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IBBME Discovery: Biomedical Engineering-based Iterative Learning in a High School STEM Curriculum (Evaluation)

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IBBME Discovery: Biomedical engineering-based iterative learning in a high school STEM curriculum (Evaluation)

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Abstract

Senior high school students often struggle with recognizing the link between human health care and engineering, resulting in limited recruitment for post-secondary biomedical engineering (BME) study. To enhance student comprehension and recruitment in the field, BME graduate student instructors have developed and launched *Discovery*, a collaborative high school outreach program that promotes and engages students in the application of science, technology, engineering, and math (STEM) concepts. The program offers a unique, immersive semester-long practicum that complements classroom curriculum but is delivered within university facilities. Further to this, BME graduate students have the opportunity to develop and deliver STEM curriculum directly aligned with their thesis research. The overall goal of the program is to immerse high school science students in inquiry-based experiential learning in a post-secondary BME environment, enhancing BME literacy and stimulating pursuit of post-secondary STEM study.

This program is a collaboration between graduate student instructors and science educators from one local public high school. Each semester, approximately 65 secondary STEM students, 4 educators, 15 graduate student instructors, and 2 faculty members are involved in *Discovery*. Small student groups work in a capstone format, incorporating iterative design principles and the scientific method to address thematically-related but subject-specific research projects that satisfy curriculum requirements. Educators assign 10-15% of semester course grades to deliverables and quantitatively assess student comprehension. The semester culminates in a final symposium where students present their findings in scientific poster format.

Discovery is unique in its delivery of iterative design to a class cohort accompanied by their educator and carries the benefit of removing socio-economic barriers to student learning and success. High school educators further benefit through co-instruction with graduate instructors within university facilities, increasing student comfort within laboratory environments. High-school educators have identified difficulties with student involvement in the regular classroom. Comparatively, to date, all students have successfully engaged in the various *Discovery* activities. During the pilot year, > 85% of participants exhibited perfect *Discovery* attendance; these students demonstrated absence for ~ 10% of classes in their school environment. Students view this experience as an integral part of their classroom curriculum and are both excited and engaged in their scientific outcomes. In post-hoc surveys, over 75% of student participants stated that this program impacted their pursuit of future studies in STEM, indicating a greater understanding of BME theory and practice, while anecdotally graduate instructors indicated that their pedagogical training greatly improved.

1 Introduction

The entire high school experience is important for influencing students' career considerations [1]. College students reported that their decision to consider a STEM (science, technology, engineering, and math) major was made during high school; student interest being the most important consideration [1]. To garner interest, students require exposure to, and comprehension of, the field. Biomedical engineering (BME) is an area to which high school students often struggle to relate, as it is difficult to recognize how traditional engineering concepts translate to the field of human health [2]. Early introduction to these fields during high school is vital if students are to pursue STEM fields, especially within engineering [3]. Further to this, many students are unaware of the research opportunities that exist during the post-secondary experience when they are considering their major of study, or even once they have begun their first year of post-secondary [4].

One strategy to better inform students is immersion within STEM curriculum to engage in real-world problem solving, internships, and/or capstone-type projects. These studies suggest that high school students, when given opportunity and support, successfully complete rigorous STEM programs [5]. Conversely, other studies have shown no significant differences in participation rates in advanced sciences and mathematics for students at STEM focused schools compared to their peers [6]. Fortunately, this suggests that academic background may be irrelevant when students are given equal opportunity for immersive BME opportunities.

Outside of interest, it has also been shown that in the context of STEM education and career choices, student self-efficacy regarding research skills predicts undergraduate student aspirations for research careers [7]. Self-efficacy has also been identified to influence 'motivation, persistence, and determination' in overcoming challenges in a career pathway [8]. Programs that produced significant differences in student self-efficacy tend to be semester-long and academically challenging, as opposed to activities such as field trips or singular class visits [9]. MEDscience, a medical simulation-based STEM program integrated into high school science classes through collaboration between the Harvard Medical School and K-12 teachers in Boston, is one example of a semester-long integrated course [10]. MEDscience promotes traditional learning but also student self-efficacy 'related to STEM and healthcare attitudes and career choices' and has been shown to influence student interest and confidence in pursuing science and healthcare-related careers.

Many institutions support the idea that post-secondary engineering outreach programs are effective ways to expose high school students to engineering education, and career options in the field. It is becoming more apparent that there is prerequisite for engineers to be involved in developing relevant STEM hands-on activities for such programs [9]. One example is the Young Scientist Program, a 9-week long intensive summer program for minority students, founded in 1991 by graduate students at the School of Medicine, Washington University in St Louis. This program was uniquely organized, designed, and led by graduate students [11]. Importantly, formative data during an 8-year longitudinal study showed that the program stimulated improvement in high school student pursuit of STEM undergraduate degrees. The benefit of inquiry-based STEM learning was also observed with immersive research for minority high school students in Atlanta, where Georgia Tech laboratories hired high school students for a one-year research project with a direct graduate student mentor. The benefits of immersive learning were quantified through drastic increases in pursuit of post-secondary education and academic excellence, suggesting students thrive when given the opportunity to learn in a different environment [12].

Further to the potential impact on high school student STEM perceptions, integrated programs also provide a platform for graduate student professional development in the context of curriculum development and teaching. The Biological Sciences Initiative at the University of Colorado Boulder engages graduate students in STEM fields related to biomedical science to visit K-12 classrooms and lead inquiry-based curriculum [13]. Semi-structured interviews with participating graduates revealed that rather than stimulating interest in education, program engagement reinforced interest and developed knowledge, professional skills, and beliefs that enhanced preparation for their chosen profession.

