The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
Paper ID #44154

Bioengineering 101: A Design Challenge to Teach High School Students about How Engineers Design and Build Complex Systems

Prof. Adam T Melvin, Clemson University

Adam Melvin obtained a BS in Chemical Engineering and a BA in Chemistry from the University of Arizona, a MS in Chemical Engineering (with a minor in Biotechnology) and a Ph.D. in Chemical Engineering from North Carolina State University. He spent the first 10 years of his independent career as a faculty member in the Cain Department of Chemical Engineering at Louisiana State University. He recently joined the faculty in the Department of Chemical and Biomolecular Engineering at Clemson University in the fall of 2023.

Bioengineering 101: A design challenge to teach high school students about how engineers design and build complex systems

In many states it has become commonplace for K-12 students to associate chemical engineering solely with the petrochemical industry. Oftentimes this belief, coupled with the fact that many of these students are unaware of what a chemical engineer does, leads to promising students abandoning the pursuit of this degree. One area in which many high school students show interest, but know little about, is bioengineering and/or biochemical engineering. This is also confounded by the fact that most high school teachers are not engineers and struggle with teaching students about complex engineering concepts or the engineering design process. To address this, we developed and implemented an engineering design challenge for high schoolers to 1) enhance student awareness of engineering applications and careers with emphasis on biological systems, 2) train students on the engineering design process, 3) challenge students to solve a current problem related to human health, 4) instruct students on how to collect and analyze data, and 5) give students experience in presenting their findings. The design challenge itself had teams of 3-4 high school students design, build, and test a system capable of trapping and isolating circulating tumor cells (CTCs) – one of the grand challenges in cancer research. The 'cells' (both health and cancerous cells in addition to red blood cells) were modeled by rice, macaroni noodles, and penne noodles in a heterogeneous mixture and the students were able to build their system them using a variety of household items such as paper plates, bowls, cups, duct tape, toothpicks, scissors, Xacto knives, straws, string, etc. to facilitate a size-based separation. Each item had a cost associated with it and the students were required to keep track of how much they spent on their system in addition to collecting separation data using established metrics like separation efficiency, purity, and throughput time. At the end of the module, the teams presented their findings to their peers and a panel of judges using a rubric based on one used for regional science fair competitions. The Bioengineering 101 module has been performed four times from 2019-2023 at the same high school; however, the design and implementation of the module significantly evolved due to student feedback, faculty observations, and the COVID-19 pandemic. The evolution of how the module was implemented included changes in the age of the students (first year vs. third year students), the duration of the modules (two weeks vs. four weeks), and how the chemical engineering faculty member was able to directly engage with the students (in-person, virtually, or asynchronously). Assessment of the program through pre- and post-surveys found that participation resulted in (i) a greater understanding of the engineering design process, (ii) higher confidence in their ability to be engineers, (iii) greater comfort in their ability to collect and present data, and (iv) a better understanding of the interdisciplinary topics that engineers can work on. While the focus of the application was on biological applications of chemical engineering, the design of the module has the potential to be implemented with other emphasis areas using a similar size-based separation approach.

Introduction

Stereotypes of what engineers do have existed for years with many people believing that all mechanical engineers do is build cars and planes, all civil engineers do is build roads and bridges, and all chemical engineers do is work for the petrochemical industry. One area where these assumptions continue to propagate are with K-12 students who oftentimes have limited exposure to what engineering is or what engineers do. This incomplete understanding, coupled with a limited knowledge of the diversity across the numerous fields of engineering of what they do, can lead promising students to abandon the pursuit of a degree in an engineering-related field [1]. This false perception of chemical engineering has recently become a major hurdle in recruiting top students to the discipline because of the negative connotation between the petrochemical industry and environmental harm. This phenomenon has been observed nearly nationwide with members of the profession working tirelessly to try and better education K-12 students (and the general population) that chemical engineers do much more than just make chemicals that can potentially hurt the environment.

