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# Engaging Community College Students in Cutting-Edge Research in Topology Optimization

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# Engaging Community College Students in Cutting-Edge Research in Topology Optimization

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**Abstract**

Topology optimization has great potential to achieve the most economical and efficient engineering designs due to its ability to allocate materials to the most effective locations. Topology optimization techniques have been applied to tall building design. However, due to the lack of an automated process, a simplified procedure is commonly used to find the optimized pattern of the exterior bracing. An automated topology optimization platform that utilizes commercially available software packages would be very helpful to promote the usage of topology optimization and adoption of the research outcomes. The California Community College System, with its enrollment of approximately 2.5 million students, is in a prime position to grow the future science, technology, engineering, and mathematics (STEM) workforce. Through the U.S. Department of Education funded collaborative Minority Science and Engineering Improvement Program: Accelerated STEM Pathways through Internships, Research, Engagement, and Support (ASPIRES) cooperative program between Cañada College, a Hispanic-Serving community college and San Francisco State University (SFSU), a public comprehensive university, a 10-week summer program is set up to provide opportunity for community college students to experience the excitement of state-of-the-art research. In this summer program, the community college students were working closely with graduate students in SFSU to develop a user-friendly platform that streamlines various software packages in different stages of the design process, from modeling to finite element analysis and topology optimization. Topology optimization of a cantilever beam with a moving point load was used to test the developed platform. Systematic workshops and learning modules were prepared to help the participating students get ready for upcoming challenges and to provide them a meaningful research experience. The feedback from the students showed that the ASPIRES program offers an effective way to engage students, even with little or no background in engineering courses or research topics, from a community college in engineering research. The pre- and post-program survey results demonstrated that the internship program helped participating students better understand research and science and increase their independency toward the goal of graduating mature, independent, informed, and globally competitive STEM graduates.

## Introduction

Topology optimization is a mathematical method that can be used to reduce structural weight, material layout, or volume of a given design by adjusting design variables, set of constraints, and design parameters. Its origin can be traced back to over a hundred years to the Australian inventor Michell, who worked on some of the first truss solutions and derived optimality criteria for the least-weight-layout of trusses [1, 2]. Topology optimization has great potential to achieve economical and efficient engineering designs due to its ability to allocate materials to the most effective locations. Research on topology optimization has advanced over the last several decades, and has been specifically focused on developing optimization algorithms [2]. There are many engineering related industries that use topology optimization, including aerospace, automobile, biological engineering, material engineering and so on. In recent years, these topology optimization techniques have attracted attention to building design, particularly in the design of the perimeter bracing [3-5]. Due to the lack of an automated process, a simplified procedure is commonly used in actual design practice to find the optimized pattern. Typically, a single static point load is applied to the top of the building. Topology optimization is then used to determine the optimized pattern. Results are generalized and the patterns are directly applied to other structures with different design domains (e.g., loading conditions and structural dimensions such as width and height), even though varying these parameters will produce different optimal topologies. An automated topology optimization platform that utilizes the commercially available software packages would be very helpful to promote the usage of topology optimization and adoption of the research outcomes from state-of-the-art research on topology optimization.

Empowering the future generation of researchers and engineers to be drivers of innovation has its roots in today's undergraduate and graduate education. Diversity is critical to innovation, bringing together different ideas and approaches to keep civil engineering on pace with technological advances. The California Community College System, with its enrollment of approximately 2.5 million students, is in a prime position to grow the future science, technology, engineering, and mathematics (STEM) workforce. Through the U.S. Department of Education funded Minority Science and Engineering Improvement Program: Accelerated STEM Pathways through Internships, Research, Engagement, and Support (ASPIRES) cooperative program between Cañada College, a Hispanic-Serving community college and San Francisco State University (SFSU), a public comprehensive university, a 10-week summer program is set up to provide opportunity for community college students to experience the excitement of the state-of the-art research. In this summer program, the community college students are working closely with graduate students and the faculty mentor in the SFSU to develop a user-friendly automated platform that streamlines various software packages in different stages of the design process, from modeling (AutoCAD) to finite element analysis and topology optimization (ANSYS). Topology optimization of a cantilever beam with a moving point load is used to validate the developed platform.

