Enhancing senior high school student engagement and academic performance using an inclusive and scalable inquiry-based program

Locke Davenport Huyer[1,2,¶], Neal I. Callaghan[1,3,¶], Sara Dicks[4], Edward Scherer[4], Andrey I. Shukalyuk[1], Margaret Jou[4], and Dawn M. Kilkenny[1*]

[1]Institute of Biomaterials and Biomedical Engineering, University of Toronto, Toronto, Ontario, Canada

[2]Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario, Canada

[3]Translational Biology and Engineering Program, Ted Rogers Centre for Heart Research, University of Toronto, Toronto, Ontario, Canada

[4]George Harvey Collegiate Institute, Toronto District School Board, Toronto, Ontario, Canada

¶ These authors contributed equally to this work

*Corresponding author:

Email: dawn.kilkenny@utoronto.ca

Short title: A scalable inquiry-based program for high school STEM students

Summary: An educational program introducing high school STEM students to iterative design, controlled failure, and the experimental method enhanced student engagement, performance, and perceptions of STEM education and careers.

Abstract

The multi-disciplinary nature of science, technology, engineering and math (STEM) careers often renders difficulty for high school students navigating from classroom knowledge to post-secondary pursuits. Discrepancies between the knowledge-based high school learning approach and the experiential approach of undergraduate studies leaves some students disillusioned by STEM. We present *Discovery*, an inquiry-focused learning model delivered by STEM graduate students in collaboration with high school educators, in the context of biomedical engineering. High school STEM students of diverse cultural and socioeconomic backgrounds engaged in iterative, problem-based learning designed to emphasize critical thinking in an iterative manner within the secondary school and university environments. Assessment of grades and survey data suggested positive impact on students' STEM pursuits, notably in under-performing and repeating student cohorts. *Discovery* presents a scalable platform blurring the divide between secondary and post-secondary learning, providing valuable learning opportunities and capturing cohorts of students that might otherwise be under-engaged in STEM.

1 Introduction

High school students with diverse STEM interests considering post-secondary options are often challenged by a limited understanding of the multi-disciplinary nature of many careers, such as the vast array of health-care related opportunities. The rapidly growing field of biomedical engineering (BME) is appealing because one can integrate fundamental concepts from electrical, mechanical, and chemical engineering into biology-based disciplines such as medicine and the life sciences; these options are attractive to high school students who are enthusiastic to have impact in the field of health care, particularly if given sufficient introduction and exposure (1). However, there is known discrepancy between the knowledge-based learning approach common in high schools and the experiential, mastery-based approaches afforded by the undergraduate model (2). In the latter, focused classes, interdisciplinary concepts, and laboratory experiences allow for the application of accumulated knowledge, practice with problem solving, and development of both general and technical skills (3). Such immersive cooperative learning environments are difficult to establish in the secondary school setting and many high school educators struggle to implement within their classroom (4). As such, high school students may become disillusioned with STEM before graduation and never experience an enriched learning environment, despite their inherent interests in STEM. This may also be reflected in pursuit of a post-secondary program other than BME, given the inability to develop a diverse array of knowledge and skills across STEM disciplines (5).

Early introduction to varied math and science disciplines throughout high school is vital if students are to pursue STEM fields, especially within engineering (6). In the context of STEM education and career choices, student self-efficacy regarding research skills has been shown to predict 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). It is suggested that high school students, when given opportunity and support, are capable of successfully completing rigorous programs at STEM focused schools (9). However, alternate studies have shown no significant differences in participation rates in advanced sciences and mathematics for these students compared to their peers at non-STEM focused schools (10). In fact, Brown *et al* studied the relationships between STEM curriculum and student attitudes, and found the latter played a more important role in intention to persist in STEM when compared to self-efficacy (11). Therefore, creation and delivery of modern and exciting curriculum is fundamental to engage and retain students.

Many public institutions support the idea that post-secondary led engineering education programs are effective ways to expose high school students to engineering education and relevant career options, and also increase engineering awareness (12) . Although singular class field trips are used extensively to accomplish such programs, these may not allow immersive experiences for application of knowledge and practice of skills that are proven to impact long-term learning and influence career choices (13, 14). Longer-term immersive research experiences, such as after-school programs or summer camps, have shown successful at recruiting students into STEM degree programs and careers, where longevity of experience helps foster self-determination, and interest-led, inquiry-based projects (3, 7, 15-17). Such activities convey the elements that are suggested to make an post-secondary led high school education program successful: hands-on experience, self-motivated learning, real-life application, immediate feedback, and problem-based projects (18, 19).

Supported by the outcomes of the identified effective program strategies and in collaboration with science educators from George Harvey Collegiate Institute (Toronto District School Board), graduate student instructors at the Institute of Biomaterials and Biomedical Engineering (IBBME; University of Toronto) have developed and launched *Discovery*, a collaborative high school science education program that stimulates application of STEM concepts within a unique semester-long applied curriculum delivered iteratively within both IBBME undergraduate teaching facilities and collaborating high school classrooms (20). The opportunity for high school student participants to work in university biomedical teaching facilities supports the concept that learning will be authentic and relevant, and consequently representative of an experience found in actual STEM practice (21). Importantly, *Discovery* allows all students within a class cohort to work together with their classroom educator, stimulating continued development of a relevant learning community that is deemed essential for meaningful context, and important for transforming student perspectives and understandings (22, 23). Multiple studies have supported that relevant learning communities improve student attitudes towards learning, significantly increasing student motivation in STEM courses, and consequently improving the overall learning experience (24). Learning communities, such as that provided by *Discovery*, also promote the formation of self-supporting groups, greater active involvement in class, and higher persistence rates for participating students (25).

Through its structure and dissemination strategy, the objective of *Discovery* is to provide class cohorts of senior high school science students with opportunities to engage in challenging, inquiry-based practical BME activities as a mechanism to stimulate comprehension of STEM curriculum application to real world concepts. The program is founded in the objective of critical thinking skill development through an atmosphere of perseverance in ambiguity, an atmosphere that is not common in a secondary school knowledge focused delivery but highly relevant in post-secondary STEM education strategies. Herein, we describe the observed impact of this differential project-based learning environment on student performance and engagement. We specifically hypothesize that value of an inquiry-focused model is tangible for students that struggle in a knowledge focused delivery structure, where engagement in conceptual critical thinking in the relevant subject area stimulates student interest and resulting academic performance. Assessment of these outcomes suggests that when provided with a differential learning opportunity, the performance of these students increased as they engaged more thoroughly in STEM subject matter. Consequently, *Discovery* provides a framework to the potential efficacy of the model for scalable application in bridging the gap in critical thinking and problem solving between secondary and post-secondary education.

2 Results

2.1 Program Delivery

The outcomes of the current study result from execution of *Discovery* over three independent academic terms as a collaboration between IBBME (graduate students, faculty, and support staff) and George Harvey Collegiate Institute (science educators and administration) stakeholders. Each term, the program allowed secondary STEM students opportunity to engage in a novel project-based learning environment with a biomedical engineering focus. The program structure uses the engineering capstone framework as a tool of inquiry-focused learning objectives, motivated by a central biomedical engineering field with research questions that are inter-related but subject-specific to STEM curriculum of the class cohort (**Fig 1**). Over each 12-week term, students worked in teams (3-4 students) within their class cohorts to execute projects with the guidance of graduate student instructors (*clients*) and their high school educators. Student experimental work was conducted in IBBME teaching facilities relevant to the research study of interest (i.e., Biology- and Chemistry-based projects held within the Undergraduate Teaching Laboratory; Physics projects held within the Undergraduate Design Studio). Students were introduced to relevant techniques and safety procedures in advance of iterative experimentation. Importantly, this served as a course term project for students, who were assessed at several points throughout the program for their performance in an inquiry-focused environment, as well as within their regular classroom (**Fig 1; S3 Appendix III**). To instill the atmosphere of STEM, student teams delivered their outcomes in research poster format at a symposium, sharing their results and recommendations with other post-secondary students, faculty, and community in an open environment. An exemplary term of student programming can be found in **S1 Appendix I**.

Over the course of three semesters there were 159 instances of tracked student participation, representing 105 individual students. More specifically, 61 students participated during only one semester, 36 students participated in two semesters, and 9 students participating during all three semesters. Multiple points of participation represent students that enrol in more than one STEM class during their senior years of high school, or who have participated in Grade 11 and subsequently in Grade 12. All assessments were performed by high school educators for their respective STEM class cohorts using consistent grading rubrics and assignment structure (summarized in **S3 Appendix III**). Here, we discuss the outcomes of student involvement in this model.

2.2 Student performance and engagement

Student grades were assigned, collected and anonymized by educators for each *Discovery* deliverable. Educators also anonymized collective *Discovery* grades and final course grades for study comparative purposes. Overall, no significant correlation ($p = 0.37$) was observed between the grade representing combined *Discovery* deliverables and the final course grade (**Fig 2A**). However, further examination of the full dataset revealed two student cohorts of interest: the "Exceeds Expectations" (EE) subset (defined as those who achieved a ≥15% grade differential in *Discovery* over their final course grade (N=67 instances); and the "Multiple Term" (MT) subset (45 individual students) who participated in *Discovery* more than once (**Fig 2B&C**). These subsets were not unrelated; 31 individual students who had multiple experiences (68.9% of total MTs) exhibited at least one occasion in achieving a ≥15% grade differential. In total across all semesters, 96% of the MT cohort demonstrated a ≥15% grade differential (43 instances). As students participated in group work, there was concern that lower-performing students might negatively influence the *Discovery* grade of higher-performing students (or vice versa). However, students were observed to self-organize into groups where all individuals received similar final overall course grades (**Fig 2D**), thereby alleviating these concerns. In addition, students demonstrated excellent *Discovery* attendance; at least 93% of participants attended all *Discovery* sessions in a given semester (**Fig 2E**). In contrast, class attendance rates reveal a much wider distribution, where 57 out of 159 (35.8%) students missed 10 or more classes in a semester (**Fig 2F**).

Discovery EE students (**Fig 3A-G; I**) exhibited grades significantly higher than classmates in every category except overall course grade, where they performed to a significantly lower degree (**Fig 3H**). Notably, the difference in final course grade would be larger if the inclusion of *Discovery* deliverables was omitted. Interesting, these students exhibited significantly (p = 0.049) lower classroom attendance (**Fig 3J&K**). There was only a single day absence in *Discovery* within the EE subset; however, this difference was not statistically significant (p = 0.081).

Discovery MT students (**Fig 4A-C; E-I**) were observed to obtain higher final *Discovery* grades than students participating in the program only one time (p = 0.027); however, no individual assignment or course grade (p = 0.33) was significantly different with the exception of the progress report (p = 0.049; **Fig 4D**). Attendance in class (p = 0.65) or *Discovery* (p = 0.45) was not significantly different between MT and non-MT students (**Fig 4J&K**).

2.3 Educator Perceptions

Qualitative observation in the classroom by high school educators emphasized the value students independently placed on program participation and deliverables. Throughout the term, students often prioritized *Discovery* group assignments over other tasks for their STEM courses, regardless of academic weight and/or due date. Comparing within this student population, educators spoke of difficulties with late and incomplete assignments in the regular curriculum but found very few such instances with respect to *Discovery*-associated deliverables. This is demonstrated by the number of incomplete assignments over the course of this study: 35 of 785 (4.4%) instances with *Discovery* deliverables compared to 326 of 3412 (9.6%) in other assignment deliverables that students were responsible for during the study period. Further, educators speculated on the good behaviour and focus of students in *Discovery* programming in contrast to attentiveness and behaviour issues in their school classrooms. Multiple anecdotal examples were shared of renewed perception of student potential; students that exhibited poor academic performance in the classroom often engaged with high performance in this inquiry-focused atmosphere. Students appeared to take a sense of ownership, excitement and pride in the setting of group projects oriented around scientific inquiry, discovery, and dissemination.

2.4 Student Perceptions

Students were asked to consider and rank the academic difficulty (scale of 1-5, with 1 = not challenging and 5 = highly challenging) of the work they conducted within the *Discovery* learning model. Considering individual *Discovery* terms, at least 85% of students felt the curriculum to be sufficiently challenging with a 3/5 or higher ranking (Term 1: 87.5%, Term 2: 93.4%, Term 3: 85%), and a minimum of 58% of students indicating a 4/5 or higher ranking(Term 1: 58.3%, Term 2: 70.5%, Term 3: 67.5%) (**Fig 5A**).

When surveyed at the end of term, 88% of students indicated they would participate in the program again (**Fig 5B**). With exposure to university teaching facilities, 96% of students indicated they felt more comfortable with the idea of performing future work in a similar university STEM laboratory environment (**Fig 5C**). Students were also queried whether they were i) more likely, ii) less likely, or iii) not impacted by their experience in the pursuit of STEM in the future. The majority of participants (> 85%) perceived impact on STEM interests, with 77% indicating they were more likely to pursue these interests in the future (**Fig 5D**).