Through involvement in numerous STEM nights and outreach events, the author observed that many K-12 students are passionate about two specific areas of concern: human health and the environment. What is concerning is that most of the students have no idea that engineers from nearly every discipline are actively involved in these two specific areas spanning both academia and industry. This is because this type of information is not commonly incorporated into the curriculum of K-12 students due, in part, to elementary, middle, and high school teachers not being trained in engineering-specific disciplines even though Next Generation Science Standard have placed an emphasis on teaching engineering concepts and practices in the K-12 curriculum [2]. The entire engineering community has been working to address this concern through STEM nights as schools, activity days at museums, and active involvement in the community. These STEM nights are amazing; however, one challenge with these events is that they are geared towards a larger audience (e.g., >50 people per event) for a short duration (e.g., 15-60 min) and the brief contact time may not be sufficient to truly inspire potential young scientists and engineers or educate them about engineering and the engineering design process. Recent efforts have attempted to overcome this, especially with a focus on bioengineering, through the development of summer camps [3-4], case studies [5], and extracurricular activities [6]. While effective, these activities also suffer limited facetime with the students that can span a few days during a single week. Additionally, these activities are not design challenges per se, but instead focus on hands-on exposure to engineering and bioengineering concepts. To address this, the author developed a six-day, hands-on outreach activity for high school students. The focus of the event was on bioengineering/biochemical engineering due to the expertise of the author and feedback from high school teachers on a specific area of interest from their class. This paper summarizes the design of the program, lessons learned from implementing the program for multiple years, and preliminary evaluation on the impact of the program on high school students.

Design of Bioengineering 101 Program

The program was designed to educate students about several facets of engineering. This was accomplished through six in-class instruction days where the author would travel to St. Joseph's Academy (SJA), an all-girls school in Baton Rouge, LA, and work with the students (**Figure 1A**). On day 1, we wanted to provide students with an introduction to engineering including (*i*) what engineering is, (*ii*) what do engineers need to know, (*iii*) the different types of engineering, and (*iv*) what types of problems these engineers work on. After this overview, we introduced the concept of bioengineering (or biochemical engineering, biological engineering, biomedical engineering) to tie into the design challenge, but also because this discipline integrates features from numerous other engineering disciplines including chemical, mechanical, and electrical engineering. We spoke about the broad array of topics bioengineers work on including human health, energy, and the environment. We tried to make this introduction as broad as possible to pique the interest of as many students as we could, but also show the students that there are several engineering disciplines that they could explore in the future that work on complex biological problems related to human health.

On day 2, we narrowed the focus of the discussion to a particular application / problem being worked on by bioengineers – the isolation, capture, and study of circulating tumor cells (CTCs). CTCs have garnered significant interest from the research community as they play a key role during metastatic spread of cancer from the primary site to the secondary site [7]. Moreover, research has shown that the CTCs are altered during metastasis which leads to higher mortality associated with metastatic cancer (we focus on breast cancer during the activity). There are numerous researchers working on new technologies to collect these cells from the blood of cancer patients (also referred to as a liquid biopsy) with only one FDA-approved technology in existence [7]. One of the challenges in the development of this technology is the sparsity of CTCs with ~1 CTC for every 100,000 red blood cells (RBCs). This topic was selected because of the strong clinical significance, but also because some of the technologies in development to separate cancer cells from other cells (e.g., RBCs and other healthy cells found in the vasculature) use a size- or shape-based separation approach which nicely links to one of the areas of expertise of chemical engineers (which is highlighted in the lecture).