Supported by the outcomes of the identified studies, graduate student instructors at the Institute of Biomaterials and Biomedical Engineering (IBBME; University of Toronto) have developed and launched *IBBME Discovery*, a collaborative high school science outreach program that stimulates application of STEM concepts within a unique semester-long applied curriculum delivered within IBBME undergraduate teaching facilities and collaborating high schools. The objective of the program is to provide high school science student class cohorts with opportunities to engage in challenging practical BME activities as a mechanism to stimulate comprehension of STEM curriculum application to real world concepts. This program not only introduces senior high school students to BME research through an immersive educational experience, but also provides IBBME graduate student researchers representing the community of BME practice with opportunities to engage in development and delivery of curriculum aligned to their specific thesis research theme(s). The goals of this study are to assess the impact of Discovery's iterative and immersive educational STEM experiences on high school student engagement in BME in the context of their course curriculum, as well as perceptions of STEM post-secondary study.

Mission Statement: *Introduce high school students to current biomedical engineering research by creating an immersive educational experience around collaborative research themes.*

Specific program Learning Outcomes:

- meet Ontario high school science curriculum-specific course learning outcomes identified by educators;
- connect course-specific scientific concepts to hands-on applications;
- understand the collaborative nature of BME within the context of IBBME research themes;
- develop real-world translation of scientific principles; and
- stimulate development of IBBME graduate student pedagogical skills.

2 Program Structure and Implementation

In the interest of facilitating data-based iterative learning and critical thinking, *Discovery* is structured to mimic a typical engineering capstone design course where student research teams work with a client to propose a solution to a problem. Small student groups work together to address a discipline-specific request for proposal (RFP) on a common theme, which culminates in a final symposium at IBBME (Figure 1).

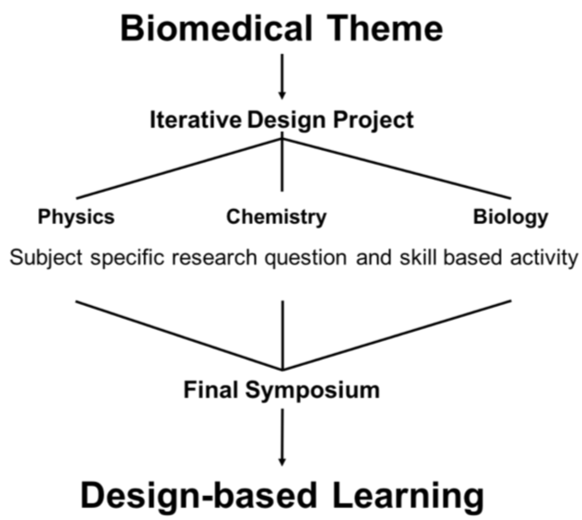

Figure 1: *Summary of design-based learning strategy employed in each IBBME Discovery semester.*

This structure provides a novel experience for students, as they present their final outcomes in research poster format to graduate and undergraduate students. We expect this format to encourage students to think critically about their recommendations to the problem in the context of their science curriculum (i.e., from either a biology, chemistry, or physics perspective).

2.1 Personnel Organization

The complexity of this program design lends itself to a hierarchical structure of graduate student leaders responsible to interact with the faculty supervisor, administrative staff, and high school teachers to optimize implementation (Figure 2). Each programming session requires program design, implementation, and assessment; the responsibilities of each team member are specifically outlined in Appendix Table A1.

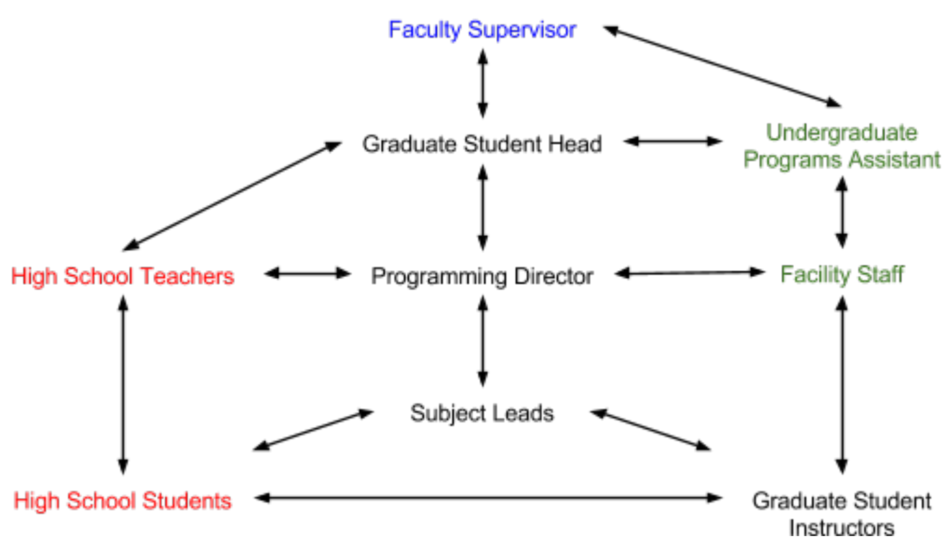

Figure 2: IBBME *Discovery* organizational structure. *Given the number of stakeholders involved in this program, this structure is employed with delegated responsibilities. Arrows denote regular communication.*

Volunteer graduate instructors interact with high school student design teams as client mentors. For each subject, there are approximately 4-5 groups composed of 4 students each (~20 students/ subject). Graduate student instructors work exclusively with one or two groups to provide guidance through completion of their experimental design. The instructors serve as university-style teaching assistants through iteration and provision of content-based feedback as students work through the scientific method.