## Proposed Automated Platform

There are several components in the proposed automated topology optimization platform, namely, modeling, topology optimization, finite element performance analysis, and information exchange and results extraction. In order to automate the topology optimization process without human interference, the need of using Graphical User Interfaces (GUI) should be minimized if not eliminated. The flowchart of the proposed platform is shown in Fig. 1 and each component is explained in detail in the following.

*Modeling*

Modeling of the structure (e.g., creating geometry and loading) is a critical first step for structural analyses, such as performance and topology optimization. However, in most commercial software that performs these analyses, the modeling ability is not satisfying. AutoCAD, developed by Autodesk [6], is one of the most popular commercial computer-aided design (CAD) and drafting software applications, famous for its modeling power.

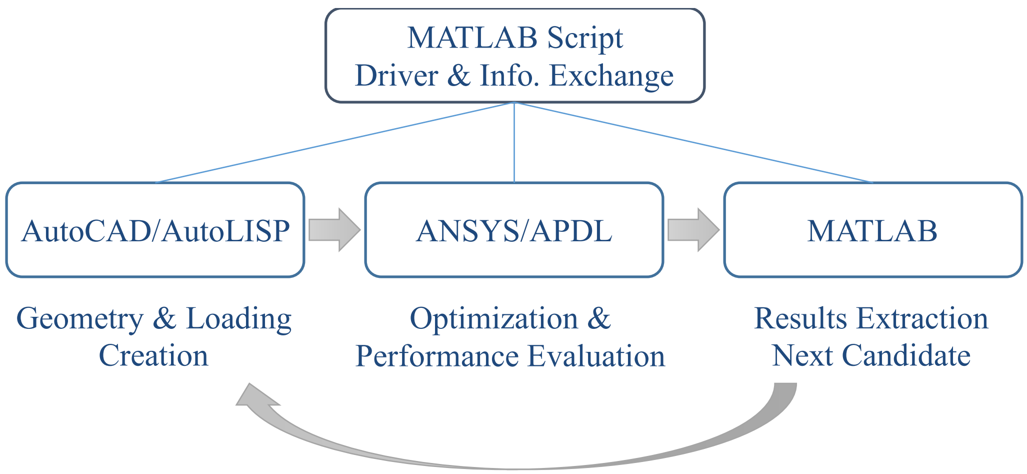


Figure 1. Flowchart of the proposed automated platform

To enable the use of AutoCAD modeling in the automated process, there is a need to reduce the user's dependency on the GUI. AutoLISP is a built-in programming language of AutoCAD [7], which can be used to create programs that will automatically generate drawings and models. It is suitable to serve as the application programming interface (API) between the modeling and other components of the proposed platform, therefore, it is adopted for use in the proposed platform. Once the model is created, it is saved as an IGES (Initial Graphics Exchange Specification) file so that other programs within the proposed platform can use it.

*Topology optimization and finite element performance analysis*

To perform the topology optimization and performance analyses, ANSYS finite element analysis software is adopted in this study. The ANSYS structural analysis software is widely used throughout the industry. The Structures suite of ANSYS not only enables users to solve complex structural engineering problems through the finite element analysis tools available in the suite, but also allows the customization and automation of the design process. [8] As one of the powerful tools in the Structures suite, ANSYS Mechanical allows users to perform topology optimization to design durable, lightweight components to ensure that manufacturing requirements are met, minimum material thicknesses are set and exclusion areas are defined [9]. The ANSYS Parametric Design Language (APDL) is a scripting language that allows users to automate common tasks and/or configure parameters for analysis [10]. With the help of APDL, users can connect easily with other analysis tools. The APDL is utilized in the proposed platform to import AutoCAD geometry models (i.e., the IGES files) and set parameters such as loading and mesh sizes before running the model through a topology optimization simulation.

*Information exchange and results extraction*

MATLAB is a multi-paradigm numerical computing environment and proprietary programming language developed by MathWorks [11]. It is a powerful tool that has been widely used in both academic research and industrial practices. In the proposed platform, MATLAB scripts are used to serve as a driver to execute the various components sequentially, extract the results from the structural performance and topology optimization outputs, compare the results with the desired objectives/constraints, and lead the modification of the model.

