 1/4 in) and pre-cut lengths of 2 in, 3 in, 4 in, 6 in, 12 in, 18 in, and 24 in. The choice of clear PVC gives them the ability to see if any components are not connected properly, causing them to leak or to ingest air. Plastic push-to-connect fittings are provided to connect these tubes, including straight connectors, reducing straight connectors, 90° elbows, reducing 90° elbows, and 180° U-bends. These fittings allow students to connect and disconnect components without the need to use hand tools. All of these fittings are acquired through McMaster-Carr and can easily be replaced or replenished as they begin to deteriorate.

The students are given a rigid four-week agenda to complete the design project. During the first three weeks they are never allowed to test a prototype of their entire system, only individual components. This constraint is implemented to enforce the need for careful experimentation and analysis.

Week 1. Students are introduced to the project. The water bench is set for two teams to work on opposite sides. Each team is given unique performance objectives for their project in the form of (1) the target height y_{sphere} to levitate the sphere, (2) the distance from the outlet of Fountain B to the center of the target ring, and (3) the flowrate Q_B that they must achieve for Fountain B. They use the remainder of the two-hour lab session to perform empirical tests on the supporting fountain. They may test two standard plastic spheres, various tube sizes, and various fountain angles. For each fixed set of these parameters, they should determine Q_A when the sphere is held at the desired height y_{sphere}.

Week 2. This week is used for experiments related to major losses through the tubes. Each team is given 6-foot lengths of straight tubing in the four sizes, as well as special connectors that allow them to measure the pressure drop through the tube. Flexible tubing is provided for them to connect to one of two pressure measurement devices. One device is a digital pressure transducer with a range of up to 10 psi, which is useful for small tubes where the pressure drop is relatively large. The other is a vented free-standing column manometer with a range of about 40 in.-H_2O that is useful for measuring small pressure drops, such as what they will encounter with the large-diameter tubing where the pressure drop is relatively low. They are allowed to use a needle valve to achieve low flowrates during this week. The students should get as much data as possible on each of the tubes during this week, investigating the largest range or Reynolds number that they can. The data should be compared against the Moody diagram to see if they can use it to estimate the relative roughness of the tubing.

Week 3. The students use the vented manometer to attempt to determine the minor loss coefficient as a function of Reynolds number for each of the available push-to-connect components. They are allowed to use a needle valve to achieve low flowrates during this week.

Week 4. Week 4 is the testing week. Each team is expected to come to the lab with a complete technical report that details the testing and results from the previous three weeks, as well as a complete design of their fountain system. The water bench facility is changed to be used by only one team at a time, as follows: One of the two splash booths is removed and the gantry with the fixed-head reservoir is rolled to take the place of that booth. A perforated steel working platform is set in its place in the middle of the water bench, allowing a full 72-inches for the team to build their fountain system. Each team is given a total of 50 minutes to build their fountains. A system of adjustable structural rods is made available, which the teams can use to build structures to lean their PVC tubing against. Zip-ties are provided to hold the tubing in place. Once the students have built their system to their own specifications, the TA tests the system and records its performance on a testing rubric document, which is included in Appendix A.

One week afterward, the student teams each submit a two-page engineering letter report that summarizes the results of the testing done in Week 4. If their fountain met all of its performance goals on the first try, then the students are rewarded by not having to write a very detailed or critical final report! Otherwise, they are required to find the errors in their design and report on them in this report, making recommendations to improve upon their design. Finally, they perform a peer evaluation, which is used to determine scale factors to adjust the grades of each student for the group work.

Evaluation of the Project

For evaluation of the design project, feedback was sought from the 25 TAs who had served in the laboratory course at any point from the Spring 2022 to the Fall 2023 semester. The TAs were asked via email to complete an anonymous IRB-exempt survey asking about their observations of student behavior and performance in the design project. Eight TAs completed the survey, which was entirely comprised of open-ended questions. The questions were:

1. In total, counting all of the semesters and lab sections that you have taught since Spring 2022, how many teams of students have you overseen in this role? (As a reminder, each lab session consists of up to two teams of students.)
2. Approximately what percentage of the teams that you observed were able to design a fountain system that met all stated performance objectives on the first try?
3. What percentage of the teams whose fountains succeeded on the first try do you feel merely got lucky, rather than as a result of rigorous testing and design?
4. In the weeks leading up to the final week of the project, did you observe different behaviors among the teams whose fountains later succeeded vs teams whose fountains did not? Explain.
5. What aspects of this lab exercise do you feel were most useful or valuable to the students?
6. How do you feel this design project could be improved?