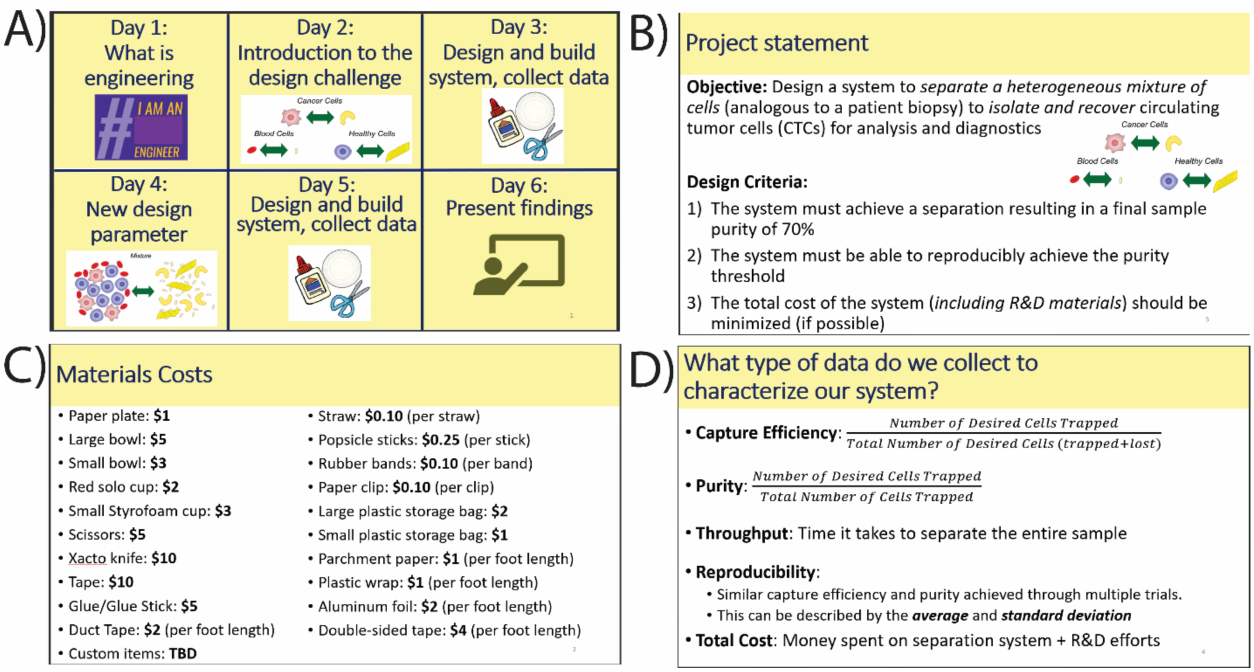

Figure 1. Organization and lecture materials for Bioengineering 101. (A) Organization of the activity included six days of in-class instruction by the author with each day having a specific focus. (B) Design project statement and criteria the student teams needed to follow. (C) Summary of the allowed materials to build the separation system and their associated cost. (D) Definition of metrics students were instructed to use to validate their system.

The lecture provided students with all the background information discussed above along with a survey of existing approaches to isolate CTC before setting up the design challenge (**Figure 1B**). The students were tasked with designing a system to separate a heterogeneous mixture of cells (analogous to a liquid biopsy) to isolate and recover CTCs. The mock 'biopsy' consisted of macaroni noodles (representing the cancer cells) and rice (representing the red blood cells). The students split themselves into teams of 3-4 and were given three design constraints (**Figure 1B**), an operating volume of the sample they need to separate (one full red Solo cup), and a list of materials they can use to design and build their system (**Figure 1C**). Each material has an associated cost with consumables (e.g., plates, bowls) being on a per item basis while tools (e.g., Xacto knife) having a single fixed cost. Moreover, the cost they incurred included both successful and failed designs meaning they were accountable for every piece of material they 'purchased' from the store. The idea was to create a similar environment as they would experience in a company or lab working on a project to meet specifications while minimizing cost. We also provided the teams with specific metrics they needed to calculate to validate the performance of their system including the capture efficiency, purity, and throughput of the system (**Figure 1D**). These are the same metrics used by engineers working on this technology and are important to include as it gives the teams exposure to not only collecting data but manipulating the data to characterize the performance of their system. Throughout this lecture we continually integrated the concept of the engineering design process starting with identifying the problem followed by designing, creating, testing, and improving their technology. This was important because most high school students had no exposure to the design process and this activity served as their first opportunity to learn about what engineers do daily. The students had the remainder of time in day 2 after the lecture and all of day 3 to design, build, and collect data on their system.