3 Discussion

We have described an inquiry-based framework for implementing STEM education in a biomedical engineering setting. Using this model, we engaged 105 students over three terms in project-based learning wherein students worked in peer-based teams under the mentorship of BME graduate students to design and execute the scientific method in answering a relevant research question. Collaboration between high school educators and graduate student instructors allowed for high school student exposure to cutting edge BME research topics, participation in facilitated inquiry, and acquisition of knowledge through scientific discovery. All assessments were conducted by high school educators and constituted a fraction (10-15%) of the overall course grade, instilling academic value for participating students. As such, students exhibited excitement to learn as well as commitment to their studies in the program.

Through our observations and analysis, it is suggested there is value in differing learning environments for students that struggle in a knowledge acquisition-focused classroom setting. In general, we observed a high level of academic performance in *Discovery* programming (**Fig 2A**). This was highlighted exceptionally in EE students, with greater academic performance observed in *Discovery* deliverables compared to normal coursework (> 15% grade improvement in relevant deliverables). We initially considered whether this was the result of strong students influencing weaker students; however, group organization within each course suggests this is not the case (**Fig 2**). With the exception of one class in one semester, students were allowed to self-organize into working groups, and they chose to work with other students of relatively similar academic performance (as indicated by course grade), a trend observed in other studies (26, 27). Remarkably, EE students not only excelled during *Discovery* when compared to their own performance in class, but this cohort also achieved significantly higher average grades in each of the deliverables throughout the program (**Fig 3**) when compared to the remaining *Discovery* cohort. This data demonstrates the value of an inquiry-based learning environment, compared to knowledge focused delivery in the classroom, in allowing students to excel. These data align with the well-supported concept that students who struggle in traditional settings tend to demonstrate improved interest and motivation in STEM when given opportunity to interact in a hands-on fashion (3, 28). Furthermore, these outcomes clearly represent variable student learning styles, where some students benefit from a greater exchange of information, knowledge and skills in a cooperative learning environment (29). The performance of the EE group may not be by itself surprising, as the identification of the subset by definition required high performers in *Discovery* who did not have exceptionally high course grades; in addition, the final *Discovery* grade is dependent on the component assignment grades. However, the discrepancies between EE and non-EE groups in both attendance categories suggests that students were engaged by *Discovery* in a way that they were not by regular classroom curriculum.

When we consider attendance of EE students compared to those with a consistent grade, differences in engagement are further exemplified (**Fig 3J&K**). Given the differences in number of *Discovery* days and implications of missing one day of regular class compared to this immersive program, attendance data cannot be directly compared. However, when combined with other subjective data including student focus, requests to work on *Discovery* during class time, and lack of discipline/behaviour issues, the attendance data importantly suggests that students were especially engaged by the *Discovery* model. Further, we believe the increased commute time to the university campus (students are responsible for independent transit to campus, a longer endeavour than the normal school commute), early program start time, and students' lack of familiarity with the location are non-trivial considerations when determining the propensity of students to participate enthusiastically in *Discovery*. Students that outperform in *Discovery* relative to their class grades tend to miss more school days than their peers; however, this trend is not carried forward to *Discovery* programming. We feel this suggests the students place value on this team-focused learning, and find this learning to be more applicable and meaningful to their interests.

The MT group was composed of students who participated in *Discovery* for more than one semester, without distinction as to the number or order of such semesters. MT students averaged significantly higher final *Discovery* grades, but not final course grades. The increase in the final *Discovery* grade seemed to result from a general confluence of improved performance over multiple deliverables; a continuous effort to improve in a STEM curriculum. Given post-secondary admission requirements for STEM programs, it would be prudent to think that students participating in multiple STEM classes across semesters are the ones with the most inherent interest in post-secondary STEM programs. Similarly, the high number of MT students who were included in the EE group suggests that students who had a keen interest in science took more than one course, and in general responded well to the inquiry-based teaching method of *Discovery*, where scientific method was put into action. It stands to reason that even if they do not do well in their specific course, students interested in science will continue to take science courses and will respond favourably to opportunities to put class materials to practical application.

The true value of an inquiry-based program such as *Discovery* may not be based in inspiring students to perform at a higher standard in STEM within the high school setting, as skills in critical thinking do not necessarily translate to knowledge-based assessment. Notably, students found the programming equally challenging throughout each of the sequential sessions; interestingly, there were more MT students in session 2 and 3, *respectively* (**Fig 5A**). Regardless of sub-section, there was an emphasis of perceived value demonstrated through student surveys where we observed indicated interest in STEM and comfort with laboratory work environments, and desire to return to future iterations given the opportunity. Although non-quantitative, we perceive this as an indicator of significant student engagement, even though some participants did not yield academic success in the program and found it highly challenging given its ambiguity. Further, we observed that students become more certain of their direction in STEM, correlating with preliminary trends of increased post-secondary application rates by *Discovery* graduates (data not shown); further study is warranted to make claim of this result. At this point in our assessment we cannot effectively assess longitudinal improvement as a result of this model, and suggest that the immediate effects observed are subject to a number of factors associated with performance in the high school learning environment. Altogether, a multifaceted assessment of our early outcomes suggests significant value of an immersive and iterative interaction with STEM as part of the high school experience. A well-defined divergence from knowledge-based learning, focused on engagement in critical thinking development framed in the cutting-edge of STEM, may be an important step to broadening student perspectives.

As we consider *Discovery* in a bigger picture context, expansion and implementation of this model is translatable. Execution of the scientific method is an important aspect of citizen science, as the concepts of critical thing become ever-more important in a landscape of changing technological landscapes. Giving students critical thinking and problem-solving skills in their primary and secondary education provides value in the context of any career path. Further, we feel that this model is scalable across disciplines, STEM or otherwise, as a means of building the tools of inquiry. We have observed here the value of differential student engagement and critical thinking through an inquiry-focused model for a subset of students, but further to this an engagement, interest and excitement across the body of student participants. As we educate the leaders of tomorrow, we suggest use of an inquiry-focused model such as *Discovery* could facilitate growth of a data-driven critical thinking framework.

4 Methods

4.1 Experimental Design

All students in university-stream Grade 11 or 12 biology, chemistry, or physics at the participating school were recruited into mandatory offerings of *Discovery* over three consecutive terms. Student grade and survey responses were collected after parent or guardian permission. Student names were replaced by educators with a unique coded identifier to preserve anonymity, but enable individual student tracking over multiple terms. All data collected was analyzed without any exclusions save for missing survey responses; no power analysis was performed prior to data collection.

4.2 Ethics statement

This study was approved by the University of Toronto Health Sciences Research Ethics Board (Protocol # 34825) and the Toronto District School Board External Research Review Committee (Protocol # 2017-2018-20). Collection of student data (both post-hoc academic data and survey administration) was collected following written informed consent of data collection from parents or guardians of participating students. Data was anonymized by high school educators for maintenance of academic confidentiality.

4.3 Program overview

IBBME graduate students created *Discovery* to develop a comfortable yet stimulating environment of inquiry-focused iterative learning for senior high school students. A selected global health research topic was sub-divided into subject-specific research questions (i.e., Biology, Chemistry, Physics) that students worked to address, both on-campus and in-class, during a term-long project. The *Discovery* framework therefore provides students the experience of an engineering capstone design project, and includes a motivating scientific problem (i.e., global topic), a discipline-specific research question, and systematic determination of a professional recommendation addressing the needs of the presented problem.

4.3.1 High school partner

The *Discovery* program evolved to the current model over a two-year period of working with one high school selected from the local public school board. This partner school consistently scores highly (top decile) in the board's Learning Opportunities Index (LOI). The LOI ranks each school based on measures of external challenges affecting student success, therefore schools with the greatest level of external challenges receive a higher ranking (30). Consequently, participating students are identified as having a significant number of external challenges that may affect their academic success. In addition, the selected school partner is located within a reasonable geographical radius of our campus (i.e., ~ 40 min transit time from school to campus). This is relevant as participating students are required to independently commute to campus for "*Discovery* Days" of hands-on activity.

4.3.2 Student recruitment

In agreement with school administration and science educators, *Discovery* was incorporated as a mandatory component of course curriculum for senior students (Grade 11 and 12) in university stream Chemistry, Physics, and Biology courses. Students therefore participated as class cohorts to address questions specific to their course discipline knowledge base, but relating to the defined global health research topic (**Fig 1**). At the discretion of each STEM teacher, assessment of program deliverables was collectively assigned as 10-15% of the final course grade for each subject. All students were required to participate; however, students were given opportunity to opt out the research study aspect of this program and parent/guardian consent was required for student data to be collected and collated for research purposes.

4.3.3 Instructional framework

Each program term of *Discovery* corresponds with a five-month high school semester. IBBME graduate students and high school educators worked collaboratively to define a global healthcare theme in advance of each semester. In addition, specific cutting-edge and curriculum-relevant research questions were developed for each discipline to align within both the overall theme and the educational outcomes set by the provincial curriculum (31). IBBME graduate student instructors were consequently responsible for developing and introducing relevant STEM skills, as well as mentoring high school students, for the duration of their projects; high school educators were responsible for academic assessment of all program deliverables throughout the term (**Fig 1**).

During the course of a term, students engaged within the university facilities four times. The first three sessions included hands-on lab sessions while the fourth visit included a culminating symposium for students to present their scientific findings (**Fig 1**). Project execution was supported by graduate student instructors who acted as engineering "clients" to mentor student groups in developing and improving their assessment protocols, as well as generate final recommendations to the overarching original questions. On average, there were 4-5 groups of students per discipline (3-4 students per group; ~20 students/class). Graduate instructors worked exclusively with 1-2 groups each term in the capacity of mentor to monitor and guide student progress.

After introducing the selected global research topic in class, educators led students in completion of background research essays. Students subsequently engaged in a discipline-relevant skill-building protocol during their first visit to university teaching laboratory facilities, allowing opportunity to understand analysis techniques and equipment relevant for their assessment projects. At completion of this session, student groups were presented with a discipline-specific research question as well as the laboratory inventory available for use during their projects. Armed with this information, students groups continued to work in their classroom setting to develop group-specific experimental plans. Educators and graduate instructors provided written and oral feedback, *respectively*, allowing students an opportunity to revise their plans in class prior to on-campus experimental execution. Once at the relevant laboratory environment, students executed their protocols in an effort to collect experimental data. Data analysis was performed in the classroom, and students learned by trial & error to optimize their protocols before returning to the university lab for a second opportunity to collect data. All methods and data were re-analyzed in class in order for students to create a scientific poster for the purpose of study/experience dissemination. During a final visit to campus, all groups presented their findings at a research symposium, allowing students to verbally defend their process, analyses, interpretations, and design recommendations to a diverse audience including peers, STEM educators, undergraduate and graduate university students, and IBBME faculty.

4.3.4 Data collection

Educators evaluated students within their classes on the following associated deliverables: i) global theme background research essay; ii) experimental plan; iii) progress report; iv) final poster content and presentation; and v) attendance. For research purposes, these grades were examined individually and also as a collective *Discovery* program grade. For students consenting to participation in the research study, all *Discovery* grades were anonymized by the classroom educator before being shared with study authors. Each student was assigned a code (known only to the classroom educator) for direct comparison of deliverable outcomes as well as survey responses.

Survey instruments were used to gain insight into student perceptions of STEM and post-secondary study, as well as *Discovery* program experience and impact (**S2 Appendix II**). High school educators administered surveys in the classroom only to students supported by parental permission . Pre-program surveys were completed at minimum one week prior to program initiation each term, and exit surveys were completed at maximum two weeks post-*Discovery* term completion.

4.4 Identification and comparison of population subsets

From initial analysis, we identified two student subpopulations of particular interest: students who performed 15% or greater in the *Discovery* portion of the course compared to their final course grade ("EE"), and students who participated in *Discovery* more than once ("MT"). These groups were compared individually against the rest of the respective *Discovery* population ("non-EE" and "non-MT", *respectively*). As we did not see a significant correlation between number of *Discovery* sessions attended and student performance, and because students could switch between subjects in which they show more or less aptitude, we did not stratify instances of student participation in *Discovery* by an individual's previous participation. Comparisons were made for all *Discovery* deliverables (introductory essay, client meeting, proposal, progress report, poster, and presentation), final *Discovery* grade, final course grade, the *Discovery*-course grade differential, *Discovery* attendance, and overall class attendance.

4.5 Statistical analysis

Student performance (N=159 total students, comprising 105 individuals) in *Discovery* was initially assessed in a linear regression of *Discovery* grade vs. final course grade. For subpopulation analysis (EE and MT, N=67 and 45 *respectively*), each data set was tested for normality using the D'Agostino and Pearson omnibus normality test. Only the MT vs. non-MT final course grade data, which were normally distributed, were compared using the two-tailed Student's T-test. All other comparisons were performed by Mann-Whitney U-test. Significance was set at $\alpha < 0.05$. Data are plotted as individual points with mean ± SEM overlaid (grades), or in histogram bins of 1 and 5 respectively for *Discovery* and class attendance. Significance was set at $\alpha \leq 0.05$.