Most of the TAs had overseen at least six teams work on the project, and on average, the respondents stated that about half of their teams were able to successfully complete the project on the first try. Five of the eight respondents said that fewer than half of those teams seemed to achieve their successful performance through luck, and three of the eight said none of their teams who succeeded did so by chance. One respondent stated that "all were perfectly engineered." When asked about the observations of different behaviors among those whose fountains succeeded vs. those whose fountains did not, common themes included that those teams were better at collaborating, that they started serious work on their overall design as early as Week 2, and that they generally put in more time on the project, including attending TA office hours more often. Some TAs observed that some teams were carried by the efforts of one or two extra hardworking individuals, and in some cases those teams went out of their way to collect more data than they needed in the weeks preceding the testing week. The TAs were nearly unanimous in their feelings that the most value from the project came from the combination of the design aspect of the project. TAs recognize opportunities to improve the project exist in the degree of detail that is provided in the lab manual, with some additional comments related to students having some problems with the fittings showing signs of wear and leaking, which can be remedied by replacing them with new ones. Complete results are given in Appendix B.

Conclusions

While not a perfect design project, the laboratory design framework used to create this exercise seems to have played out mostly as desired, as students who exemplify good practices such as hard work and collaboration tend to be rewarded for their efforts by achieving a successful design. The problem is by no means trivial to solve, but success does appear to be within reach for those students who take it most seriously. The fact that the main problem is that the push-to-connect fittings are showing wear and need to be replaced seems to support the premise that home-grown labs are relatively inexpensive to maintain, as a full replacement of all fittings would cost perhaps a few hundred dollars at most, and they would arrive in mere days. The author notes that most of the equipment used in this lab is now approximately 8 years old, and none of the most expensive components, such as the fiberglass tank and the Coriolis Force Mass Flowmeters, have had any problems to date.

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Appendix A:

Week 4: Fountain Performance Trials

Week 4 represents the culmination of the fountain system design project. The water bench has been remodeled over the previous weekend such that its full length can be used for the fountain testing. As a result, there no longer are two identical stations that can be operated simultaneously. Student groups will be assigned by their TAs to come to either the first hour or second hour of the lab with hard copies of their written status reports; electronic copies are due to the SafeAssign portal at the beginning of the first hour of the lab section (i.e. the group that arrives for hour two is not being given an extra hour to complete their report). Each group will be given one hour to build, test, and tear down their fountain systems. The group TA will fill in the following chart as the student teams carry out their work. NOTE: Only the TA will be allowed to turn on the flow.

Activity	Time	Value	Notes
Begin construction			
Construction complete			
Measure key distances			
*Arcing fountain outlet height y_0 relative to datum		in.	
*Length L from tube outlet to target center		in.	
*Height of vertical supporting fountain outlet relative to datum		in.	
*Measure angle of supporting fountain outlet tube		°	
*Measure angle of arcing fountain outlet tube		°	
*Supporting fountain tube ID		in.	
*Arcing fountain tube ID		in.	
*Planform distance from target center to supporting fountain		in.	
Turn on flow & pump			
Set pump voltage so that arcing fountain hits the target			
*Balance sphere and measure its height relative to datum		in.	
*Record height of vertical fountain without sphere relative to datum		in.	
*Record total flowrate		L/min	
Set pump so that sphere is supported at its prescribed height			
*Observe whether the arcing fountain hits its target			
*Record total flowrate		L/min	
*If not, by approximately what distance does the fountain miss the target		in.	