Volunteer instructors are organized into a subject group within biology, chemistry, or physics according to their preference and research focus. The theme leads for each subject oversee and communicate with their assigned volunteers, as well as develop curricula in concert with the programming director and administrative lead. The STEM teachers and administration at the partner school are routinely consulted throughout this process. To ensure graduate volunteers are effective in their assigned subject area, they are first introduced to the semester topic and given an opportunity to confirm skill and interest compatibility with subject leads. A training session is also scheduled at the beginning of the semester to ensure volunteers are comfortable with the methods, as well as expected outcomes from each activity. This program structure supports strong transfer of practical knowledge to participating high school students.

2.2 Program delivery

Each *Discovery* program equates to a four-month high school academic project that aligns with a single high school semester. Students enrolled in university-stream Grade 11 and 12 STEM courses are designated to the corresponding *Discovery* subject (biology, chemistry, or physics). Those students enrolled in more than one participating course within a semester (e.g., Biology 12 and Chemistry 11) are assigned to a *Discovery* subject based on teacher insight and logistical needs to balance participant numbers across the sections. To further motivate students and meet curriculum requirements, *Discovery* activity deliverables represent 10-15% of the final course grade. High school teachers are responsible for rubric development and deliverable assessment, including RFP documents (two drafts and the final version), attendance, participation/engagement, and presentation of a scientific poster at the final symposium.

To prepare for the semester, teachers work alongside the program executive to develop suitable curricula to address a current global challenge in BME (specific roles identified below). Classroom materials such as introductory lectures and prelab activities, as well as laboratory protocols and expectations for the semester-long design project, are developed according to Ontario educational guidelines. The process is completed through informal meetings and email communication. To ensure that students are prepared to work in an innovative lab environment, they first complete a skill-based activity early in the semester to teach them necessary lab skills that they are likely to utilize in their projects. Following this, students gain an understanding of the theme of the semester-long project and are presented with an RFP detailing a specific research question tailored to the class in which they are enrolled. This is accompanied with an inventory list to allow students to begin to formulate their planned investigative experiments. Proposals are reviewed by both teachers and the graduate student instructor assigned to their student team, in advance of their lab trials. After their first lab visit, students debrief with their graduate student instructor and determine areas for improvement for the next visit to complete a usable data set. Students conclude the program by providing an assessment of their findings and a quantitative recommendation to address their assigned problem in the format of a poster presentation as part of the final symposium held at the IBBME. The chronological timeline of *Discovery* program milestones during one semester are summarized in Table 1 below, and in more detail in Appendix Table A2.

Table 1: Strategic semester milestones, ordered by occurrence. Blue boxes denote scheduled events, while red boxes denote virtual milestones (by email, teleconference, ad hoc meetings, etc.).

Milestone	**Approximate timing**	**Stakeholders involved**	**Goals, deliverables, and outcomes**
1. Curriculum planning	Ongoing before semester start	• Faculty supervisor • Program executive • IBBME staff • Teachers	• Finished protocols, worksheets, and expectations for review by teachers • Overarching theme established to link subgroup topics
2. Initial teacher meeting	Weeks 1-4	• Faculty supervisor • Program executive • Teachers	• Confirm overarching theme of projects aligned with global challenge in BME, and curricula of individual subjects
3. Recruitment event	Weeks 1-4	• Program executive • Potential volunteers	• Short lecture by executive on program structure and goals • Acquisition of contact information - interested volunteers
4. Volunteer Welcome meeting	Weeks 1-4	• Faculty supervision • Program executive • Volunteers	• Faculty supervisor outlines duties, incentives, and important dates • Volunteers are sorted by subject of interest
5. Combined teacher/volunteer orientation	Weeks 3-6	• Program executive • IBBME staff • Teachers • Volunteers	• Teachers test protocols on-site • Materials are prepared to introduce students to specifics required for lab visits • Confirm alignment of program materials to approved Ontario curriculum
6. Skill lab at IBBME	Weeks 6-8	• Program executive • IBBME staff • Teachers • Volunteers • Students	• Lab safety training • Introductory lecture • Skills-based activity according to set protocol • Presentation of RFP to students
7. RFP client meeting	Weeks 9-10	• Teachers • Volunteers • Students	• On-site or virtual meeting to establish proposal feasibility and identify areas to improve
8. IBBME experimental visit 1	Weeks 11-12	• Program executive • IBBME staff • Teachers • Volunteers • Students	• Students begin collecting data according to their proposals • Protocol feasibility is assessed *in situ* • Students establish what needs to be done during the next visit to collect a complete data set from which to make a recommendation
9. IBBME experimental visit 2	Weeks 13-14	• Program executive • IBBME staff • Teachers • Volunteers • Students	• Students finish collecting data according to protocol modifications made since Experimental Visit 1 • Students begin work on posters for the Final Symposium
10. Final symposium	Weeks 16-18	• Faculty members • Program executive • Teachers • Volunteers • Students	• Poster presentations by student groups to undergraduate judges • Keynote speaker addressing overall semester theme • Undergraduate/graduate student panel on postsecondary education • Campus tour • Potential for IBBME lab tours
11. Debriefing	After Final Symposium	• Faculty supervisor • Program executive • IBBME staff • Teachers • Volunteers	• Feedback solicited on program structure, curriculum, funding, and engagement • Strategic development and logistical planning for future programming

3 Curriculum Examples

IBBME Discovery has undergone two iterations using the identified program structure, with each STEM subject pertaining to an overarching theme (Table 2). As discussed, the themes are broken down into subject-specific questions that student groups work to address through experimental design and iteration. Herein we provide detail on the second iteration of the current structure where the overarching theme of heart disease was chosen.