5 References

1. Rebecca W. Biomedical Engineering Projects: Integrating Outreach Into Engineering Education. 2007/06/24; Honolulu, Hawaii: ASEE Conferences.
2. Gilmore MW. Improvement of STEM education: Experiential learning is the key. Modern Chemistry & Applications. 2013.
3. Roberts T, Jackson C, Mohr-Schroeder MJ, Bush SB, Maiorca C, Cavalcanti M, et al. Students' perceptions of STEM learning after participating in a summer informal learning experience. International journal of STEM education. 2018;5(1):35.
4. Gillies RM, Boyle M. Teachers' reflections on cooperative learning: Issues of implementation. Teaching and teacher Education. 2010;26(4):933-40.
5. Nasir M, Seta J, Meyer E, editors. Introducing high school students to biomedical engineering through summer camps. Proc ASEE Annual Conference, 2014a, Indianapolis, IN; 2014.
6. Sadler PM, Sonnert G, Hazari Z, Tai R. Stability and volatility of STEM career interest in high school: A gender study. Science Education. 2012;96(3):411-27.
7. Adedokun OA, Bessenbacher AB, Parker LC, Kirkham LL, Burgess WD. Research skills and STEM undergraduate research students' aspirations for research careers: Mediating effects of research self-efficacy. Journal of Research in Science Teaching. 2013;50(8):940-51.

8. Bandura A, Barbaranelli C, Caprara GV, Pastorelli C. Self-Efficacy Beliefs as Shapers of Children's Aspirations and Career Trajectories. Child Development. 2001;72(1):187-206.
9. Scott C. An investigation of science, technology, engineering and mathematics (STEM) focused high schools in the US. Journal of STEM Education: Innovations and Research. 2012;13(5):30.
10. Wiswall M, Stiefel L, Schwartz AE, Boccardo J. Does attending a STEM high school improve student performance? Evidence from New York City. Economics of Education Review. 2014;40:93-105.
11. Brown PL, Concannon JP, Marx D, Donaldson CW, Black A. An Examination of Middle School Students' STEM Self-Efficacy with Relation to Interest and Perceptions of STEM. Journal of STEM Education: Innovations & Research. 2016;17(3).
12. Anthony AB, Greene H, Post PE, Parkhurst A, Zhan X. Preparing university students to lead K-12 engineering outreach programmes: a design experiment. European Journal of Engineering Education. 2016;41(6):623-37.
13. Brown JS, Collins A, Duguid P. Situated cognition and the culture of learning. Educational researcher. 1989;18(1):32-42.
14. Reveles JM, Brown BA. Contextual shifting: Teachers emphasizing students' academic identity to promote scientific literacy. Science Education. 2008;92(6):1015-41.
15. Boekaerts M. Self-regulated learning: A new concept embraced by researchers, policy makers, educators, teachers, and students. Learning and instruction. 1997;7(2):161-86.
16. Honey M, Pearson G, Schweingruber H. STEM integration in K-12 education: Status, prospects, and an agenda for research: National Academies Press Washington, DC; 2014.
17. Moote JK, Williams JM, Sproule J. When students take control: Investigating the impact of the crest inquiry-based learning program on self-regulated processes and related motivations in young science students. Journal of Cognitive Education and Psychology. 2013;12(2):178-96.
18. Fantz TD, Siller TJ, Demiranda MA. Pre-collegiate factors influencing the self-efficacy of engineering students. Journal of Engineering Education. 2011;100(3):604-23.
19. Ralston PA, Hieb JL, Rivoli G. Partnerships and experience in building STEM pipelines. Journal of Professional Issues in Engineering Education and Practice. 2012;139(2):156-62.
20. Huyer MLD, Callaghan NI, Saab R, Smieja D, Effat MA, Kilkenny DM. IBBME Discovery: Biomedical Engineering-based Iterative Learning in a High School STEM Curriculum (Evaluation).

21. Kelley TR, Knowles JG. A conceptual framework for integrated STEM education. International Journal of STEM Education. 2016;3(1):11.
22. Johri A, Olds BM. Situated engineering learning: Bridging engineering education research and the learning sciences. Journal of Engineering Education. 2011;100(1):151-85.
23. O'Connell KB, Keys B, Storksdieck M. Taking Stock of Oregon STEM Hubs: Accomplishments and Challenges. 2017.
24. Freeman KE, Alston ST, Winborne DG. Do Learning Communities Enhance the Quality of Students' Learning and Motivation in STEM? The Journal of Negro Education. 2008:227-40.
25. Weaver RR, Qi J. Classroom organization and participation: College students' perceptions. The Journal of Higher Education. 2005;76(5):570-601.
26. Chapman KJ, Meuter M, Toy D, Wright L. Can’t we pick our own groups? The influence of group selection method on group dynamics and outcomes. Journal of Management Education. 2006;30(4):557-69.
27. Hassaskhah J, Mozaffari H. The impact of group formation method (student-selected vs. teacher-assigned) on group dynamics and group outcome in EFL creative writing. Journal of Language Teaching and Research. 2015;6(1):147-56.
28. Ma VJ, Ma X. A comparative analysis of the relationship between learning styles and mathematics performance. International Journal of STEM Education. 2014;1(1):3.
29. Weinstein CE, Hume LM. Study strategies for lifelong learning: American Psychological Association; 1998.
30. Board TDS. The 2017 Learning Opportunities Index: Questions and Answers. 2017.
31. The Ontario Curriculum Grades 11 and 12: Science. 2008.

6 Acknowledgements

The authors would like to acknowledge the support of the many graduate student volunteers from the Institute of Biomaterials and Biomedical Engineering for their countless hours in program planning and execution. In particular, members of the executive organizing team that have assisted study authors with curriculum development to date include Genevieve Conant, Sherif Ramadan, Daniel Smieja, Rami Saab, Andrew Effat, Serena Mandla, Cindy Bui, Janice Wong, Dawn Bannerman, Allison Clement and Shouka Parvin Nejad. We further acknowledge the staff of the science department at George Harvey Collegiate Institute for collaboration with program development, execution and administrative support. In particular, Jennifer Alves and Figen Irumekhai (staff) and principals Anthony Vandyke and Sam Micelli (administration) have assisted study authors with programming ideation, delivery, and data collection. *Discovery* has been established with the support of IBBME Directors (Dr. Christopher Yip, Dr. Craig Simmons, and Dr. Warren Chan) and the logistical assistance provided by the IBBME Undergraduate Programs Office administrator (Brittany Lawrence, Brittany Lauton, Andrew Novoselac, and Carina Kamango Esmael). *Discovery* facility support is provided by Dr. Max Giuliani, Dr. Lindsey Fiddes, Nguyen Hoang, and undergraduate work study students Michael Belhu, Rafia Kouser and Shreyashi Saha. We also thank Benjamin Rocheleau for contributions to data collation. This program is financially supported by IBBME and the National Science and Engineering Research Council (NSERC) PromoScience program as part of the IBBME “Igniting Youth Curiosity in STEM” initiative (PROSC 515876-2017) co-directed by DMK and Dr. Penney Gilbert. LDH and NIC were supported by Vanier Canada graduate scholarships from the Canadian Institutes of Health Research and NSERC, respectively. DMK holds a Dean’s Emerging Innovation in Teaching Professorship in the Faculty of Engineering & Applied Science at the University of Toronto.

7 Figures

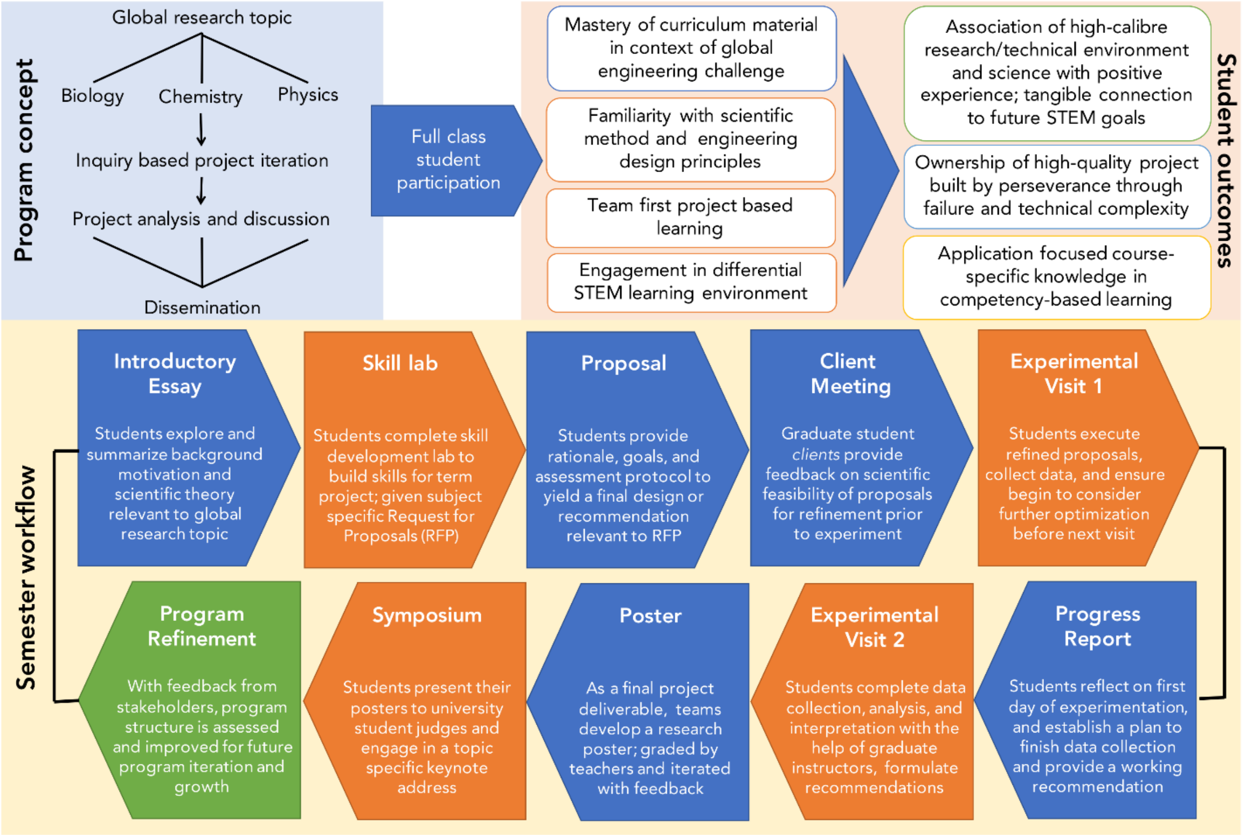

Program concept
Global research topic
Biology
Chemistry
Physics
Inquiry based project iteration
Project analysis and discussion
Dissemination
Full class student participation
Mastery of curriculum material in context of global engineering challenge
Familiarity with scientific method and engineering design principles
Team first project based learning
Engagement in differential STEM learning environment
Association of high-calibre research/technical environment and science with positive experience; tangible connection to future STEM goals
Ownership of high-quality project built by perseverance through failure and technical complexity
Application focused course-specific knowledge in competency-based learning
Student outcomes
Semester workflow
Introductory Essay
Students explore and summarize background motivation and scientific theory relevant to global research topic
Skill lab
Students complete skill development lab to build skills for term project; given subject specific Request for Proposals (RFP)
Proposal
Students provide rationale, goals, and assessment protocol to yield a final design or recommendation relevant to RFP
Client Meeting
Graduate student clients provide feedback on scientific feasibility of proposals for refinement prior to experiment
Experimental Visit 1
Students execute refined proposals, collect data, and ensure begin to consider further optimization before next visit
Progress Report
Students reflect on first day of experimentation, and establish a plan to finish data collection and provide a working recommendation
Experimental Visit 2
Students complete data collection, analysis, and interpretation with the help of graduate instructors, formulate recommendations
Poster
As a final project deliverable, teams develop a research poster; graded by teachers and iterated with feedback
Symposium
Students present their posters to university student judges and engage in a topic specific keynote address
Program Refinement
With feedback from stakeholders, program structure is assessed and improved for future program iteration and growth

Fig 1. Structure and rationale underlying *Discovery*. The general program concept (blue background; *top left*) highlights a global research topic examined through student dissemination of subject specific research questions, yielding multifaceted student outcomes (orange background; *top right*). Each program term (semester workflow, yellow background; *bottom panel*), students work on program deliverables in class (blue), iterate experimental outcomes within university facilities (orange), and are assessed accordingly at numerous checkpoints in an inquiry-focused learning model (**S3 Appendix III**).