Appendix B:

Raw data from TA evaluation survey

1. **In total, counting all of the semesters and lab sections that you have taught since Spring 2022, how many teams of students have you overseen in this role? (As a reminder, each lab session consists of up to two teams of students.)**

   6, 6, 6, 16, 5, 2, 4, 6

2. **Approximately what percentage of the teams that you observed were able to design a fountain system that met all stated performance objectives on the first try?**

   60, 50%, 33.30%, 40, 0, 50%, 75, 83% (5 out of 6 succeeded)

3. **What percentage of the teams whose fountains succeeded on the first try do you feel merely got lucky, rather than as a result of rigorous testing and design?**

   60
   0%, all were perfectly engineered
   50%
   80
   0
   0%
   33
   2

4. **In the weeks leading up to the final week of the project, did you observe different behaviors among the teams whose fountains later succeeded vs teams whose fountains did not? Explain.**

The teams that eventually got their fountains to work had their initial calculations and design plans decided well ahead of the final week. And in most of the cases, they were also the teams that would show up at the TA office hours.

They clearly paid more attention and worked harder

Yes. The teams whose fountains succeeded did more testing during project lab week 2 and 3, whereas the other teams were relying more on the TA to suggest design considerations.

Those teams usually have one or two students who carry the main load of designing the fountain, mostly they are more concerned about gathering enough data

Teams whose designs eventually succeeded were more collaborative than those that did not. Obvious evidence of higher effort was shown in the form of on-paper schematics and calculations with tabulated information on dimensions, flow rates, minor and major losses etc.

The team that succeeded actually put in more time and was really interested to collect as much data as possible. The other team that was unsuccessful just wanted to get the bare minimum done in the weeks leading to the final demonstration.

Not necessarily. During lab time, all of my groups worked well together and got all of the data they needed. I do remember the team that got the best final results did more testing in the weeks leading up to the final week than they needed. Most teams found the data they thought they needed, but this team found that data, as well as extra data just in case. I believe most of the success of this lab came outside of the lab. The teams that met multiple times outside of lab to work on the project had better and more thorough designs than the teams that only met once or did the project separately outside of class.

Among the successful teams, some less active students gradually took more and more active roles in the teamwork. In comparison, in the unsuccessful team, some active students became less active in teamwork.

5. **What aspects of this lab exercise do you feel were most useful or valuable to the students?**

The design to determine the correct measurements

Honestly, only the calculations and the report

The most valuable part for the students was the vision of the final design and coming up with experimental plans to build that fountain.

I think doing a design project is more interesting to students than a regular lab with reports but they need more information on how to design their fountain iteratively

I think the applied form of this project is great for engineering students who rarely get to see a design or theory be proven in reality. It provides them with a stronger foundation for their thinking around fluid mechanics and gives better intuition on how fluids behave.

The mandatory design of experiment, giving them time/lab exercises that help them gather the necessary data to design their setup.

I feel the design aspect of this lab was very helpful. The students were able to take data they acquired and use it to design the fountain for specific requirements. I feel this skill is an important part of being an engineer. I could also tell the students enjoyed how this lab was directly applicable to what they were learning in lecture. Sometimes labs can feel separated but this lab was directly involved with the class.

The group project at the last week, where students work together to create a design and report. Everyone is so actively involved.

6. How do you feel this design project could be improved?

The lab manual could be made more detailed with proper instructions on how to correctly perform all the calculations. A lot of the teams faced difficulty understanding what to do since the lab manual didn't provide clear instructions.

By explaining the project goals more clearly and better

By providing less problematic equipment to the students - getting rid of some the flow connectors that leak, inventory needs to increased, and finally a detailed overview of the project (focusing on energy balance) on the project lab week 1 may improve this.

By explaining the process of fountain design and checking and correcting them a week in advance

I feel that some of the components which students have access to were showing moderate wear and as such were not able to properly seal causing pressure losses along the length of the flow. I think investing in newer, better fitting components would cause less frustration from students attempting to test their designs.

"Another extra lab just as a buffer to collect more data

Give the teams to test their setup as a pre-final test and then make any necessary changes and finally run it on the last lab."

The biggest issue my students had was the equipment not working properly. Most of the fittings did not work well, so it was hard to find pieces they needed that worked. One other issue I saw was that students figured out beforehand what tube sizes they needed based on the flowrate and distance. Because they knew before the testing, they only tested what they thought they would use in their design, instead of making their design from what they tested.

The first 3 weeks of experiment can be reduced to 2 weeks and leave out one extra week for the design project. Students almost use the last week only to do the major part of the project, which is very stressful for teams that have lower numbers of students.