The process of the proposed platform is as following: MATLAB script will first create the model of the structure of interest in AutoCAD through activating a predefined AutoLISP program. The created model by the AutoLISP will then be imported to ANSYS when the APDL command is executed by the MATLAB scripts. After that, all through APDL commands, the model will be meshed, loading will be applied, and the topology optimization in ANSYS will be launched. The optimized shape obtained from ANSYS will then be used to perform the structural performance evaluation before the results are saved locally. The results contained in the files will then be extracted and imported to MATLAB through the MATLAB script to evaluate if it satisfies the desired objectives/constraints. If not, the MATLAB scripts will revise the AutoLISP program accordingly to modify the model. This loop is iterated until the objective/constraints are satisfied.

**Case Study**

To validate the developed platform, a topology optimization case study is used to test the platform. In this case study, topology optimizations were performed for a cantilever steel beam under a point load with varying location along the length of the beam. The effect of different mesh sizes to the optimization results was also investigated. The beam is 500 mm (length, $l$) x 100 mm (width, $b$) x 50 mm (thickness, $h$) as shown in Fig. 2. The objective is to find the most optimized topology of the beam to minimize the deflection ($\Delta$) of the beam under a point load ($P$ = $25kN$) while retaining 50% (maximum) of its volume. The location ($a$) of the point load was changing along the length ($l$) of the beam with a 50 mm increments from the cantilever end of the beam to a location of 50 mm from the fixed end of the beam as shown in Fig. 3. The mesh size of the finite element model was varied from 10 mm to 50 mm by 10 mm increments.

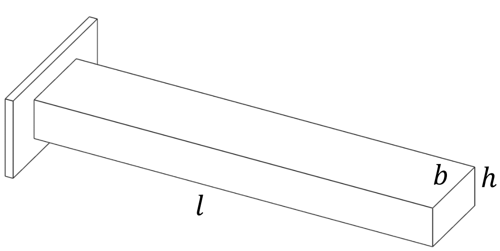


Figure 2. Isometric view of a cantilever beam

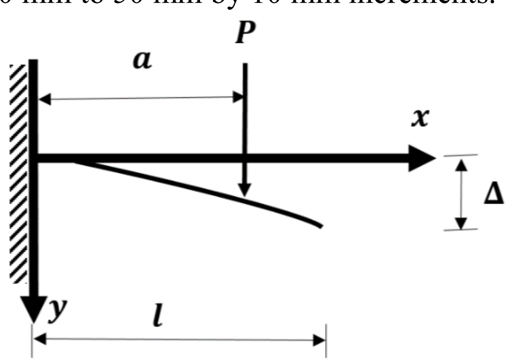


Figure 3. Cantilever steel beam with a point load varying along the length

*Results and Discussion*

Through the developed topology optimization platform, iterations were automatically run to loop through the various point load locations as well as the various mesh sizes. Results from ANSYS for each case scenario were then extracted by the APDL command and imported into MATLAB for post-processing. The results of this case study are shown in Fig. 4, which illustrates the variation of the beam's maximum deflection under a point load, acting at the different locations with the mesh sizes changing from 10 mm to 50 mm. As expected, the results converge when the mesh size gets smaller. To graphically observe the role of mesh size, a two-dimensional plot is shown in Fig. 5.