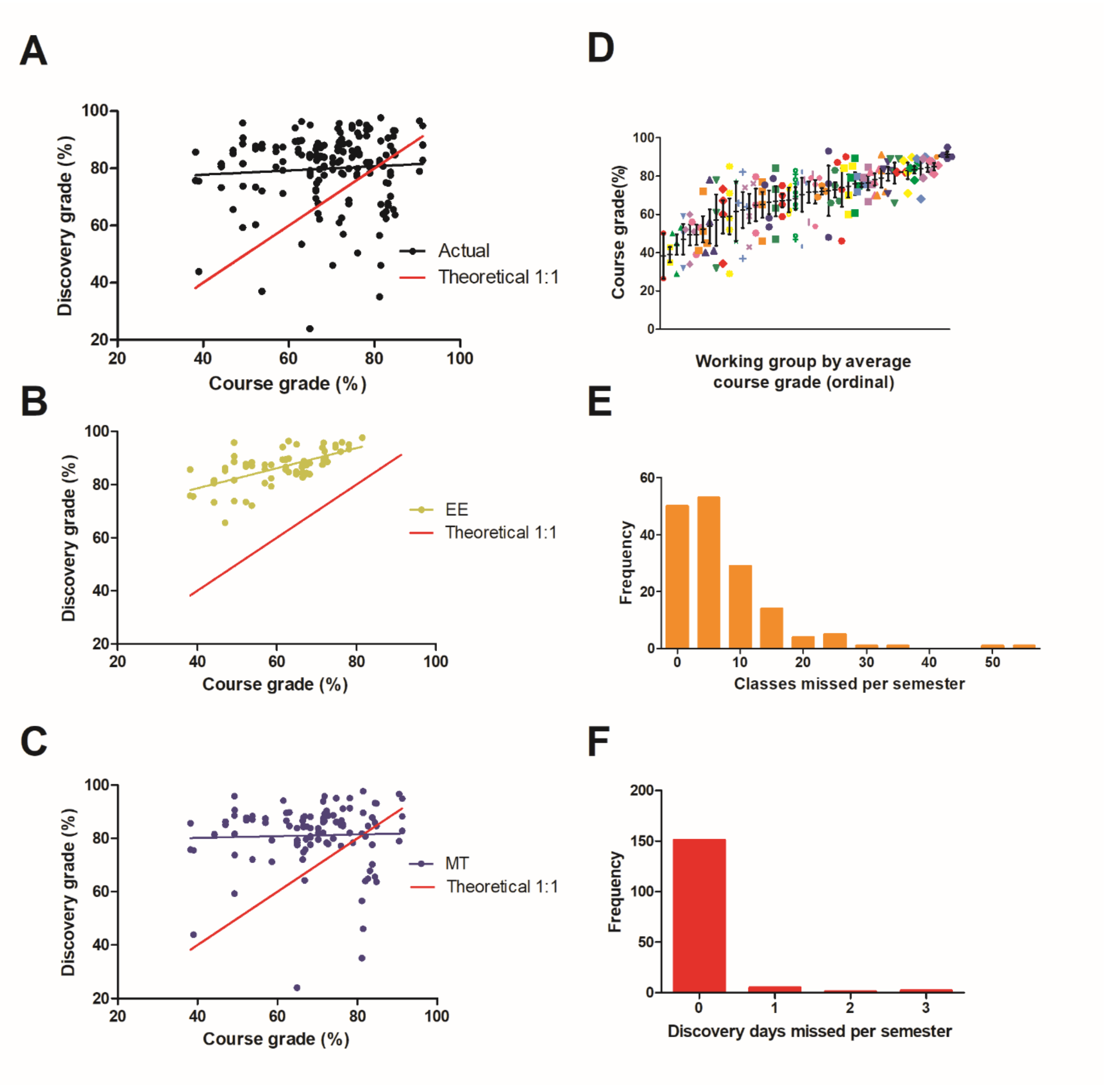


Fig 2. Student aggregate performance in *Discovery* and identification of subsets. (A) Linear regression of student grades reveals no significant correlation (p = 0.37) between *Discovery* performance and final course grade, as assessed by educators. (B & C) Identification of subgroups of interest, Exceeds Expectations (EE; N = 67, *yellow*) and Multi-Term (MT; N = 101, *blue*), of which N = 43 students were present in both subgroups. (D) Students tended to self-assemble in working groups according to their final course performance; data presented as mean ± SEM. (E) Students missed 7.16 ± 8.27 (mean ± SD) days of class per semester (median 4, 380 total student-days of absence per semester on average).

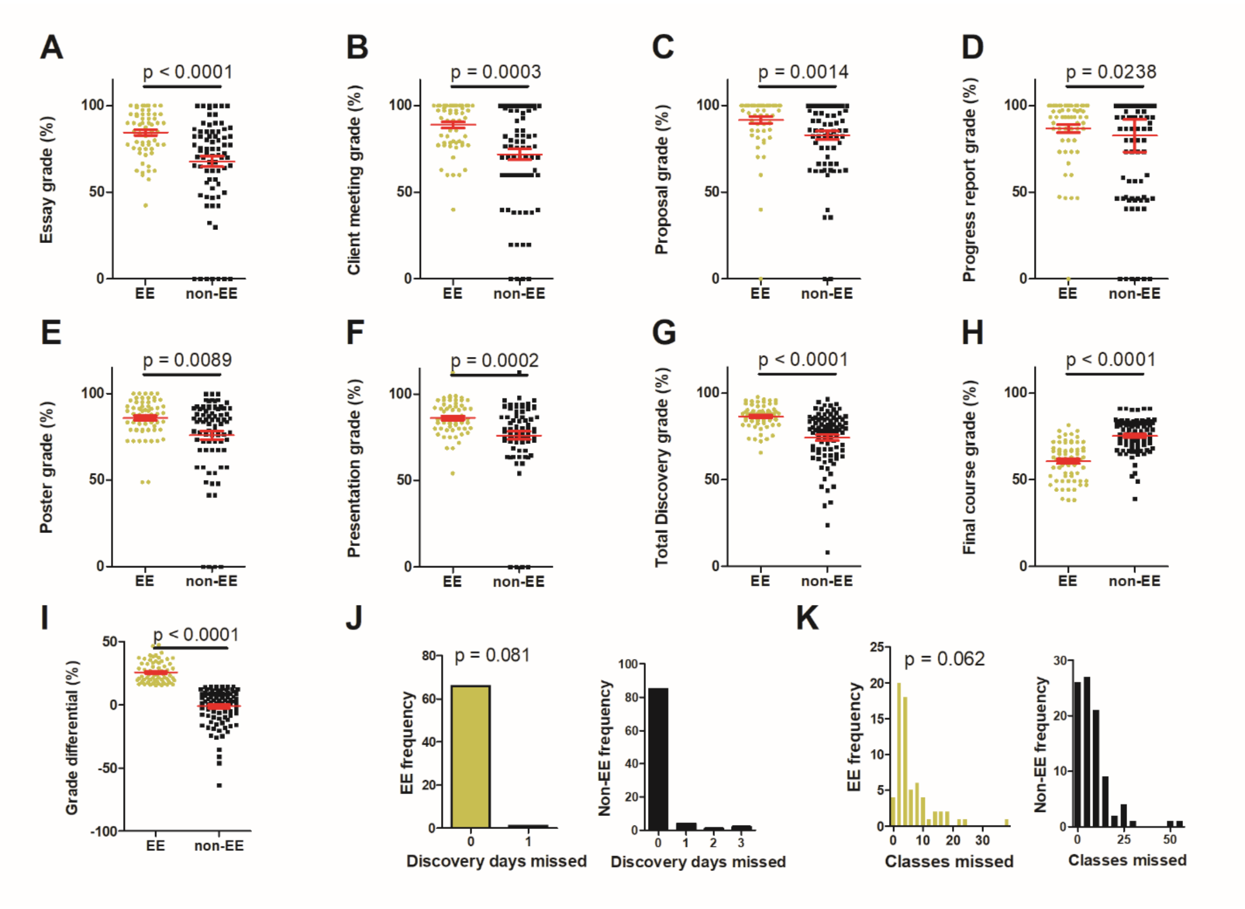


Fig 3. Performance of exceeds expectations student subset. The "Exceeds Expectations" (EE) subset of students (defined as those who received a combined *Discovery* grade ≥15% higher than their final course grade) received consistently higher grades on every *Discovery*-associated deliverable (A-F), the *Discovery* program as a whole (G), and lower course grades (H) compared to their classmates. (I) The mean grade differential of the arbitrarily-defined EE subgroup was actually 25.7% between their *Discovery* grade and their final course grade. The EE subset also tended (J, p = 0.081) to have a higher relative rate of attendance during *Discovery* sessions and a lower (K, p=0.062) rate of attendance in class. N = 67 EE students and 92 non-EE students (159 total). Grade data expressed as mean ± SEM.

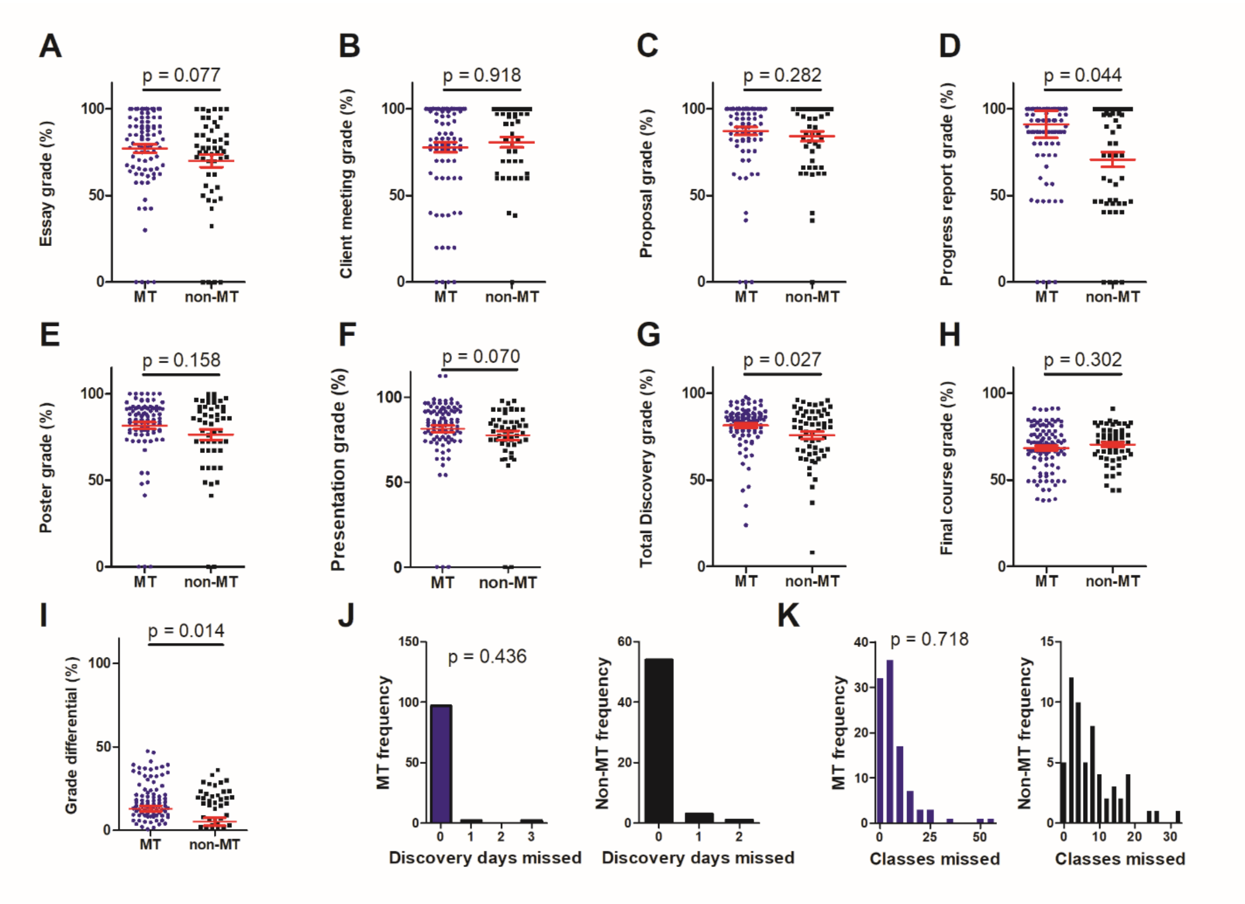


Fig 4. Performance of multi-term student subset. The "multi-term" (MT) subset of students (defined as having attended more than one semester of *Discovery*) demonstrated favourable performance in *Discovery* deliverables throughout their participation period. Independent of the number of times participating in *Discovery*, MT students tended to perform better on their introductory essay and final presentation, and scored significantly higher on their mid-project progress report compared to the non-repeating cohort (A-F). MT students also received a significantly higher final *Discovery* grade (G); there was no significant difference between final course grade between groups (H). MT students also showed no statistical difference in attendance in either the *Discovery* or class sections of their course (J-K). N = 101 MT students and 58 non-MT students. Grade data expressed as mean ± SEM.