Table 2: Summary of research themes and design questions executed in *IBBME Discovery*

		Subject Topics		
Term	**Theme**	**Biology**	**Chemistry**	**Physics**
1	Next-generation prosthetics for lower limb amputees	Characterizing a new strain of bacteria and promoting its effective clearance from a prosthetic	Optimizing PDMS (silicone rubber) chemistry for use as a prosthetic sock	Design of an above-knee prosthesis for active use
2	Engineering cardiac health	Quantitatively comparing the toxicity of an unknown substance to known cardiotoxic drugs	Optimizing the release of a beta-blocker from a biocompatible hydrogel within a safe but effective range over time	Portable plethysmographic heart rate monitor

Biology

In the Biology section of the program, students were asked to quantitatively compare the cardiotoxicity of an unknown compound to mammalian cells, relative to known controls. The RFP discussed mechanisms of cytotoxicity, dose-response physiology, and the roles of different cell types in the heart. During the introductory student visit to IBBME, graduate instructors delivered short lectures on microscopy, cell culture, toxicity, dilution, and cell staining protocols. To prepare students for future hands-on activities and gain comfort in preparing their group proposals, the Skill Lab involved fluorescence microscopy (imaging of green fluorescent protein-labeled fruit flies and cells), a liquid serial dilution activity, and instruction in sterile mammalian cell culture technique.

During the two Experimental Visits, students tested various concentrations of the unknown substance on the viability of an immortalized line of fibroblast cells. Students were encouraged to incorporate control substances (such as caffeine, ionic silver, sodium chloride, etc.) into their experiments. Biological responses were measured by microscopic imaging of fluorescent calcein-AM/propidium iodide cellular uptake (live/dead assay). Using automated ImageJ (NIH) analysis, students were able to quantify cell death to define the toxic range of the unknown substance.

Chemistry

Chemistry students were challenged to design a hydrogel to maintain safe and effective release of a drug over 24 hours in the human body. The RFP presented the issue of therapeutic toxicity using the example of metoprolol, a commonly-used beta blocker. As a "dirty drug", metoprolol has severe side effects at high concentrations and loses efficacy below a certain level in the body. Therefore, dosage timing and load is critical in maintaining a safe and effective dose. Students were presented with an introductory lecture on the role of pharmaceuticals in heart failure, drug release kinetics, and engineered hydrogels. For their Skill Lab, students completed activities in liquid serial dilution, spectrophotometry, standard curve generation and data analysis, and hydrogel formation.

During their Experimental Visits, students compared the timed release of food dye (metoprolol mimic) from gelatin and/or alginate hydrogels while varying the gel's density, chemical composition, or physical dimensions. Spectrophotometric analysis using known extinction coefficients allowed for quantitation by Beer's Law and validation by standard curves. The rates of dye release were fit to a model of metoprolol disposition in a human body that calculated effective instantaneous dose using first-order release and half-life kinetics. Students then calculated the amount of time that their gel would maintain a safe dose, without achieving a high-dose threshold.

Physics

Physics students were challenged to build and validate a portable heart rate monitor that was cost-effective, easily-prototyped, comfortable and easy to use, and capable of indicating both heart rate as well as provide an alert when detecting abnormalities. The RFP further outlined current methods used to measure heart-rate such as electrocardiography and IR plethysmography. During the initial IBBME visit, graduate student instructors presented short introductory lectures on the fundamentals of electrical engineering including circuits, microcontroller programming, and interfacing a microcontroller with peripherals. The Skill Lab protocol introduced circuit design, 3D printing, basic Arduino programming, and user-centred design [14].

During Experimental Visits, student groups worked on building their devices. To produce a piece of hardware that could be worn by the user, students made models in *Solidworks* which were 3D printed by the instructors between sessions. For the main infrared sensor, students integrated a manufactured pulse sensor device into a circuit with an Arduino microcontroller and their choice of buzzers, LEDs, and switches. Finally, students used the Arduino Integrated Development Environment (IDE) to read in serial data from the sensor and interact with their device. Students then used basic data filtering protocols to program the device to detect heart beats, calculate heart rate, and give feedback to the user by blinking an LED or producing a tone. After building their initial prototypes, students performed a series of validation tests including comparison of results against a commercial product, as well as manually measuring pulse compared to the device's readings.

All Disciplines

During the final visit and continuing at school, each student group prepared a research poster to present at the *IBBME Discovery* Symposium. Graduate student instructors and invited undergraduate student judges assessed all presentations. Two rounds of judging occurred to allow members of each group to present in pairs and therefore have an opportunity to practice presentation skills and demonstrate subject mastery. The group with the highest judged score in each subject was recognized.

4 Program Outcomes

Now entering its third academic session with an inquiry learning based model, *IBBME Discovery* has observed measured, multi-tiered outcomes for involved members. The focus of the program structure is on increased inquiry in STEM subjects for participating students. Given the program structure, we have observed additional benefit for high school teachers and graduate instructors, yielding a holistic approach to program delivery.