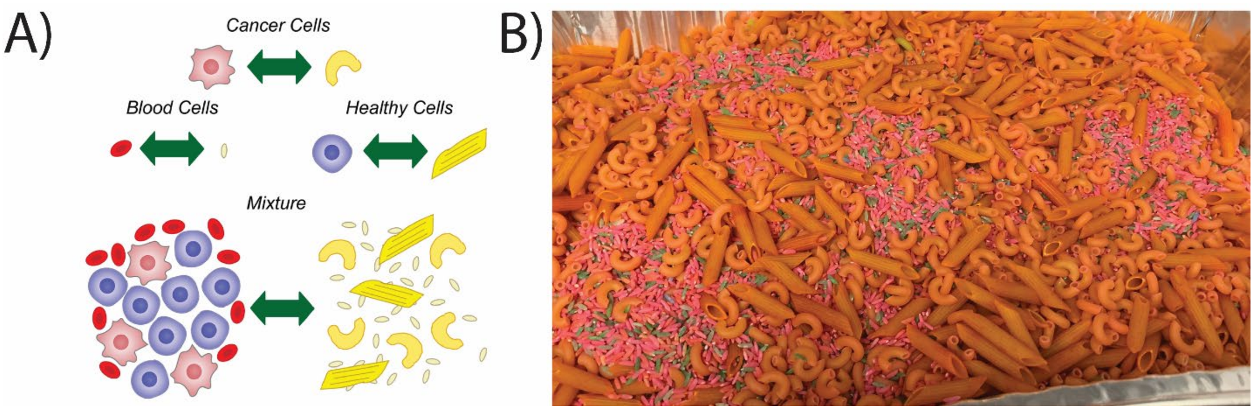

Figure 2. Design of the mock 'biopsy' introduced on day 4 to be separated as part of the design challenge. (A) Three different cell types found in a liquid biopsy include cancer cells (macaroni noodles), healthy cells (penne noodles), and red blood cells (rice). (B) Photo of the actual sample students were tasked with separating.

Day 4 began with the introduction of a new design constraint, the inclusion of a third component to the mock biopsy - penne noodles representing healthy cells (**Figure 2**). This was included for two reasons: (***1***) the two component, sized-based separation of the rice and macaroni was quite easy (which the students discovered early in day 3) and we wanted to challenge the students with a more difficult separation since the penne is larger than the macaroni and (***2***) to show students how design criteria can change when new problems or challenges are introduced (or identified) halfway through the project. The students had the rest of day 4 and all of day 5 to modify and test their system while still focusing on optimizing the design metrics (e.g., high capture efficiency, purity, and throughput while minimizing the cost). The beginning of day 5 also included a brief

(~10 min) lecture on effective oral communication as most students had limited experience presenting to a class. On day 6 all the students presented their findings to the class as well as a panel of judges consisting of other teachers from the school. The judges used a rubric similar to one used by the Louisiana Science Fair Competition to provide them with practice and similar metrics of success that they would see if/when they competed in the science fair competition. All the judges scores were compiled and then winners from each class and an overall winner were identified.