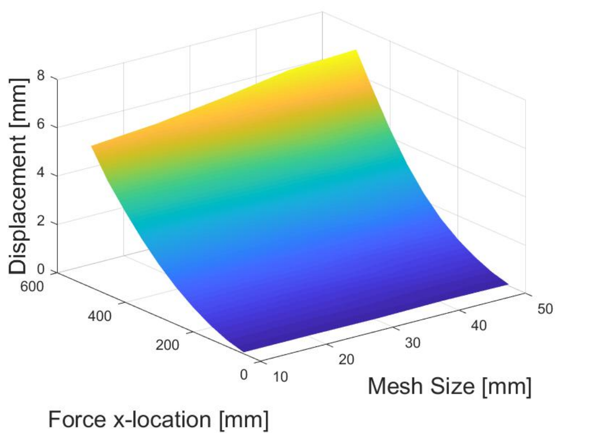


Figure 4. 3D plot on beam deflection under point loads with different mesh sizes

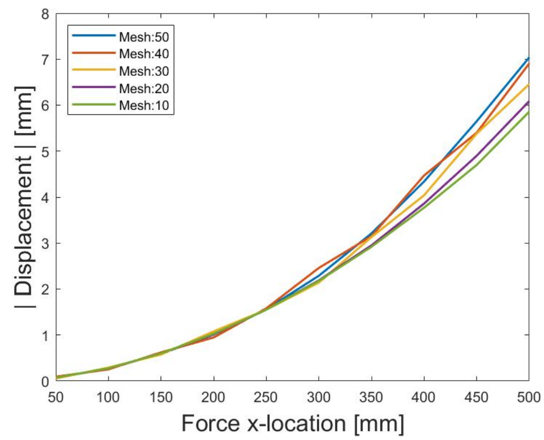


Figure 5. 2D plot on beam deflection under point loads with different mesh sizes

To better illustrate the advantage of the topology optimization, the results obtained from the developed platform were compared to the theoretical values without optimization. The deflection of a cantilever beam can be calculated from Eq. 1:

$$\Delta = \frac{Pa^2}{6EI}(3l - a) \tag{1}$$

where $E$ is Young's modulus of the steel and the moment of inertia of the beam can be calculated using Eq. 2:

$$I = \frac{bh^3}{12} \tag{2}$$

The comparison results are shown in Fig. 6. As can be seen from the figure, with 50% allowable material usage as the original beam, the deflection of the optimized beam (10 mm mesh size) was 5.86 mm while the deflection of the non-optimized beam ($l$ = 500 mm, $b$ = 50 mm, $h$ = 50 mm) was 9.52 mm. A reduction of 38.5% was achieved.