4.1 High school students

The observed academic impact of *Discovery* on participating students has grown in conjunction with the program. Iterative design curriculum delivery to a high school class accompanied by their educator is unique to this program, yielding the benefit of removing social barriers to student learning and success. By engaging students as classes with their staff, we observe immediate interaction with the new workspace and graduate student instructors. As such, students are comfortable with their colleagues and maintain group consistency as they work through problem-solving in a collaborative setting. Further, this program ensures the participation of an entire student population regardless of initial interest, ability, or economic/social means. Many other programs select high achievers from different high schools, looking to ensure that top students succeed. Herein we take a different approach, subscribing to the belief that that those students who have both an interest in STEM and are high academic achievers will likely seek future opportunities within the field. Rather, *Discovery* engages students exhibiting a range of academic abilities and interests. Our preliminary observations indicate that a new learning environment, in conjunction with the familiarity of peers, improves engagement, performance, and observed inquisitiveness of many students. To date, all participating students (~60 students per session) have successfully engaged in the various activities. Many of these students were identified by course teachers as demonstrating lacklustre involvement in the regular classroom. More than 75% of student participants stated that this program has impacted their interest to pursue future studies in STEM, in association with a greater understanding of BME theory and practice (Fig. 3A). During Session 1, > 85% of participants exhibited perfect *Discovery* attendance; these same students demonstrated absence for ~ 10% of their regular classes during that semester (Fig. 3B). Notably, the time spent on campus is equivalent to 4-5 science classes (6 hours vs 1.25 hours), giving it relevant time weight to other programming within the class term (15 class equivalence over one term). As such, we feel the level of student engagement measured through attendance is an impactful observation of student interest. This is further exemplified by student requirement to transport themselves across the city on public transit for this program, a feat that is relatively significant to a student used to a daily routine. When examining the select population of students near the pass/fail margin, it was observed that the new learning environment had great impact on their academic success (Fig. 3C). The impact of student enjoyment of a different learning environment should not be ignored as a contributing factor to increased engagement. The program design strives to give students a representative experience of the daily life of an individual executing research. Students are subject to the difficulties of developing a method of assessment toward addressing a research question. Further, we allow students to execute and make errors within this format, both yielding skills of problem solving and a feeling of agency and ownership in their successes.

4.2 Graduate instructors

Discovery was founded, organized, and executed by graduate students with the focus of providing unique learning opportunities for high school students. Interestingly, when surveyed anonymously for their motivation of involvement in the program (selection of all relevant options), graduate instructors indicate a range of motivations for involvement, demonstrating the impact and value of this program as a platform for pedagogical skill development (Fig. 3D). Curriculum development and teaching have been observed to improve graduate instructor methods of interaction with students, suggesting that the program engagement provides valuable pedagogical opportunities for our graduate trainees (Fig. 3E). The structure of this program also provides several unique opportunities for skill development. Curriculum is developed from the cutting edge of BME and is directly related to ongoing research at the IBBME. Although we cannot objectively delineate the reasoning for improved graduate student pedagogy, we feel that the enhanced opportunity for collaboration, translation of complex concepts, and comfort with students is valuable to achievement and enjoyment in teaching. This provides a strong opportunity for graduate students to directly translate the knowledge used in their own research. In Fall 2017, research translation in the context of *Discovery* was formally introduced as a project in a required IBBME graduate course. The outcomes of this project are detailed in “Knowledge Translation for

Biomedical Engineering Graduate Students", Biomedical Engineering Division of the 2018 ASEE Annual Meeting.