The Bioengineering 101 activity has been delivered four times during the fall semester of 2019 and the spring semesters of 2021, 2022, and 2023. A major success of the program was the active involvement of the two high school teachers who were able to adjust their lesson plans to allow for the inclusion of the activities during the normal class period and incorporate graded elements of the activity to ensure continued student involvement in the activity. We found having some graded element (which was usually submitting a daily log of the teams' data/findings) helped to keep the students on task and invested in the activity. The fall 2019 offering was given to third year students in the chemistry honors class while all three spring offerings were given to first year students in the physical science honors class (with a rationale for this shift included below in the lessons learned section). A summary of the six-day schedule (where the author was at the school performing the tasks described above) is included in **Table 1**. The exact schedule of the six days the author was at the school varied based on their teaching load, other university commitments, and the high school calendar (e.g., accounting for school holidays like spring break). The spacing of the lecture days were due, in part, to the fact that there were multiple sections for both the chemistry and physical science honors classes which occurred throughout the day (e.g., period 1 to period 7) which required the author to be on the SJA campus all day. In designing the activity, we felt it was important for all students in the class to have this experience, so efforts were made to accommodate the schedules of all involved parties.

Table 1. Schedule of Bioengineering 101 in-class activities. The dates correspond to the days defined in the schedule from Figure 1A where the author was on-campus working with the students. *Lecture was held synchronously via zoom. **Lecture was presented as pre-recorded videos. Days are Monday (M), Tuesday (T), Wednesday (W), Thursday (R), and Friday (F).

	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**
Fall 2019	10/21 (M)	10/24 (R)	10/25 (F)	10/28 (M)	10/29 (T)	10/31 (R)
Spring 2021	1/28 (R)	2/2 (T)	2/4 (R)	2/9 (T)	2/11 (R)	3/2 (T) & 3/4 (R)
Spring 2022	Video	3/29 (T)	3/31 (R)	4/1 (F)	4/12 (T)	4/14 (F) & 4/15 (F)
Spring 2023	Video	5/1 (M)	5/2 (T*)	5/3 (W*)	5/8 (M**)	5/11 (R) & 5/12 (F)

Lessons Learned and Program Improvements

Several lessons were learned during subsequent offerings of the Bioengineering 101 activity which has led to continuous improvements and alterations into the organization and delivery of the activity. Many of the lessons were based on informal student feedback in addition to observations by the high school teachers. The first major change was made between the fall 2019 and spring 2021 offerings changing from giving the demo to third year to first year high school students. This change was made because we suspected that content of the program was more beneficial to first year students as the attrition of students dropping the honors sections (or giving up on a focus in science) was substantially larger between first and second year than between third and fourth year.

Another motivating factor was that many students had already made up their minds with respect to exploring engineering as a future career path by the third year, so the hope was to engage, educate, and excite them at an early age. Finally, many of the students at SJA compete in science fair competitions during the second year and we felt the training they received in the activity would better prepare them for this competition and/or get them excited to compete in it. The second major change was increasing the number of presentation days from one to two. This is because we found it nearly impossible to have to teams (usually 6-9 teams per class) give an adequate presentation during a 50-min class period. Expanding to two days allowed students sufficient time to present and field questions. It also resulted in a less stressful presentation day for both the students and the author/teachers.

A third change made in later iterations was to space out the days that the author was on campus. We found during the fall 2019 offering that the students did not have sufficient time to design, build, or test their system (especially after introducing the penne noodles) in 2-3 days. As such, we expanded the scope of the program starting in the spring 2021 cohort to provide the students with more in-class periods where they could build and test their system (note the dates between days 3-6 in **Table 1**). This extra time allowed students to explore new/different ideas if their initial ideas failed or if they observed how their system could be improved. It also eliminated the need for students to have to come in during lunch breaks or before/after class which was observed during the fall 2019 cohort. This expanded timeline also allowed greater flexibility with the author's schedule and other time conflicts with the high school's schedule (e.g., short days, holidays). One thing that is important to note is the overall length of the spring 2021 cohort (nearly two full months). This heavily extended timeline was due to the COVID-19 pandemic with both Louisiana State University (LSU) and SJA having a mixture of both in-person and virtual (synchronous and asynchronous) instruction which impacted the author's availability to come to SJA and the attendance of the students due to intermittent COVID outbreaks where large groups of students had to remain off campus in quarantine. Even with these extended dates, we were fortunate to be able to give the demonstration in-person following all CDC guidelines.