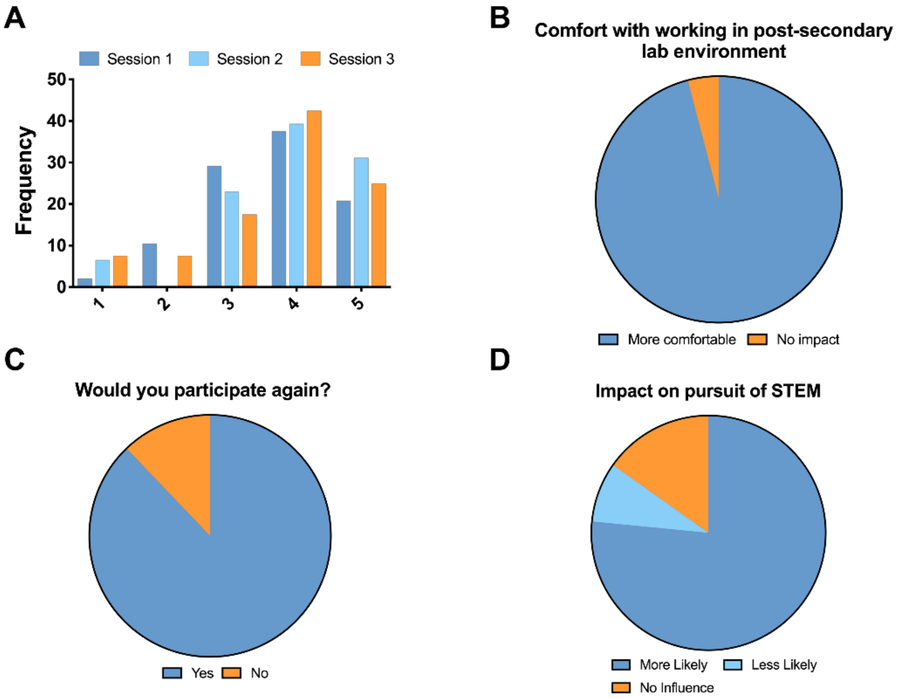


Fig 5. Student survey responses following participation in *Discovery* programming. (A) Histogram of relative frequency of perceived *Discovery* programming academic difficulty ranked from not challenging (1) to highly challenging (5) for each session (total responses: 149). (B) Students indicated their interest for future participation in *Discovery* (total responses: 140). (C) Program participation increased student comfort with navigating lab work in a university or college setting (total responses: 147). (D) Considering participation in *Discovery* programming, students indicated their likelihood to pursue future experiences in STEM (total responses: 145). Students were given the opportunity to opt out of individual survey questions, partially completed surveys were included in totals.

8 Supplementary Materials

S1 Appendix I: Sample teaching materials for one representative term of *Discovery*

S2 Appendix II: Entrance and exit student surveys for program assessment of *Discovery*

S3 Appendix III: Mark breakdown for student assessment in *Discovery* programming

S1 Appendix: Sample teaching materials for one term of IBBME Discovery

Enhancing senior high school student engagement and academic performance using an inclusive and scalable inquiry-based program

Locke Davenport Huyer[1,2,¶], Neal I. Callaghan[1,3,¶], Sara Dicks[4], Edward Scherer[4], Andrey I. Shukalyuk[1], Margaret Jou[4], and Dawn M. Kilkenny[1]

[1]Institute of Biomaterials and Biomedical Engineering, University of Toronto, Toronto, Ontario, Canada

[2]Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario, Canada

[3]Translational Biology and Engineering Program, Ted Rogers Centre for Heart Research, University of Toronto, Toronto, Ontario, Canada

[4]George Harvey Collegiate Institute, Toronto District School Board, Toronto, Ontario, Canada

Contents

Introduction 3

Biology 5

- Biology project outline 5
- Biology skill lab 7
- Biology request for proposal 15

Chemistry 18

- Chemistry project outline 18
- Chemistry skill lab 21
- Chemistry request for proposal 26

Physics 28

- Physics project outline 28
- Physics skill lab 31
- Physics request for proposal 34

Research Proposal Template 36

Acknowledgements, usage, and adaptations 41

Introduction

The goal of IBBME is to provide students with a real challenge in biomedical engineering, for which an introductory skill lab provides them with the technical ability to address the challenge in some way. In addition to the subject-specific technical skills that students will gain, the curriculum is also designed to give students highly transferable general scientific and engineering skills including:

- Literature review
- Experimental design
- Prototyping
- Data collection
- Validation
- Interpretation

For each subject (i.e. biology, chemistry, and physics), we have included:

- An outline of the research project for the purposes of logistical and curricular planning, and indicating the nature of the challenge, research question, expected methodology, and learning outcomes for students
- A skill lab protocol in the style of a standard 3-hour undergraduate laboratory, adjusted for technical and theoretical level and designed to introduce experimental and analytical techniques necessary to complete the conceived project
- A request for proposal (RFP) presented to the students outlining the motivation underlying the biomedical engineering challenge that the students are expected to contribute to, and to which the students must respond with a formal proposal

At the beginning of the skill lab, students were required by the facility to undergo a brief safety training that covered considerations of the facility in general, as well as safety procedures specific to the techniques and equipment in use and standard emergency procedures. Material safety data sheets (MSDS) for chemicals used were made available to all participants before the day of the skill lab. All graduate instructors participated in all department-mandated safety training modules.

After safety training, students typically took part in a 30 to 60 minute interactive lecture pertaining to the grand challenge of the semester, as well as introducing the theory and technical knowledge required to complete the skill lab protocol for the rest of the day. Students had been provided the skill lab protocol before attending, and they were given the rest of the day to complete the protocol as written, with instructor assistance as needed. At the end of the day, the RFP outlining the challenge was distributed to the students, and time was taken to discuss with students the nature of the project and potential avenues of inquiry.

Here we have provided sample documents for a past semester of Discovery, including outlines, skill labs, and RFPs for all three subjects. We have also included the template students use to complete the proposed research plan. The central theme of the semester was “Cardiovascular Disease: Engineering diagnostics and treatments”. This served to constrain project directions, rationalize the skills and techniques covered, and motivate students.

Biology

Biology project outline

Motivation: Currently in Canada there are over 1.6 million people with cardiovascular disease, and cardiac health is one of the leading causes of death in the developed world. These patients suffer from a significant reduction in their quality of life as reduction in heart function makes everyday life difficult. Although healthcare continues to advance treatment, there is a need for continued focus on preventing, identifying and treating this prominent health problem.

Cardiotoxicity effects are the leading cause of pharmaceutical drug withdrawal from markets; and delays in regulatory approval. Thus, cardiac safety assessment has become an important regulatory step in drug development. Inappropriate drug formulations or excessive drug exposure can lead to cardiac toxic effects that include arrhythmia, cardiac electrical instability, and sudden cardiac death. Some of these toxicity effects can be regulated in a time-dependent and dose-dependent manner. We want to investigate the cardiotoxicity effects of an unknown chemical compound, Substance X; however, we will require the expertise of cell biologists to conduct experiments comparing Substance X to known cardiac toxic drugs.

Research question: How can we characterize the toxic effects of chemical compounds on cardiac cells?

Rationale: Knowledge of cardiac cell characteristics (beating frequency, morphology, calcium oscillations, etc.) allows us to distinguish between cardiac cells that are functioning normally and cardiac cells that are beginning to fail. Once there is an understanding of the differences between healthy and dysfunctional cardiac cells, we can start to evaluate the potential cardiac toxicity effects of chemical compounds on cardiac cells.

Skill-based activity: A full day of introductory programming will include:

- Laboratory Biosafety (lecture, demonstration, quiz)

- Introduction to Pipetting & Serial Dilutions (lecture, pipetting practice)
- Cell Morphology and Microscopy (lecture, microscopy demo, cell imaging)
- Cell Staining - live/dead, DAPI (lecture, cell imaging)

Required equipment: Students will be given plates of cardiac cells, access to fluorescence microscopes, and a chemical inventory to characterize the cardiac tissue and explore how cell characteristics are impacted by various chemical compounds.

Expected outcomes: By the end of the module, students will be able to:

- Become familiar with basic laboratory practices and techniques
- Understand cell properties and how to measure them
- Develop testable hypotheses and experiments to prove or disprove them
- Perform fluorescence microscopy and imaging

Relevant literature topics: Further reading that may provide a deeper understanding of material covered in this research project can be done by searching relevant topics such as:

- How to use a pipette and perform serial dilutions
- Cell structures and properties of (cardiac) cells
- Changes to cardiac cells at the onset of cardiac cell dysfunction
- Common cellular dyes and how to prepare them for use in cell cultures
- How a fluorescence microscope works
- Components and format for writing a scientific report

Biology skill lab

Questions to consider during lecture:

Why do we culture and experiment on cells?

What are common good practices in sterile technique?

What is the purpose of cell culture medium?

What is fluorescence microscopy used for? What does it mean to "label" something for fluorescent microscopy?

What is phase-contrast microscopy used for?

How do cells gain and use energy? Where does the energy source come from?

At what temperature do we culture mammalian cells? Why else do we keep them in an incubator?

What is the aim of sterile technique? Why do we use it?

What is experimental variability? Why do we take replicate measurements in an experiment?

How large are most mammalian cells? What happens to their apparent size as we increase magnification on a microscope?

Sterile technique and pipetting practice

Materials

Ultrapure water
5 mmol/L blue dye stock
Microplates
Pipettes and pipette tips
Epitubes

1. While working in the Class II Biosafety Cabinet, and with sterile technique as demonstrated by your instructors, serially dilute the 5 mmol/L blue dye stock solution.
2. Set up 8 Epitubes and label them # 1-8.
3. Pipette 100 µL of the stock solution into a tube # 1 with 900 µL of water by depressing to the second stop, and gently mix by pipetting up and down above the first stop (be careful not to draw solution into the barrel of the pipette!). What concentration do you have now? Label the Epitube with the new concentration.
4. Transfer 100 µL from tube # 1 to tube # 2. Add 900 µL of water to tube # 2. Mix well as before. What concentration do you have now? Label the Epitube with the new concentration of dye solution.
5. Repeat this serial dilution with tubes # 3-8.

What is the concentration of dye within each tube? What happens to the colour of each solution?

Protocol: Cell culture and microscopy practice

For today’s lab, you will be working with HeLa cells. You aren’t expected to know the answers to the questions in the protocol ahead of time. Feel free to discuss with your instructors, and make sure to ask any questions you have. There are no stupid questions in a biology lab!

What do you know about these cells? Where do they come from?

Cell Culture

1. Obtain two dishes of cells from your instructor. Label them both with your group number or names, and mark one as “control” and one as “room temperature”.
2. Replace the cell culture media in both dishes as directed by your instructor, using sterile technique. Return the “control” plate to the incubator and leave the “room temperature” plate in the sterile flow hood before you go to lunch.

Based on what you know about cell culture, what do you think will happen to these cells? How could you test this hypothesis?

3. When you return from lunch, obtain the stock solution tubes of ethidium homodimer (EthD) and calcein-AM from your instructor. Make sure to leave the aluminum foil on the tubes.

Why is it important to shield these solutions from light?

4. Using sterile technique, add 5 μL of EthD and 2.5 μL of calcein-AM to 5 mL of phosphate-buffered saline (PBS) in a new 15 mL Falcon tube. This is your dye solution.
5. Remove the cell culture medium from both plates and add 2.5 mL of your dye solution to both plates. Allow them to incubate for 30-45 min.

Fluorescent Microscopy

1. With the instructor’s help, look at your cells using the microscope. Image your plates using brightfield, phase contrast, and red and green fluorescent channels. Record representative images (at least 3 replicates per plate) in all modes using both 10X and 40X objectives. Note that you need to capture all channels in the same place before moving your sample.

2. For each filter and magnification, use the same exposure time (i.e. all 10x TX2 images should have the same exposure time. This can be different from the 40x TX2 exposure time and from the 10x L5 exposure time).
3. In total, you should take 24 images (control: 3 brightfield, 3 phase contrast, 3 green, 3 red; room temp: 3 brightfield, 3 phase contrast, 3 green, 3 red).
4. When saving your image, save it as a tif file and make sure the filename includes the following details: Cell name, treatment, objective magnification, filter and exposure time. For instance: *HeLa_room temp_10x, L5, 80 ms.tif*
5. Save the images in a folder with your name or group number and today's date.

TIP: do *not* include a scale bar in the exported image. You can add a scale to the image in ImageJ without hard-coding a scale bar into the raw image.