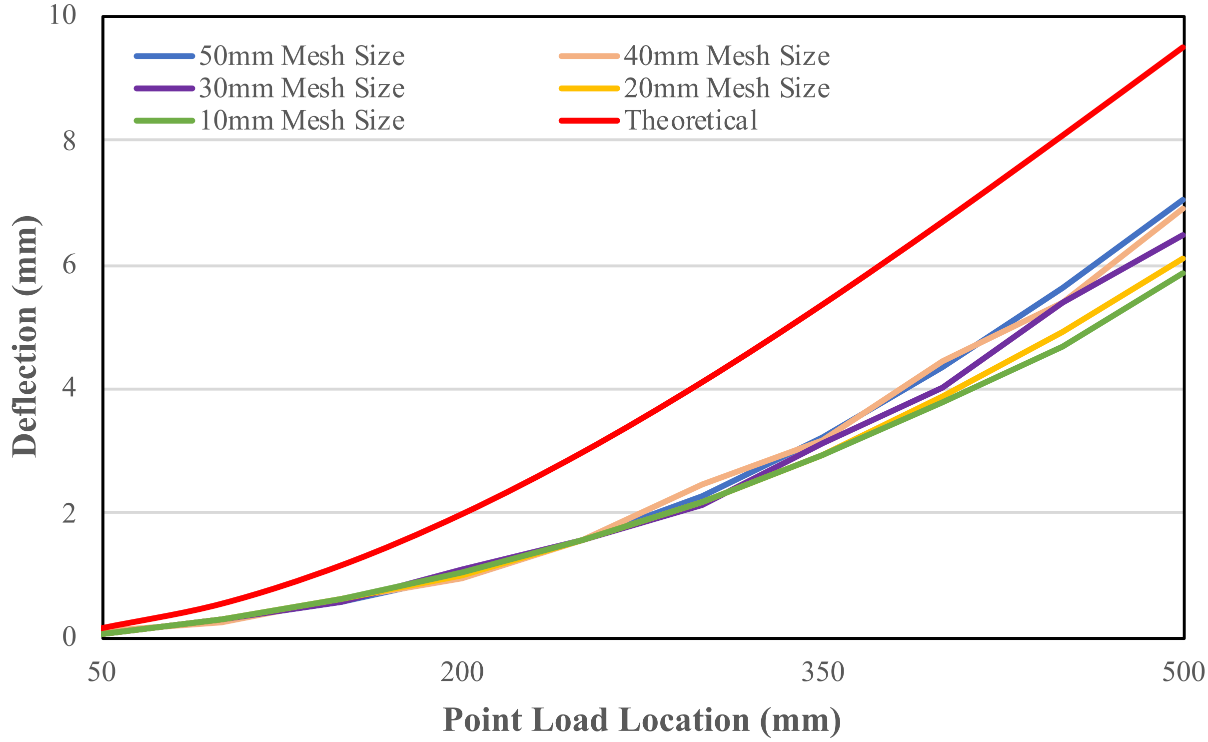

Figure 6. Comparison between numerical and theoretical values

**Strategies for Student Success and Project Assessment**

There were five research groups in the internship program, each generally consisting of one fulltime student intern and three part-time student interns that were supervised by one SFSU graduate student and mentored by an SFSU engineering faculty member. The participating students are typically sophomores who have no previous research experience and have at least one more year of courses to complete at Cañada College before transferring to a four-year university. To ensure the participating students to have a meaningful experience, for the particular Civil Engineering group who authors this paper, several strategies were implemented to help students succeed in the program in addition to those offered by the ASPIRES program. First, a group meet-and-greet meeting was held on the first day of the internship program. In this meeting, students were provided with an introduction of the program as well as the research direction and expected outcomes. Seminars and workshops have shown to improve participant's satisfaction [12]. The faculty advisor of this group has an ongoing NSF Research Experiences for Undergraduates (REU) program [13] that is concurrently running at the time of the ASPIRES program. The developed formal training, workshops, and supplemental activities through the REU program were also made available to the participating students in this ASPIRES program. These workshops include Responsible Conduct of Research and Ethics, Research Process, Literature Review and Conducting Research, Verbal and Written Communication Skills, Learning to Give Powerful Oral and Poster Presentations, The Elevator Pitch: Advocating for Your Good Ideas, and project-specific topics, such as structural dynamics, topology optimization, and training tutorials for prevalent software. These workshops intend to help students develop independent research ability, better present research outcomes, and effectively promote research findings. Since MATLAB is one of the essential tools needed for this particular research project, all interns were required to participate in an intense MALTAB training at the beginning of the program. It is recognized that students joined with different knowledge levels. Weekly project specific seminars were prepared by the faculty advisor and delivered by the graduate mentor to help students acquire necessary knowledge for the upcoming research activities. Additionally, weekly meetings and roundtable discussions were set up to ensure research to be in the right direction and help students to practice their presentation skills.

Pre- and post-program surveys were conducted to evaluate the success of the internship program. The pre-program survey was administered on the first day of the summer internship program and the post-program survey was administered after final presentations delivered by the students at the end of the program. The participating interns were asked about their perception of skills and knowledge before and after the program. A Likert scale was used to evaluate the responses, where “1” representing “strongly disagree” and “5” for “strongly agree”. The survey results are shown in Table 1.

Among various questions being investigated, results from those where changes in average response were statistically significant (highlighted with bold fonts) are of particular interest. Results show that the summer internship program had a positive effect on students, evident by the increase in average response from all of the pre- and post-survey questions with statistical significance. Students responded that they gained better understanding of research and science, indicating that the exposure to research with fundamental science offered by this program, at an early stage of their educational career, provided students a better understanding on the research process, where to start if given a real-world problem, and how to implement the research outcomes to tackle the problem. Traditional education focuses on the understanding of theory, but not necessarily applying it to real-world problems. This summer internship opportunity allowed students to relate theories to real-world problems, something that is not always offered in the classroom. In addition, this process better prepared students to take on future research in their field and helped students transition from a relatively dependent status to an independent a status as their competence level increases, as supported by the survey results.

Table 1. Student Perception of Skills and Knowledge for Academic and Research Success.

| **Question: Please indicate your level of agreement with the following statements.** | **Average Response** | | |
|---|---|---|---|
| | **Pre** | **Post** | **Change** |
| **I am confident I will transfer to a four-year institution.** | 4.80 | 4.76 | -0.04 |
| **I am confident I will complete a BS in a STEM field.** | 4.72 | 4.64 | -0.08 |
| **I can imagine myself continuing after my BS to pursue a Master’s Degree in a STEM field.** | 4.24 | 4.32 | 0.08 |
| **I can imagine myself continuing after my BS to pursue a Ph.D. in a STEM field/Medical School/other education beyond the Master's level.** | 3.60 | 3.88 | 0.28 |
| **I have a clear career path.** | 4.04 | 4.28 | 0.24 |
| **I have skill in interpreting results.** | 3.96 | 4.28 | 0.32 |
| **I have tolerance for obstacles faced in the research process.** | 4.12 | 4.40 | 0.28 |
| **I am ready for more demanding research.** | 3.88 | 4.28 | 0.40 |
| **I understand how knowledge is constructed.** | 3.96 | 4.32 | 0.36 |
| **I understand the research process in my field.** | **3.56** | **4.28** | **0.72**** |
| **I have the ability to integrate theory and practice.** | 3.84 | 4.20 | 0.36 |