A fourth change made to the activity was based on some skills learned during the COVID-19 pandemic including the use of pre-recorded videos and Zoom. For the spring 2022 cohort, we switched the day 1 lecture to a pre-recorded video made by the author that the high school teacher played during class. This allowed greater flexibility for the author to be able to come to the high school for the activities on days 2-5 which required a greater degree of one-to-one interactions. It also gave the students a resource they could revisit throughout the activity. For the spring 2023 cohort we used the same day 1 video, but also had to rely on pre-recorded videos for the short lectures on day 4 (new design criteria) and day 5 (effective presenting) and a synchronous zoom presentation on day 3. This was due to other commitments keeping the author from being able to come to SJA for the entire day that semester. To account for the missing face time, the high school teacher would have the student teams record videos with their questions and send to the author (usually as a text message) to allow them to be able to provide real-time feedback to the teams while the author was off campus. This new model allowed even greater flexibility with all the schedules and still provided students with both the time and feedback needed to complete the design. Moving forward the plan is to use the spring 2023 model with respect to timing and author involvement.

Program Evaluations

Overall, the program has been well received by the students based on the overall enthusiasm of the students during the event and afterwards. Informally, the high school teachers and administration have received numerous positive comments from both the students and parents with respect to how much the students enjoyed the program and how much they were able to learn. While this is good, we also wanted to perform quantitative evaluation of the effectiveness of the program. To this end, we administered pre- and post-surveys to the students at the beginning of day 1 and after the day 6 presentations to gauge the impact of the program. The pre- and post-survey contained a list of eight questions gauging the high school students' knowledge of engineering and their perception of their ability to be an engineering. We also included questions related to specific aspects of the program including their knowledge of the engineering design process and their ability to collect and present data. The pre- and post-surveys were given to all four cohorts; however, we are only able to present data for the fall 2019 (n=94), spring 2021 (n=90), and spring 2023 (n=148) cohorts. This is because all the paper surveys from the spring 2022 cohort (n=78) were thrown out by custodial staff before the author could retrieve them (the authors wish they were making this up and never thought they would be writing it in a technical paper but here we are).

The results from the pre- and post-surveys are included in **Table 2** and are listed as aggregate percentage differences across all three cohorts (fall 2019, spring 2021, and spring 2023) to visualize the overall impact of the program. A positive value corresponds to an increase in that response in the post-survey compared to the pre-survey while a negative value corresponds to a decrease in that response between the post- and pre-surveys. A zero value corresponds to no change. We used a five-point Likert scale with adjusted wording to better relate to the high school cohort (e.g., 'Yes, a lot!' is the same as 'strongly agree'). We found no observable change in responses to learning more about engineering or planning on going to college. We attributed this to an above average number of students with family/friends/neighbors who worked as engineers in the Baton Rouge area. We observed a small change in the number of students who believe they could be engineers or want to work as engineers. While we were hoping for a greater net change, these small percentages correlate to ~18 students across three years who now have the confidence to one-day become an engineer which we viewed as an important outcome. We observed the highest change between pre- and post-surveys in the students' understanding of the engineering design process (~33% for the strongly agree/agree groups) which indicates that the design of the activity achieved one of its desired goals. This trend was observed equally across both the third year (2019) and first year (2021, 2023) students. We also found an increase in student responses to their ability to analyze data and reach conclusions which also aligns with the goal of the program. The change in students' confidence in their ability to analyze data was greater in the first-year students (a change in ~20 students per year) when compared to the third-year students (a change in ~14 students). The authors attribute this to the third-year students having already competed in school/regional science fair competitions. These findings support the implementation of the program as a method to expose high school students to engineering and the engineering design process.