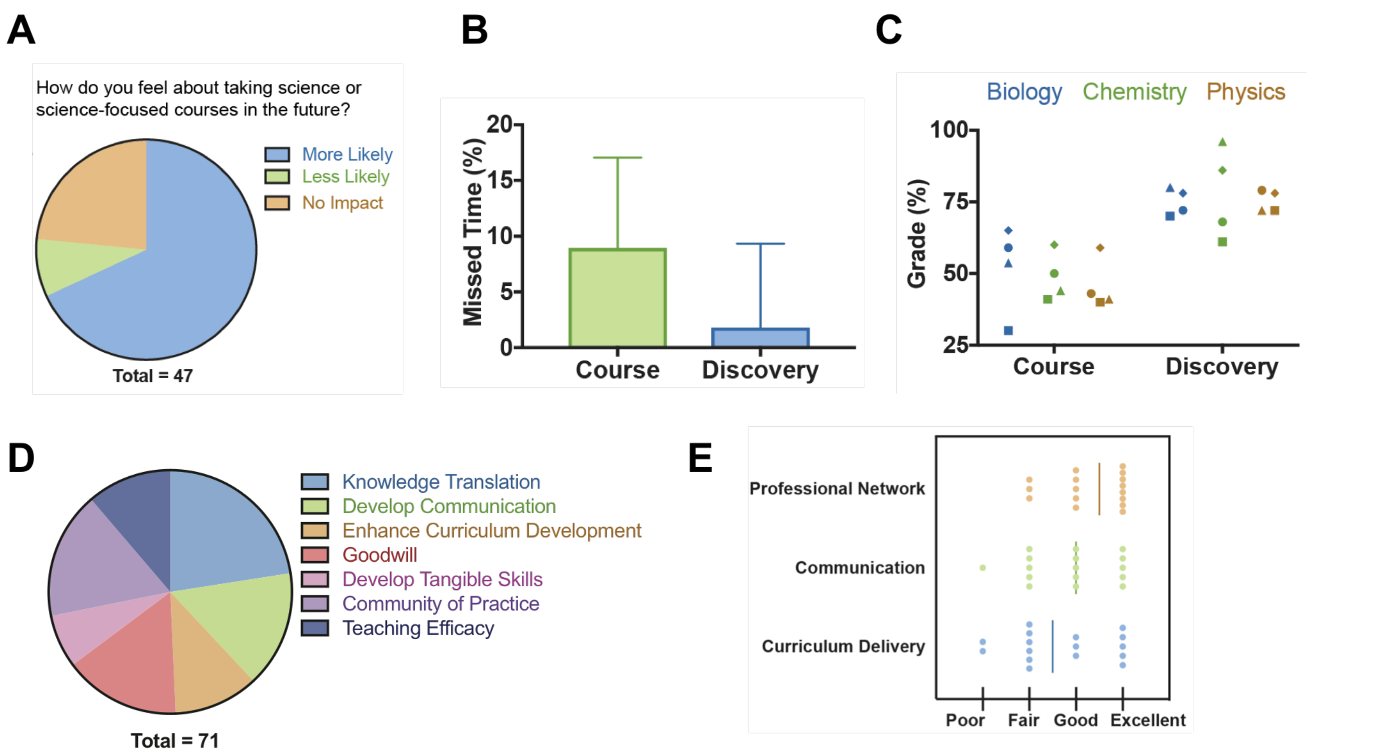

Figure 3: Pilot outcomes of *Discovery*. *(A) Exit survey results from participating high school students demonstrate ignition of curiosity and impact on future pursuit of STEM. (B) Averaged student attendance at Discovery sessions compared to typical attendance in the school classroom (n=57 students). (C) Academic benefit to immersive learning environment. For a student cohort, grades noticeably increased for Discovery deliverables compared to course average for lower achieving students (four sample selected by course; each symbol represents one student). (D-E) Impact on skill development for participating graduate student instructors. (D) Rationale for program involvement in context of skill development and (E) resultant personal perception of skill development.*

As the need for teaching stream faculty within the university environment continues to grow, there is a desire for opportunities to grow pedagogical skillsets within the graduate school experience. We observe meaningful improvement in the mentorship, communication, and teaching skills of participating graduate student instructors. Through collaboration, instructors gain insight into teaching methods from high school educators as they co-design and deliver various activities. We have observed strong two-way interaction in this regard, where instructors garner insight on methods of teaching while discussing the cutting edge in BME. We are excited to see this collaboration continue to grow, building a strong professional network to advance STEM education.

4.3 High school teachers

Through observation, there are multiple benefits for high school educators given the opportunity to engage pedagogically with their students in the university environment. First and foremost, teacher presence provides familiarity to the students, allowing them to productively immerse at the onset of each session. This method allows the teachers to extend their classroom pedagogy beyond normal classroom methods using newly-available resources in the post-secondary teaching facilities. Second to this, the teachers strongly benefit from collaboration and co-instruction with graduate instructors, who provide a direct link to modern technologies and up-to-date information in relevant STEM fields. This is impactful given that program content often exceeds outdated textbook information. As the students garner exposure to cutting edge research, methodology, and outcomes, the *Discovery* model necessitates teachers immerse themselves in background theory and formulate an understanding of the expected experimental outcomes each session. This model provides teachers with dynamic exposure to novel instrumentation, scientific process, and unfamiliar/less familiar topics. It is our expectation as we look to the future that we will observe the curriculum and teaching methods of these teachers to expand in their regular classroom environment. Teachers also recognize the opportunity to co-develop curriculum experiences that can have greater impact across the school board – methods that can be shared with their colleagues and reach a greater number of secondary STEM students.

Given the evolution of post-secondary education, *Discovery* provides real-time exposure to teachers so that they may better inform their students and shape expectations beyond high school. The iterative nature of the program promotes true teacher engagement and provides a mechanism to better prepare their students for the demanding realities of cutting-edge STEM careers. One of the most interesting outcomes to date has been the acknowledgement of participating teachers that *Discovery* has allowed them to view many students, often those categorized as being under-achieving, through a different lens. In these instances, teachers have demonstrated enthusiasm for the improved success of these students in all program deliverables compared to regular classroom outcomes. The teachers have consistently reiterated that although some students do not excel in the knowledge-based learning environment of the regular classroom, they often have the interest and ability to grasp the subject area when presented with an alternative learning environment, such as that provided by *Discovery*, and are already observing these outcomes (Fig. 3C).

The *Discovery* model thrives on multi-tiered collaboration between senior STEM educators, graduate students, and faculty alike, blurring the traditional divisive lines in education. The eagerness of involved parties, notably senior STEM educators, to participate in this model of challenging inquiry is a testament to the potential for inquiry-based learning to have beneficial outcomes to all involved parties. As we move forward with this model, it is exciting to consider the ease of program translation across teaching staffs and disciplines. It is our goal to reach and impact inquiry in STEM beyond the knowledge base, and overall these outcomes give us confidence in the ongoing development of this program.

5 Conclusions and Future Directions

With the motivation of stimulating passion and inquiry in STEM, rooted in the concepts of BME, University of Toronto graduate students and faculty have created *IBBME Discovery*. We have built a model of inquiry-based learning that supports the development of proper scientific method meanwhile demonstrating the cutting edge of biomedical engineering research. *Discovery* has had strong pilot success as measured by participating student academic performance and survey data. Further to this, the ongoing commitment of continued teacher engagement in the program is a strong indicator of the value from an educator's perspective. Strong student interest and participation have been observed to date, with an increased understanding and passion for BME. As we continue to focus on student outcomes, it is our expectation that student interest in STEM subjects will translate into their pursuit of science-based careers. The outcomes of this program are two-tiered given that graduate students are responsible for, and involved in, all aspects of program design, organization, and execution. This initiative provides valuable opportunities for graduate development of collaboration, communication, and curriculum design skills, as well as generating an internal community of practice. Holistically, this program is a novel approach to collaboration in facilitating inquiry-based education in STEM. In a multi-tiered approach, the execution of learning focused around the scientific method is valuable to skill development. We believe this will serve great value in future STEM pursuits, academic or otherwise, and see valuable in blurring the lines between levels of education in the forward progression of STEM education.