What is the purpose of each channel with which you are taking images?

Why is it important to capture images in all channels in one area?

Why is it important to keep exposure time constant between images with same filter and magnification? What would happen otherwise?

Densitometry using ImageJ

1. For specific details and guides, see the "ImageJ" section below.
2. Open ImageJ on your computer.

3. Open an image by dragging & dropping it on the ImageJ interface. Before starting to work with your images, it is important to set the scale of the image, i.e. tell the software how large it is in real world units. To do this, click Analyze>Set scale and enter the appropriate information from the table in Appendix 2.
4. Cell counting: From your 10X images, use a particle counting tool (Plugins > Analyze > Cell Counter) to count how many cells are fluorescing red, and how many are fluorescing green. Calculate the percentage of dead cells for each sample.
5. Make a composite image incorporating your phase contrast, red, and green channels (Image > Color > Merge Channels). Add a scale bar based on the scale information you added in step 8: Analyze>Tools>Scale Bar.
6. Intensity measurement**:** Set your image measurements: Analyze > Set Measurements, enable “Area”, “Integrated density” and “Display Label”. (The label is not necessary but helps you keep track of which image the data comes from). For a 40X green fluorescent image, select the interior of a single cell by tracing its perimeter with the Magic Wand and/or Freehand Selection tool(s). Take a measurement of the cell (M or Analyze > Measure). This will produce both an area and density measurement and display them in a Results table. Repeat for ten cells in each treatment. Save your Results.
7. Analysis: Use excel to open your results file. Divide each cell’s RawIntDen value by its area. List these intensity/area ratios by each treatment.
8. Calculate the mean (Excel: “=AVERAGE([cell1]:[cell10])”) and standard deviation (Excel: “=STDEV([cell1]:[cell10])”) of both treatments.
9. Run a two-sample t-test (Excel: “=TTEST([cell1a]:[cell10a],[cell1b]:[cell10b],2)”) to see if your treatments are significantly different.

What is the purpose of density? Area? Density over area (normalized density)?

What does statistical significance mean? How is it determined?

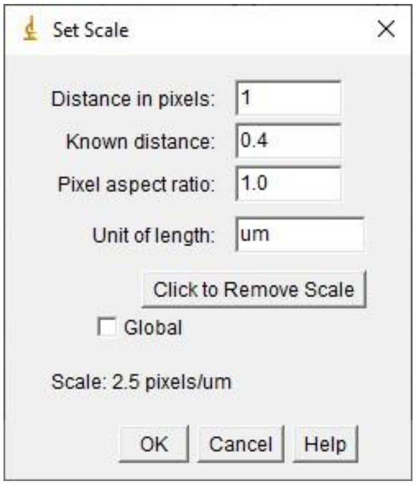
Would you expect your two treatments to differ in normalized density? Why or why not? What other parameters might you expect to be different?

ImageJ

ImageJ is a free to use, open source image manipulation and analysis software which is very popular in the microscopy community. It has been around since 1997 and its open source status has enabled researchers to create their own plugins, expanding the usefulness of the program. If you want to try it at home, you can find installation instructions here: https://imagej.nih.gov/ij/download.html.

Set scale: The scale of an image is a product of camera pixel size and the microscope's total magnification and is an important aspect of microscopy; it is required to know how large anything in your image actually is. To encode an image's scale in the data for the image click Analyze>Set Scale and fill out the dialog box according to this table:

Obj.	**Distance in pixels**	**Known distance**	**Pixel aspect ratio**	**Unit**
5x	1	0.41	1	um
10x	1	0.20	1	um
20x	1	0.10	1	um
40x	1	0.05	1	um



Distance in pixels: 1
Known distance: 0.4
Pixel aspect ratio: 1.0
Unit of length: um
☐ Global
Scale: 2.5 pixels/um

Fig. 1: Set scale dialog and validated scale distances for microscope objectives in ImageJ.

Cell counting: Use the plugin "Cell counter" to count cells in your images. Open the plugin: Plugins>Analyze>Cell counter and then click on your image, making it active. Click initialize in the plugin window, select a counter type and make sure you have one of the selection tools active (e.g. click on the "freehand selection" tool in the ImageJ toolbar). Click on all cells of interest.

If you make a mistake, you can press "delete" in the plugin and the last click of that type will be removed. If you check the box "delete mode", you can click in the image to delete the closest marker of that type.

Obsolete: In newer installations of ImageJ, the Cell Counter plugin has been removed and is replaced by the native Multipoint Tool which is even easier to use. The plugin should be available on all lab computers but if you install ImageJ at home, this might not be the case. To run the multipoint tool, simply launch it from the toolbar, select a colour and cell type number and click away. (Alternately, try to open the plugin as normal and ImageJ will automatically launch Multipoint tool for you.)

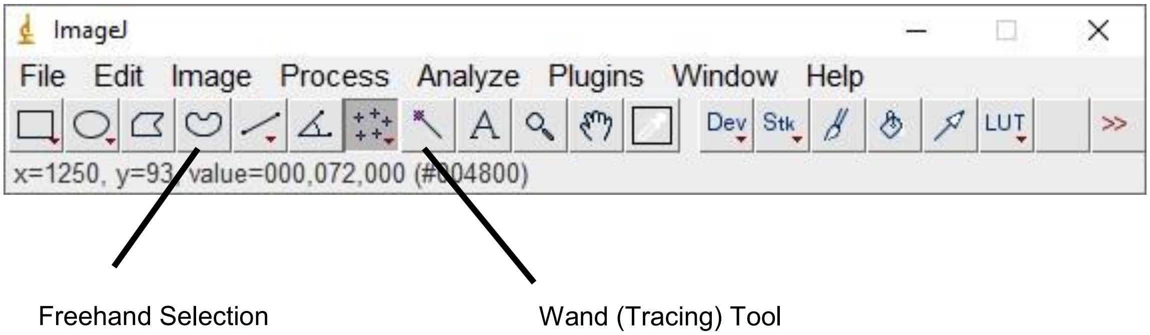
Tracing cells:

Wand tool: Using the Wand Tool, you can click on a pixel and all connected pixels of similar intensity will be selected. This is good if there is high contrast between cells (e.g. a darker area between). If you double click the wand tool, you can try different methods to determine “neighbouring” pixels and you can set tolerance for variations. A tolerance of 0 means pixels need to have the same intensity to be selected. Increasing the tolerance gives more leeway and pixels of similar intensity will be selected. This can be done live by selecting a cell and moving the slider.

Freehand selection: if the image is such that the wand tool is working poorly, cells can be manually traced with the freehand selection tool. Select the tool, click and hold the mouse button while tracing the outline of your cell.

Modifications: if you make a bad drawing, rather than starting over from scratch, you can modify it. By holding Shift while tracing, the new area will be added to the original area. (The two areas do not need to overlap.) By instead holding Alt while tracing, you can subtract areas.

These modifications can be combined with the wand tool: select a cell using the wand tool and add or subtract areas with the freehand tool.



x=1250, y=93, value=000,072,000 (#004800)

Fig. 2: Selection tools in ImageJ’s simple interface.

Biology request for proposal

Currently in Canada there are over 1.6 million people with cardiovascular disease, and cardiac health is one of the leading causes of death in the developed world. These patients suffer from a significant reduction in their quality of life as reduction in heart function can make everyday life difficult. Although healthcare continues to advance treatment, there is a need for continued focus on preventing, identifying and treating this prominent health problem. We are looking for the next generation of great minds to help us improve the lives of these people around the world!

Cardiotoxicity effects are the leading cause of pharmaceutical drug withdrawal from markets and delays in regulatory approval. Thus, cardiac safety assessment has become an important regulatory step in drug development. Inappropriate drug formulations or excessive drug exposure can lead to toxic effects including arrhythmia, cardiac electrical instability, and sudden cardiac death. Some of these toxicity effects can be regulated in a time-dependent and dose-dependent manner. **We want to investigate the cardiotoxic effects of a newly developed chemical compound, Substance X. However, we will require the expertise of cell biologists to conduct experiments comparing Substance X to known chemicals and/or drugs.**

We will be collecting proposals from multiple teams and will consider all options at a collective symposium. Please submit your project proposal using the RFP template provided. We have attached a list of the materials available in our facilities, so please take a look at these as you build your experimental plan. These will be reviewed by IBBME representatives who will meet with you to finalize the experimental details. You will then utilize our facilities to carry out your project and deliver a final presentation in poster format (template provided). We are looking forward to seeing the innovative solutions you will develop!

Notes:

Be aware of experimental constraints

Time: Plan for 5h in the laboratory per visit (2 visits total) to do your experiments and as well as some data analysis

Materials & Equipment: See attached inventory list

Proposals requiring materials that are not on the inventory list may also be approved on a case-by-case basis

Do your research

- How do we define the best dose for a drug?
  {e.g. dose concentration, number of doses, time between doses, etc.}
- What are properties used to characterize a drug's cardiotoxic effects?
  {e.g. effects on cell health/viability, cell morphology, cell behaviour, etc.}
- What techniques exist to measure these properties?
  {e.g. changes in cell adherence, changes in cell morphology/phenotype, changes in cell viability staining results, etc.}

Choose a cellular property to investigate as well as a set of known chemicals and/or drugs. Describe the procedures you would perform in order to characterize the potentially cardiotoxic effects of Substance X relative to known substances.

- Provide justification for your decisions
- Keep your proposal simple, you are limited in time and other resources

If your proposal is approved, be prepared to make it happen!

- Consider developing a spreadsheet/table for recording your observations

- Contact lenses are not allowed in the laboratory (please wear glasses)

Long pants, closed-toed shoes, and socks are required to work in the laboratory

Chemistry

Chemistry project outline

Motivation: Currently in Canada there are over 1.6 million people with cardiovascular disease, and cardiac health is one of the leading causes of death in the developed world. These patients suffer from a significant reduction in their quality of life as reduction in heart function makes everyday life difficult. Although healthcare continues to advance treatment, there is a need for continued focus on preventing, identifying and treating this prominent health problem.

Metoprolol is a beta-blocker that is frequently used to treat high blood pressure and tachycardia (chronically elevated heart rate). It can be taken by pill or intravenously but is a “dirty drug” in that it has numerous side effects, including depression, insomnia, fatigue, dangerously low heart rate, or respiratory depression, among others. Part of this toxicity can be avoided by tightly regulating the concentration of the drug within the body. We are working on bringing a new metaprolol treatment to market in either pill or implant form but need chemical engineering expertise to optimize the release of the drug within safe limits.

Research question: Can a hydrogel’s properties be engineered to release a drug within safe limits over time?

Rationale: Knowledge of cardiac cell characteristics (beating frequency, morphology, calcium oscillations, etc.) allows us to distinguish between cardiac cells that are functioning normally and cardiac cells that are beginning to fail. Once there is an understanding of the differences between healthy and dysfunctional cardiac cells, we can start to evaluate the potential cardiac toxicity effects of chemical compounds on cardiac cells.

Skill-based activity: Students will compare prepared gelatin to alginate beads in their release kinetics of food colouring using a spectrophotometer and standard curve. Knowledge of the Beer-Lambert law and chemical equilibria will be necessary. Students will gain experience with all relevant techniques and will learn to use Excel graphing to draw quantitative conclusions. Students will use FCF Brilliant Blue #1 (blue food colouring) for all activities. First, they will be required to create a serial dilution series of stock dye to find a dilution suitable for reading in a spectrophotometer. By using a known extinction coefficient, they will be able to calculate the stock concentration. Next, they will need to create a 5-point linear standard curve within the optimal range of the spectrophotometer based on their understanding of the relationship between absorbance and concentration. Finally, they will use this curve to measure the release of Blue #1 from premade alginate beads into media over time.

Project: Students will create hydrogels from alginate and/or gelatin and measure their release of blue dye over time. They will be able to modulate gel composition and density, form (size/shape), and initial amount of dye loaded. Using a standard curve and timepoint measurements, they will generate release profiles that will be loaded into a premade mathematical model of metoprolol absorption and clearance from the human body. This will allow them to assess the efficacy and safety of their hydrogel drug delivery system.

Required equipment

- Gelatin
- Alginate
- Calcium chloride
- Microplates
- Pipette tips
- Beakers

- Food colouring (Blue 1: 628 nm, 1.30*10^5 M-1cm-1, 792.844 g/mol; Yellow 5: 425 nm, 2.73*10^4 M-1cm-1, 534.36 g/mol; Red 40: 504 nm, 2.59*10^4 M-1cm-1, 496.42 g/mol)
- Miscellaneous materials for casting shapes (glass slides, tape, PDMS strips, etc)
- Pipettes
- Spectrophotometer

Expected outcomes: At the end of this module, students will be able to:

- Apply concepts and use common equations in equilibrium and the Beer-Lambert Law.
- Understand the theory and limitations of a spectrophotometer.
- Understand hydrogel structure and function.
- Design a proposal to tailor the rate of drug release within a specified range, based on modifying common material properties of a hydrogel (size, shape, polymer content, starting concentration).