| | | | |
|---|---|---|---|
| **I understand how scientists work on real problems.** | **3.52** | **4.40** | **0.88**** |
| **I understand that scientific assertions require supporting evidence.** | **4.04** | **4.52** | **0.48*** |
| **I have the ability to analyze data and other information.** | 4.04 | 4.40 | 0.36 |
| **I understand science.** | **3.88** | **4.36** | **0.48*** |
| **I have learned about ethical conduct in my field.** | 3.96 | 3.96 | 0.00 |
| **I have learned laboratory techniques.** | 4.00 | 4.32 | 0.32 |
| **I have an ability to read and understand primary literature.** | 4.00 | 4.40 | 0.40 |
| **I have skill in how to give an effective oral presentation.** | 4.04 | 4.40 | 0.36 |
| **I have skill in science writing.** | 3.68 | 4.08 | 0.40 |
| **I have self-confidence.** | 4.08 | 4.32 | 0.24 |
| **I understand how scientists think.** | 3.84 | 4.24 | 0.40 |
| **I have the ability to work independently.** | **4.16** | **4.64** | **0.48*** |
| **I am part of a learning community.** | 4.36 | 4.16 | -0.20 |
| **I have a clear understanding of the career opportunities in science.** | 4.16 | 4.24 | 0.08 |

* The change is statistically significant at $p < 0.050$.
**The change is statistically significant at $p < 0.010$.

## Conclusion

Topology optimization has great potential to achieve the most economical and efficient engineering designs due to its ability to allocate materials to the most effective locations. However, due to the lack of an automated process, a simplified procedure is commonly used to find the optimized pattern of exterior bracing in the building design. To resolve this, an automated topology optimization platform that integrates several commercially available software packages in different stages of the design process was proposed as one of the research topics in the U.S. Department of Education funded collaborative ASPIRES program between Cañada College, a Hispanic-Serving community college and SFSU, a public comprehensive university. Through this summer internship program, students evaluated the feasibility of developing such a platform and validated the developed platform through a numerical study on minimizing the defection of a cantilever beam under a point load. Systematic workshops and training were provided to help students succeed and ensure a meaningful research experience. Weekly meetings with mandatory presentations and roundtable discussions were utilized to guide the students toward the right path while providing them enough freedom to explore new ideas. From the pre- and post-program survey results, this 10-week ASPIRES Summer Internship program was successful in providing opportunities for students, especially those from underrepresented minority groups, to experience the excitement of state-of-the-art research. As can be seen from Tables 1, the internship program helped participating students better understand research and science, and how to relate the theory to real-world problems and implement the research outcomes to tackle these problems. This learning exercise contributed to the increase of students' independency toward the goal of graduating mature, independent, informed, and globally competitive STEM graduates. The program showed that even students with little or no background in engineering courses or research topics were able to succeed in the program and experience the excitement of research. It also demonstrated that the ASPIRES program offers an effective way to engage students from a community college in engineering research.

The ASPIRES program is a learning process for both participating students and faculty advisors. Several thoughts gained through the program on how to enhance student learning and engagement are provided herein as a possible means to improve program outcomes. Firstly, the commitment of the participating faculty advisors is an important factor in motivating students. Given that it is likely their first research experience for the participating students, more efforts are recommended to place at the beginning of the program to guide students on how to transit from a dependent learner to a more independent researcher. Exercises such as roundtable discussion and weekly presentation appear to be useful to connect with students and ensure that they are moving along the right path toward a meaningful research project. Clearly identified expectations and research outcomes are also crucial to engage students by providing them feasible goals and allowing them to set daily and weekly tasks for the goals. Lastly, as engineering is practical science, a hands-on experiment is another engaging means to bring excitement to participating students. For the future implementations, these approaches will be applied and their effects on the program outcomes will be evaluated.

## Acknowledgement

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