Moving forward and with strong support of the IBBME, we look to clearly outline the logistical, programming, and graduate student involvement aspects of the program. To do so, we have garnered ethical research approval from both University of Toronto and Toronto District School Boards. This will serve as a basis to quantitatively measure outcomes. The program has also received financial support of the Canadian federal government, National Science and Engineering Research Council (NSERC) PromoScience fund. Collectively, *Discovery* now has the capacity to expand programming and we will look to apply this model to multiple schools during each semester. The symposium will act as a conduit to bring students from different schools together during the program finale. Finally, as we move forward we look to more formally highlight and structure graduate student involvement in the program. To do so, we have preliminary approval to gather recognition for participation from the University of Toronto School of Graduate Studies Graduate Professional Skills (GPS) program. This will provide formal documentation in support of the outcomes we believe already exist in this program structure. We also believe that *Discovery* program structure can be adapted to many disciplines and are excited for the opportunity to allow inquiry-based learning in STEM to flourish.

6 Acknowledgements

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8 Appendix

Table A1: Description of personnel responsibilities in the organized deployment of *IBBME Discovery*

Position	**Roles and Responsibilities**
Faculty Supervisor	● Overarching program vision and progression ● Acquisition and administration of funding ● Liaison with IBBME director and high school/school board administrations in support of Graduate Student Head ● Correspond on research publication and ethical research approvals ● Oversee graduate student skill development and facilitation of graduate professional skills (GPS) designation
Graduate Student Head	● Overall supervision of program operation ● Liaison between involved high school staff, ensuring day to day operation of program, data collection and dissemination. ● Supports programming but does not directly liaison with subject leads unless needed, receives updates from the programming director. ● Focus is on big picture vision, data collection, and liaison with IBBME faculty and high school educators in ● Logistical coordination - food ordering, supply ordering and approvals ● Approval and input on overall semester theme and sub themes, gather and coordinate feedback from high school teachers and IBBME faculty
Programming Director	● Supervises the implementation of programming. ● Coordination of subject leads on program execution and a common logistical schedule. ● Serves as a liaison between the graduate student lead and programming, as well as a contact with programming staff in the teaching facilities. ● The administrative and program leads will commonly work together with soft definitions between each role, with common goal of big picture vision of consistent implementation.
Undergraduate Programs Assistant	● First contact to coordinate administration of the program on a departmental level. ● Coordination of budgets ● Initiating contact with external organizations, and coordination of communications.
Facility Staff	● Contacts for logistical and safety issues for their respective spaces. ● Direct contact is made with the programming director to organize and implement the space in preparation for student visits. ● Expect consistent updates from programming director as to the upcoming needs of the program.
Subject Leads	● These graduate students coordinate the subject specific project content for delivery to students. ● Development of activity design content, fit to the overall theme, and coordination of graduate student instructors within each subject area. ● These leads coordinate the direct interactions with students on site. ● Focus on assisting with setup, coordination, and take down of activities around student visits. ● These roles can be filled by different members semester-to-semester.
Grad Student Instructors	● Comprised of about 20 students, who change semester-to-semester. ● These members support in the delivery of curriculum content, interacting with visiting students to help with the implementation of their projects. ● Each student serves as a mentor to 1-2 student teams within a specific subject. Communication with high school students is conducted in person and electronically through Skype and Google Docs comments.
High School Teachers	● Engagement in program ideation with graduate instructors and IBBME faculty to ensure relevance to curriculum content; your engagement best represents your student interests to optimize concept delivery and learning outcomes; ● Development, delivery and assessment of student assignments in relation to *Discovery* hands-on curriculum; ● Use of aligned school class time work periods to maintain iterative discussion and learning; ● Logistical support in tracking student attendance, transportation, and parental consent for excursion and data collection; ● Coordination and responsibility of student behaviour, attendance, supervision, and safety while at IBBME ● Administration of student entrance and exit surveys, for IBBME assessment of student engagement and perceptions; ● Anonymization of completed surveys, and correlation with participating student grades and attendance, for sharing blinded out data with IBBME parties.

Table A2: Detailed description of semester milestones in chronological order. Blue boxes denote scheduled events, while red boxes denote virtual milestones (by email, teleconference, ad hoc meetings, etc.).