Table 2. Impact of Bioengineering 101 on student perceptions of engineering. Data is presented as percent difference in student response to the same questions from the pre- and post-surveys and is aggregated across the fall 2019, spring 2021, and spring 2023 offerings. A positive value indicates an increase in that response, a negative value indicates a decrease in that response, and a zero value indicates no change.

	Yes, a lot!	**Yes, a little bit**	**Not Sure**	**Probably Not**	**No way!**
I want to learn more about engineering	0.6	-0.6	-5.5	0.6	1.2
I think I have what it takes to be an engineer	5.1	7.6	-11.5	-2.4	-0.3
I know someone who is an engineer	4.2	-1.5	-1.5	-3.6	-0.3
I am planning on going to college	-2.1	-0.3	0	0.3	0
I want to work as an engineer or scientist	2.4	0.9	-1.8	-3.9	0.6
I understand the engineering design process	23.1	10.0	-12.8	-13.7	-8.2
I can analyze data and reach conclusions	16.9	-13.0	-4.2	-1.5	-0.3
I am confident in my ability to present to a group	3.3	-0.6	-2.1	-3.0	0.3

Two additional questions were asked as part of the post-survey to gauge students' opinion on the program itself (**Table 3**). We found that ~90% of students either strongly agreed or agreed that the program should be continued to be offered at SJA in subsequent years. We also found that ~64% of students either strongly agreed or agreed that the program influenced their opinion of engineers as a future career option. This last point was viewed as a significant finding as a majority of the cohort had a more defined idea of whether engineering could be a potential vocation for them in the future. It is an interesting finding given the small change in their perception of seeing themselves as engineers; however, overall, it is indicative that the program can be viewed as successful.

Table 3. Impact on Bioengineering 101 on student future career goals. Data is presented as percent in student response to the two questions only asked in the post-survey and is aggregated across the fall 2019, spring 2021, and spring 2023 offerings.

	Strongly agree	**Agree**	**No opinion**	**Disagree**	**Strongly disagree**
Would you recommend that SJA offer the Bioengineering 101 module again?	63.5	25.6	9.6	0	1.3
Do you feel that Bioengineering 101 has influenced your opinion of engineering as a future career option?	26.3	37.8	22.4	8.3	5.1

Conclusions

The paper summarizes the design and implementation of a six-day, hands-on outreach activity to educate and excite high school students about engineering. We designed the activity to mirror the engineering design process and to challenge students with tasks commonly encountered by practicing chemical engineers including addressing a real-world problem, designing and testing a potential solution to that problem, and evaluating its success using well-defined metrics all the while trying to minimize cost. The design of the program has been improved during its four years from fall 2019 to spring 2023 based on formal and informal student feedback and by observations of the author and high school teachers. Evaluation of the program is mostly positive with the students indicating an increased understanding of the engineering design process and their ability to collect data along with a significant number of students being influenced on engineering as a potential future career. While the design of the activity was focused on a biological aspect of chemical engineering, the size-based separation could be easily tailored to other real-world applications such as polymer science (e.g., making new membranes to separate out biomolecules or environmental hazards) or colloids (e.g., separating nanomaterials) depending upon the scope/design of the activity. Future work includes expanding the program to new high schools and increasing the overall throughput (e.g., offering the program more than once per year). Additionally, future offerings of the program will expand the question pool of the pre- and post-survey to ask discipline specific questions to address questions and concerns of the "image" of chemical engineers as discussed in the introduction.

Acknowledgements

The authors would like to thank Ms. Rhonda Baird, Ms. Brianna Sommers, and Ms. Jacqueline Savoia from St. Jospeh's Academy in Baton Rouge, LA for all their effort to help design and implement the Bioengineering 101 demonstration during the past four years. The authors would also like to thank Reese Richard and Abigail Melvin for their help in compiling all the data collected in the pre- and post-surveys. The work was supported in part by CBET 1846900 (ATM). The author is happy to provide any colleagues with the complete lecture materials (e.g., slides, handouts, supply lists, rubrics) if they are interested in implementing the activity.

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