Relevant literature topics: Custom protocols and presentations will be provided. Readings on equilibrium, conservation of matter, etc. in their own textbooks will be helpful for review.

Chemistry skill lab

To be completed during lecture:

Metoprolol is a beta-blocker. What is the role of a beta-blocker in cardiac medicine?

What are three of the side-effects of metoprolol?

In general, how can we avoid side-effects while gaining desirable effects of a drug?

What properties of a hydrogel can be changed to tune drug release?

Today's activity:

Today we will be modeling drug concentrations and controlled release using a blue dye (FCF Brilliant Blue #1, or blue food colouring). Blue #1 shows peak absorbance at 628 nm, has a molar mass of 792.84 g/mol, and an extinction coefficient of 130 000 L/mol/cm.

You should be writing down all steps and data obtained in your notebook. A volunteer must sign off on this protocol/worksheet and your notebook before you leave for the day. All of the techniques and calculations you do today will be important for your design project.

Sketch a plot of absorbance vs. wavelength for Blue #1:

Why should we measure absorbance at the peak wavelength?

1. Place 10x 1.6 mL epitubes in a rack. Add 2 drops of blue food colouring to one. This is your working dye stock solution.
2. To another 1.6 mL epitube, pipette 10 μL of blue food colouring using a P10 or P20 pipette. Add 90 μL of ultrapure water.

What is the dilution of this solution in relation to the original dye stock?

Why should we use ultrapure water for spectrophotometry?

3. Add 10 μL of the solution made in (2) to 90 μL of ultrapure water in a new tube.

What is the dilution of this solution in relation to the original dye stock?

4. Add 50 μL of the solution made in (3) to 450 μL of ultrapure water in a new tube.

What is the dilution of this solution in relation to the original dye stock?

5. Repeat steps 2-4 two more times until you have 3 **triplicate** samples. Pipette 200 μL of this solution each into wells A1, A2, and A3 of a spectrophotometry microplate
6. With the help of a volunteer, measure the absorbance at 628 nm of these wells.

Record your three absorbances here as well as in your lab notebook

7. Using $A = \varepsilon \times C \times l$, compute the current (diluted) concentration of Blue #1 in each of the three triplicate samples you measured. Multiply by the dilution factor to give three replicate values for the initial stock concentration of FCF Brilliant Blue #1.

Record the three absorbances here, as well as their mean (average) and standard deviation $\boldsymbol{SD} = \sqrt{(\frac{(\boldsymbol{repl_1} - \boldsymbol{mean})^2 + (\boldsymbol{repl_2} - \boldsymbol{mean})^2 + (\boldsymbol{repl_3} - \boldsymbol{mean})^2}{\boldsymbol{2}}})$. Record all computations in your lab notebook.

What is the purpose of a standard deviation?

8. Make another 1 in 1000 dilution by diluting 10 µL of the original dye stock in 90 µL water, 20 µL of this dilution in 180 µL water, and 120 µL of this dilution in 1080 µL water (2x 540 µL). Repeat this process once to generate triplicates. Be careful to not mix up tubes in your rack.

Why should we dilute samples stepwise, and not by a 1 in 1000 factor in a single step?

9. Make a serial dilution series for a standard curve by diluting your triplicate 1 in 1000 stocks. From the tube made in (8), add 960 µL to 240 µL water.
10. Add 960 µL of the solution made in (9) to 240 µL water. Repeat this serial dilution process two more times in this dilution series, and then produce two more series using the triplicates you generated in (8). At this point, you should have 3 x 5-point standard curves for 15 total tubes.
11. Add 200 µL from each tube to a well in your microplate, so that B1, B2, and B3 hold the triplicate samples made in step 8; C1, C2, and C3 hold the triplicates made in (9), etc.

12. With a volunteer's help, measure the absorbance of each well at 628 nm. Copy the values into your notebook and generate a standard curve on Excel, plotting absorbance vs concentration. Add a linear trendline and use Excel to compute the trendline fit equation and R^2.

What is the significance of the trendline equation? What is the significance of R^2? What value should R^2 be above in order to use the trendline?

13. 2% (w/v) and 4% sodium alginate solutions have been prepared. In new epitubes, add 10 µL of stock dye to 990 µL of each sodium alginate stock.
14. Using a wide-bore pipette tip on the P1000, slowly and gently extrude 100 µL of coloured sodium alginate into 5 mL of $CaCl_2$ (10% w/v).

What happens to the alginate?

15. Repeat step 14 5x times.
16. Let the alginate sit for 15 min, then gently drain off the liquid. Add each bead to a new epitube containing 1 mL of water. Do this with both 2% and 4% solutions of alginate.
17. At 5, 10, 20, 30, and 60 minutes post-addition, take 200 µL from one tube and add it to a new well of the microplate. Once you have completed the time course, measure the absorbance of all wells at 628 nm.

Copy these values into your notebook.

Calculate the amount of dye (in mol) released into each tube (remember you are only sampling 200 µL of a 1000 µL volume). Generate release curves (amount in mol released vs. time in minutes), in triplicate, of both 2% and 4% alginate solutions. What trends do you observe?

S1 Appendix: Sample teaching materials for one term of IBBME Discovery

Chemistry request for proposal

The Institute of Biomaterials and Biomedical Engineering (University of Toronto) is working to improve the lives of patients around the world. Currently in Canada there are over 1.6 million people with cardiovascular disease, and cardiac health is one of the leading causes of death in the developed world. These patients suffer from a significant reduction in their quality of life as reduction in heart function makes everyday life difficult. Although healthcare continues to advance treatment, there is a need for continued focus on preventing, identifying and treating this prominent health problem. We are looking for the next generation of great minds to help us improve the lives of these people around the world!

Metoprolol is a beta-blocker that is frequently used to treat high blood pressure and tachycardia (chronically elevated heart rate). It can be taken by pill or intravenously but is a “dirty drug” in that it has numerous side effects, including depression, insomnia, fatigue, dangerously low heart rate, or respiratory depression. Part of this toxicity can be avoided by tightly regulating the concentration of the drug within the body. **We are working on bringing a new metaprolol treatment to market in either pill or implant form, but need chemical engineering expertise to optimize the release of the drug within safe limits. We want you to design a metoprolol-releasing hydrogel and quantify its rate of release to fall within safe limits.**

We will be collecting proposals from multiple teams, and will consider all options at a collective symposium. Please submit your project proposal using the RFP template provided. We have attached a list of the materials available in our facilities, so please take a look at these as you build your experimental plan. These will be reviewed by IBBME representatives who will meet with you to finalize the experimental details. You will then utilize our facilities to carry out your project and deliver a final presentation in poster format (template provided). We are looking forward to seeing the innovative solutions you will develop!

Notes:

Be aware of experimental constraints

You will have access to calcium and alginate solutions, food dye, materials to cast gels, microplates and spectrophotometers, and potentially other chemicals or materials available upon request.

Do your research

- How can we modify hydrogels to change delivery of a drug?
- What changes to current treatments would patients benefit from?

Engineering is an iterative and creative process

Some ideas you have might not be directly in line with the precise problem posed. There are plenty of issues in healthcare today, and given appropriate resources, you can adapt the project to your interest!

If your proposal is approved, be prepared to make it happen!

- Have a step-by-step protocol ready
- Be prepared to troubleshoot difficulties as they arrive
- Practice with Excel (and the sample worksheet) might be very useful!

Physics

Physics project outline

Motivation: Currently in Canada there are over 1.6 million people with cardiovascular disease, and cardiac health is one of the leading causes of death in the developed world. These patients suffer from a significant reduction in their quality of life as reduction in heart function makes everyday life difficult. Although healthcare continues to advance treatment, there is a need for continued focus on preventing, identifying and treating this prominent health problem.

Improved resources for patients with cardiovascular disease to monitor their conditions would allow them to track parameters of interest, and schedule appointments or alert emergency services as needed if key metrics of cardiovascular performance change. A portable infrared plethysmograph capable of tracking pulsatile blood flow can be easily built using simple Arduino-compatible components.

Research question: Can we build a cost-effective infrared pulse sensor device to monitor cardiac function?

Rationale: Biomedical instrumentation is necessary to monitor and diagnose medical conditions. Students will learn the scientific basis of biological signals and the technical principles involved in detecting and measuring them. Close monitoring of a condition is also necessary for optimized intervention.

This project would also complement the “Waves and Sound” and “Electricity and Magnetism” units from the grade 11 and 12 physics curricula:

Skill-based activity: Several small tasks will teach the students some of the following concepts:

- Fundamentals of circuits: basic electronic components, units and concepts associated with electricity, and voltage/current laws.

- Signal Processing: signal filtering and amplification
- Coding: Writing code to calculate and display heart rate

The skill-based learning activity will involve a guided-session where students are introduced to the Arduino, a popular microcontroller, which is effectively a very simple computer. Students will follow steps to setup the Arduino, learn about its various components and features and how to upload code to the Arduino. At the end of the skill laboratory, students will have created a simple circuit interfaced with the Arduino that allows them to control the blink frequency of an LED by adjusting a potentiometer (a variable resistor device). This will teach skills including basic circuit design, collecting signals into the Arduino (a process known as analog-to-digital conversion) and how to send signals from the Arduino to an LED.

Project: Students will create a prototype of an IR pulse sensor/plethysmography device for measuring pulsatile blood flow in an extremity. This device and the process of creating this device will expose students to biomedical device design and development. By combining the scientific principles of cardiac physiology and engineering students will see first hand how scientific research can be translated into an engineering device that can be used to improve patients' quality of life.

Required equipment

- Laptops (for coding and 3D design)
- Arduino Microcontrollers
- Prototyping boards// breadboards
- Resistors + Capacitors
- Pulse Sensors (Contains LED, light sensor, and analog filter + amplifier)
- 3D Printers

Expected outcomes: At the end of this module, students will be able to:

- Understand basic electronic components and be able to plan and assemble rudimentary electronic circuits
- Obtain, modify, and run basic Arduino code
- Understand basic data acquisition and filtering processes
- Understand principles of 3-dimensional CAD and additive manufacturing

Relevant literature topics: Custom protocols and presentations will be provided. Readings on equilibrium, conservation of matter, etc. in their own textbooks will be helpful for review.

Physics skill lab

Purpose

This lab will introduce several important microcontroller concepts and features. First, it introduces the concepts of inputs and outputs. Inputs can allow the Arduino to connect to sensors, which detect variables from its environment (such as temperature) or allow a user to interact with it through buttons or a potentiometer. On the other hand, outputs allow the microcontroller to control other components or devices in order to display information back to the user or run a system. In this lab, we will see how programming the microcontroller allows us to control the relationship between those inputs and outputs.

Materials

- PC + Arduino IDE
- Arduino microcontroller + USB cable
- Breadboard
- 10kΩ potentiometer
- LED
- Jumper Wires

Procedure

Part 1: Hook up an LED and make it flash at the rate of 1Hz:

1. Connect the positive rail on the breadboard to +5V on the Arduino and the ground rail to any GND pin on the Arduino.
2. On the breadboard: Following the diagram in *Figure 1*, connect the digital output pin D13, the 100Ω resistor, the LED, and the ground rail *in series*. Note that the LED has polarity [a].

3. Connect your Arduino to a PC using the provided USB cable
4. In the Arduino IDE [b] open the Blink example code and set the blink rate by changing the number in the delay() function.
5. Compile your code by clicking this button in the Arduino IDE: ✓. Compiling your code checks your code for errors and tells you if there are any problems.
6. Next, upload your code to the Arduino by clicking this button: →
7. Voila, you're done! Enjoy endless hours of watching your LED blink!

[a] *Remember, as a result of polarity you can only insert the LED into the circuit in one way. Do some basic research on this.*

[b] *An IDE or "integrated development environment" is a program that you can use to write and then send code to the Arduino*

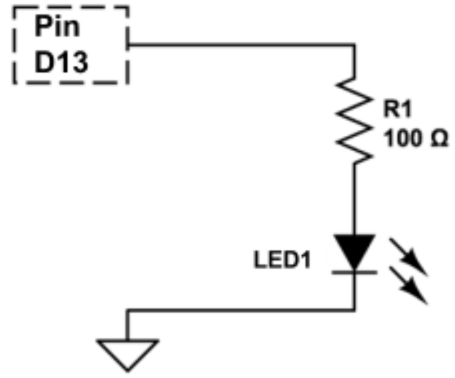


Figure 1: The LED should be hooked up in series with a resistor. Remember to consider the connectivity of the circuit, not the geometry!