Milestone	**Detailed description**
Curriculum development	- The *Discovery* team works alongside the high school teachers to develop an overarching theme to link the three subgroups, chemistry, biology and physics. The team then prepares the experimental protocols, associated worksheets and program expectations for review by teachers.
Initial teacher meeting (only in the fall)	- The faculty supervisor and program executive meet with STEM teachers. Program curricula are finalized, and student numbers estimated for logistical purposes. An invitation to participate as a keynote speaker at the final symposium is sent to an IBBME faculty member whose research aligns with the selected theme.
Recruitment event (only in the fall)	- The program executive delivers a presentation on the history, goals, and program structure of *Discovery* to interested IBBME graduate students. An online form allows graduate student volunteers to sign up for program participation, identify their skill sets, indicate subject preferences, provide availability and receive regular communication from program leads.
Welcome meeting (only in the fall)	- The faculty supervisor formally welcomes volunteers to the program, and discusses volunteer responsibilities, incentives, and program structure throughout the semester. Subject leads consequently introduce their respective curricula and design project ideas. After the meeting, volunteers are formally assigned to a subject based on previously-identified skills and personal preferences.
Combined teacher/volunteer orientation	- Teachers and graduate student instructors undergo lab training during a formal half-day session administered by IBBME staff and subject leads. Lab safety training occurs prior to discussions related to student safe lab practice, as well as equipment and reagent use. All teachers and volunteers consequently engage in the Skill Lab protocol that will be provided to all high school student participants. Program executive and subject leads also provide details on the upcoming student visits during this session.
High School Classroom Introduction	- Because curriculum protocols and expectations are established before the start of the semester, teachers are able to introduce necessary concepts gradually, in advance of active student participation in *Discovery*. With graduate student instructors present to answer questions, teachers deliver an introductory lecture to participating students. The lecture is prepared in advance by teachers and graduate student instructors, and covers the basics of the BME challenge that will serve as the semester's theme, as well as subject-specific concepts that will be necessary for the upcoming Skill Lab.
Skill lab at IBBME	- Students visit IBBME for their first full day on-site visit, marking the official start to the program semester. Students receive lab safety training and participate in subject-specific introductory activities and lectures. Students must also complete a guided laboratory protocol (similar to an undergraduate laboratory session) that introduces relevant skills needed to complete the semester-long design project (e.g. pipetting, microscopy, cell culture, CAD drawing, mechanical testing, spectrophotometry, spreadsheet data analysis, etc.). - *Student deliverable:* A small assignment is to be completed after lab, incorporating relevant theory and experimental analysis. This assignment is assessed by the teachers. - *Educational outcome:* Students gain basic skills in laboratory technique and familiarity with the tools and environment with which to complete their projects.
Presentation of RFP	- Teachers introduce the subject-specific RFP to students during their regular class. Students are divided into groups and begin preparation of their proposal to address the challenge posed. - *Student deliverable:* Students must complete a first and second draft of their proposal. Teachers provide feedback on the first draft while the second draft is submitted to IBBME graduate student instructor for electronic review. - *Educational outcome:* Students will be alerted to any major issues in their proposal, and be able to identify key components of the proposal-crafting process, including: ● A focused review of relevant literature; ● Identification of the current state of the art and directions of advancement; ● Iterative design of an experiment by all group members and stakeholders; ● Generation of a clear objective & hypothesis; ● The value of a step-by-step protocol to evaluate potential challenges and workarounds; ● The pre-identification of clear metrics by which to interpret results.
Client Meeting (1-2 weeks following RFP release)	- IBBME graduate student instructors ("clients") meet with the students in person or by Skype ("client meeting") to review student-developed proposals and address any questions the students might have on the electronic feedback they received on their second RFP draft. *Student deliverable:* Students must present their completed proposal to the client and be able to justify their timeline, resource use, and proposal targets. *Educational outcome:* Client provides feedback on in-lab feasibility, soundness and completeness of protocol. Students are encouraged to consider the capacity for their protocol to generate quantitative and qualitative data for analysis as well as formulation of a final recommendation.

IBBME experimental visit 1	- Students will begin on-campus hands-on experimentation aligning with their proposals. Graduate instructors will be available for assistance and oversight. - *Student deliverable:* Students must prepare a preliminary report and revised plan to complete data collection and analysis/interpretation within the time available in the next experimental visit. - *Educational outcome:* Students make progress in their designs, data collections, and/or analyses. More importantly, students will assess the soundness and completeness of their protocols *in situ* and adapt their proposals accordingly. Students undergo the practice of scientific iteration, reviewing their data and adapting their experiment for the next lab visit.
IBBME experimental visit 2	- Students finish carrying out their experimental proposals and begin analysis and interpretation of collected data. Symposium poster design, content, and presentation delivery is discussed with the graduate student instructors. - *Student deliverable:* Students should be able to provide a completed data set, a final recommendation addressing the RFP, and a presentation-quality scientific poster. Students also submit a final report to their teachers. - *Educational outcome:* Students gain experience in data analysis and interpretation from an experiential data set to provide a final, concrete recommendation to their client regarding the initial challenge posed. Students also gain communication in designing a clear, concise, and engaging poster.
IBBME Discovery Symposium	Students disseminate their experimental procedures and outcomes by presenting a scientific poster. BME undergraduate and graduate students participate to judge and provide constructive feedback, allowing for non-biased determination of the best presentations. Teachers concomitantly assign student marks for poster content and overall delivery. A professor from IBBME whose research aligns with the overall semester program theme delivers a short keynote address, and awards are given for the best presentations. Following all student presentations, a lunchtime panel of undergraduate and graduate BME students discuss their experiences in postsecondary education including admissions, university life, research opportunities, and BME/STEM career outlooks. Students complete their day with a campus tour. - *Student deliverable:* Students disseminate their experimental procedures and results as scientific poster presentations and are assessed by IBBME (feedback and ranking) and teachers (grades). - *Educational outcome:* Students gain presentation skills, learn about post-secondary and career opportunities in STEM/BME, and experience firsthand an important form of academic communication (the scientific meeting).
Debriefing	- After the formal events of the semester have been completed, the *Discovery* program undergoes a thorough debriefing process. The faculty supervisor and program executive seek feedback and suggestions for improvement from all stakeholders (students, teachers, graduate student instructors, undergraduate students, IBBME faculty and staff). The program structure, strategy, personnel, and budget are assessed for continued improvements.