Part 2: Controlling the rate of an LED using a potentiometer:

1. Do not change the circuit from Part 1!
2. On a different part of the breadboard, connect the circuit shown in *Figure 2*: connect the **positive rail** to one end of the potentiometer, the **ground** rail to the other, and connect analog input pin **A0** to the wiper or center pin on the potentiometer

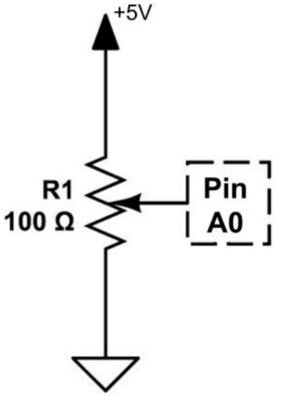


Figure 2: The potentiometer circuit to control the LED blink rate

3. Upload the controlBlink.ino file to the Arduino.
4. Now move the potentiometer and observe how it changes the blinking rate of the LED. Pretty cool eh!?

Physics request for proposal

The Institute of Biomaterials and Biomedical Engineering (University of Toronto) is working to improve the lives of patients around the world. Currently in Canada there are over 1.6 million people with cardiovascular disease, and cardiac health is one of the leading causes of death in the developed world. These patients suffer from a significant reduction in their quality of life as reduction in heart function makes everyday life difficult. Although healthcare continues to advance treatment, there is a need for continued focus on preventing, identifying and treating this prominent health problem. We are looking for the next generation of great minds to help us improve the lives of these people around the world!

Early detection of abnormal heart rhythms is important in order to provide timely and appropriate treatment for cardiac conditions. There are two main techniques that can be used to monitor a person's heart rhythm. These include measuring the electrical activity of the heart (an *electrocardiogram*) or detecting changes in the amount of oxygenated blood within a tissue region (e.g. a fingertip) based on the amount of infrared (IR) light that is reflected or transmitted (known as *IR plethysmography*). This works because the oxygenated blood contains higher levels of oxy-hemoglobin (hemoglobin is a compound in red blood cells which transports oxygen around the body), which reflects more infrared light than deoxygenated blood. **We are looking for a cost-effective device to measure a patient's heart rate. The design should be able to be easily prototyped and demonstrate the conceptual design of the device. The device should be comfortable, easy-to-use, and portable. It should be able to indicate the user's heart rate and alert them if there are measured abnormalities.**

We will be collecting proposals from multiple teams and will consider all options at a collective symposium. Please submit your project proposal using the RFP template provided. We have attached a list of the materials available in our facilities, so please take a look at these as you build your experimental plan. These will be reviewed by IBBME representatives who will meet with you to finalize the experimental details. You will then utilize our facilities to carry out your project and deliver a final presentation in poster format (template provided). We are looking forward to seeing the innovative solutions you will develop!

Notes:

Be aware of experimental constraints

Time: ~4 hours per visit, 2 visits

Materials & Equipment: See attached inventory list

Do your research

- Why is it important to monitor heart rate?
- What are some techniques that can be used to measure heart-rate?
- Compare the two most common techniques. What are their advantages and disadvantages?
- What is IR plethysmography (photoplethysmography)? How does it work?
- What are normal ranges for heart-rate?
- How can the device give feedback to the user?

If your proposal is approved, be prepared to make it happen!

Have detailed protocols ready and be aware of safety considerations around fabrication and electronics.

Research Proposal Template

The following is a condensed version of the proposal template students complete in response to their subject specific RFP each term. Blue text is descriptors that guides student writing into specific categories, which is removed prior to submission.

TEMPLATE INTRODUCTION

Use this template to respond to the "Request for Proposal" from IBBME Discovery, thereby developing a proposal for executing your experimental plan. The document should include: an introduction to the subject area and background research; scope and specific objectives; a detailed experimental plan including required materials and stepwise procedure as appropriate; breakdown of project management including a breakdown of team member responsibilities; and a summary of your expected outcomes. Throughout this template, italicized blue text is a descriptor of what information must be provided in a particular section, and therefore must be replaced with your own information. Remove all sections that include blue text from your submitted version, including this template introduction section.

BACKGROUND RESEARCH & INFORMATION

<A brief overview and background information>

A summary of the initial research for this project

- *This is not a copy and paste of the background essay assignment*
    - *Include any information from the initial research that is relevant to the experiments you will be conducting*
- *Try to answer the following questions in this section:*
    - *What is the problem?*
    - *What effect does this problem have on society? Why is it important to solve?*
    - *What general approach will you be taking to solve this problem?*

- *Finally, what are you planning to design/test and how will this contribute to solving the problem?*

SCOPE OF WORK

<A short introduction about the project and what testing will be performed>

What will you be designing in this project?

What need will this meet?

What is the general approach to test/evaluate your design?

What is the end goal?

SPECIFIC OBJECTIVES

<This Section describes the project structure, outlining which areas of focus you choose and why.>

What specific conditions will you be testing?

What specific tests will be carried out?

What tools will you use for performing these tests?

PROJECT REQUIREMENTS FOR ANALYSIS/EXPERIMENTS

<This is the core section in any research proposal. Each project requirement should be listed and described in specific detail. This section will outline your intended experiments. Think of this as being similar to materials and methodology for lab experiments.>

Materials

What do you need to create your design and carry out your experiments?

Procedure

<Describe the steps of your design and testing. Describe the main steps you plan to take to achieve the desired outcome. Provide a detailed list of what you will do in the experimental workspace>

What will you make?

What measurements will you take?

How will you analyze the data?

If you find that you need to make changes to your design, what changes will you make? What steps of your procedure will you perform again after?

Consider your variables – what will you change? What will you control?

What tests will you do?

What are your controls?

Examples of content to include:

Solutions you will prepare and respective dilutions

Preliminary design you have in mind and steps you will follow to fabricate

Experimental groups that will be considered.

RESPONSIBILITIES IN PROJECT MANAGEMENT

This section outlines when you will achieve each part of your proposed project and who is responsible for each step. Explain who is responsible for which deliverables. If a deliverable has more than one person assigned, detail each person's contributions. Indicate the planned timeline for accomplishing each task

Deliverables & Parties Responsible

Responsible Party	Date	Deliverable

EXPECTED OUTCOMES

<Summarize what you have proposed to do.>

What do you expect you will be able to demonstrate with this work?

How will you know you have succeeded?

Summarize briefly how this work can address the need you described in the background information.

Acknowledgements, usage, and adaptations

All Discovery materials are provided under the Creative Commons Attribution 4.0 (CC BY 4.0) license allowing the adaptation and usage of these materials for other educational purposes, provided that credit is given to the original authors and the Discovery program, and indication of any changes made is provided. Discovery does not endorse any external use or modification of these materials.

Discovery Biology materials were conceived and developed by Dr. Henrik Persson, Huntley Chang, Romario Regeenes, Cindy Yip, Janice Wong, Neal Callaghan, and Locke Davenport Huyer. Discovery Chemistry materials were conceived and developed by Neal Callaghan and Locke Davenport Huyer. Discovery Physics materials were conceived and developed by Daniel Smieja, Rami Saab, Neal Callaghan, and Locke Davenport Huyer.

S2 Appendix: Entrance and exit student surveys for program assessment of IBBME Discovery

Enhancing senior high school student engagement and academic performance using an inclusive and scalable inquiry-based program

Locke Davenport Huyer[1,2,¶], Neal I. Callaghan[1,3,¶], Sara Dicks[4], Edward Scherer[4], Andrey I. Shukalyuk[1], Margaret Jou[4], and Dawn M. Kilkenny[1]

[1]Institute of Biomaterials and Biomedical Engineering, University of Toronto, Toronto, Ontario, Canada

[2]Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario, Canada

[3]Translational Biology and Engineering Program, Ted Rogers Centre for Heart Research, University of Toronto, Toronto, Ontario, Canada

[4]George Harvey Collegiate Institute, Toronto District School Board, Toronto, Ontario, Canada

Discovery Entrance Survey

Name: ___________________________

1. In which course(s) are you enrolled: Physics Chemistry Biology

2. What grade are you in: 11 12

3. Have you participated in IBBME Discovery before? Yes No

   a. In what subject? (circle all that apply) Physics Chemistry Biology

   b. In which term? (circle all that apply)

   Fall 2016 Spring 2017 Fall 2017 Spring 2018 Fall 2018

4. How do you feel about taking science or science-focused courses in the future? (Circle one answer)

   a. I am likely to take science courses in the future.

   b. I am not likely to take science courses in the future

5. In your own words, what is biomedical engineering?

   ____

6. Are you planning to graduate high school this year? Yes No

7. Did you apply to post-secondary institutions? Yes No

8. a. Where did you apply?

____

____

b. To what program(s) did you apply?

____

____

c. What factors are important in selecting a post-secondary destination (circle all that apply)

Program
Tuition Cost
Available financial aid
Far from Home
School Size
Reputation
Near Home
Social Environment
Campus Size
Personal Fit
Athletics

Other: ____

Additional Comments:

Discovery Exit Survey

Name: ____________________________

1. What project did you work on? Physics Chemistry Biology

2. What grade are you in? 11 12

3. What is one thing you learned from this project?

____

____

____

4. Did you feel well-prepared for the project? Yes No

5. Did you feel challenged by the project? (Circle one number)

Yes I felt challenged academically **5** **4** **3** **2** **1** *No I did not feel challenged academically*

6. Did this experience make you feel more comfortable with the idea of doing lab work in university or college?

Yes No

7. What did you find to be the most difficult aspect to the project?

____

____

____

8. Did you feel comfortable discussing your project in the Symposium setting? Yes No

9. How do you feel about taking science or science-focused courses in the future (Circle one answer)?

   a. I am more likely to continue in science or engineering after IBBME Discovery.

   b. I am less likely to continue in science or engineering after IBBME Discovery

   c. IBBME Discovery had no influence on my future course selection.

10. Would you be interested in participating in a program like this again? Yes No

11. Have you participated in IBBME Discovery before? Yes No

   a. In what subject (circle all that apply): Physics Chemistry Biology

   b. In which term (circle all that apply):

Fall 2016 Spring 2017 Fall 2017 Spring 2018 Fall 2018

12. In your own words, what is biomedical engineering?

____

____

13. Are you planning to graduate high school this year? Yes No

14. Did you apply to post-secondary institutions? Yes No

15. a. Where did you apply?

____

____

b. To what program(s) did you apply?

____

____

c. What factors are important in selecting a post-secondary destination (circle all that apply)

Program
Tuition Cost
Available financial aid
Far from Home
School Size
Reputation
Near Home
Social Environment
Campus Size
Personal Fit
Athletics

Other: ____

Additional Comments:

Thank you for your participation!

S3 Appendix: Mark breakdown for student assessment in *Discovery* programming

Enhancing senior high school student engagement and academic performance using an inclusive and scalable inquiry-based program

Locke Davenport Huyer[1,2,¶], Neal I. Callaghan[1,3,¶], Sara Dicks[4], Edward Scherer[4], Andrey I. Shukalyuk[1], Margaret Jou[4], and Dawn M. Kilkenny[1]

[1]Institute of Biomaterials and Biomedical Engineering, University of Toronto, Toronto, Ontario, Canada

[2]Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario, Canada

[3]Translational Biology and Engineering Program, Ted Rogers Centre for Heart Research, University of Toronto, Toronto, Ontario, Canada

[4]George Harvey Collegiate Institute, Toronto District School Board, Toronto, Ontario, Canada

The following table provides a mark breakdown of the assessments and evaluations that comprise the *Discovery* cumulative assessment for participating students. All assessment was performed by participating educators for their respective students according to this template. It includes a mixture of written groupwork (Final Proposal, Progress Report, Poster), individual written work (Background Essay), and group presentation (Client Meeting, Poster Presentation). Percentage weight for each deliverable is divided to ensure that (1) there are both group and individual components of assessment and (2) students are assessed on both written and oral communication of their work.

Table 1: Summary of mark breakdown for Discovery programming

ITEM	DESCRIPTION OF ASSESSMENT	POINTS (/145)	PERCENTAGE OF GRADE
BACKGROUND ESSAY	Relevant summary of research topic motivation	20	13.8%
CLIENT MEETING	Student presentation skills in virtual client meeting that pitches proposed workflow in response to subject specific request for proposals	5	3.4%
FINAL PROPOSAL	Group submission of planned workflow for the skill lab visits. Assessment of workplan completeness, appropriate research question, hypothesis, and expected outcomes. Description of groupwork breakdown clearly described	35	24.1%
PROGRESS REPORT	Reflection on first skill lab visit outcomes, summary of progress to date Updated plan of next steps to ensure research outcomes are complete at the end of next skill lab visit	15	10.3%
POSTER	Assessment of poster content: Research question and motivation clearly outlined Clear communication of results Reasonable conclusions drawn Appropriate references to relevant literature	40	27.6%
POSTER PRESENTATION	Assessment of each student's communication skills in poster presentation setting. Graded on ability to succinctly communicate research outcomes and answer relevant questions	30	20.7%