A STRUCTURED APPROACH TO DEVELOPING OPEN-ENDED SCIENTIFIC RESEARCH PROJECTS FOR SECONDARY STUDENTS IN A GRADUATE STUDENT-LED EDUCATION PROGRAM

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Abstract – *Discovery is an educational program where engineering graduate mentors develop and implement inquiry-based learning projects aligned with secondary school science curriculum over a semester with feedback from secondary school educators. Ongoing development of new inquiry-based projects is essential for maintaining relevance within evolving STEM curricula and accommodating increasing numbers of program participants. However, graduate mentors face challenges developing and delivering new curricula due to research commitments and varying levels of teaching experience. We introduce a standard, generalized template with specific success criteria for the structured development of new projects that incorporate open-ended research aspects into each project. We outline this template using a recent Chemistry project and evaluate the new curriculum against success criteria to identify areas for continuous, iterative improvement. We anticipate this template will provide greater support and organization for graduate mentors when designing new projects, enabling development of relevant materials that are well-aligned with current science curricula.*

Keywords: Inquiry-based learning, graduate student teaching, STEM curriculum, pedagogical development

1. INTRODUCTION

Inquiry-based learning (IBL) is increasingly recognized as important to developing STEM (science, technology, engineering, and mathematics) skills and interest amongst secondary school students. Indeed, use of IBL has been associated with enhanced student engagement and learning outcomes compared to more passive lecture-based instruction [1], [2]. Additionally, IBL provides students with opportunities to explore real-world applications of STEM principles and gain a better understanding of the multifaceted nature of STEM professions. Consequently, greater integration of IBL has been identified as an important approach to fostering interest in post-secondary STEM education or careers amongst a diverse range of students [3], [4], [5].

Despite the benefits of IBL, there are often practical constraints that limit implementation within secondary school education curricula. Principal components of effective IBL include hands-on experience motivated by real-life applications [4], [6], [7], [8]. However, secondary teachers are frequently impeded from creating such experiences due to a lack of resources (e.g., laboratory spaces, equipment, software) and comprehensive knowledge of current STEM research areas and the associated links to secondary curricula [5].

The *Discovery* educational program addresses these resource and knowledge gaps by partnering engineering graduate students with secondary school teachers to produce and implement IBL projects inspired by current engineering research taking place within university laboratories [9], [10]. For teachers, *Discovery* projects provide access to modern teaching laboratory spaces and equipment that are generally not available in schools, as well as tangible context to motivate student learning. Graduate students, on the other hand, benefit by co-designing and receiving feedback from trained educators on instructional material creation and delivery. By providing an opportunity to fully design and implement a learning curriculum, *Discovery* provides graduate students the opportunity to develop increasingly desired teaching skills [11], [12], [13]. However, given that graduate students must balance research, teaching assistantships and other activities, the need for the development of a structured, generalized template for project design is necessary to accommodate the time constraints faced by graduate students when they are developing instructional materials.

1.1. Program Structure

Discovery is a semester-long educational program and partnership between graduate students at the University of Toronto and secondary science educators from the Toronto District School Board. Participating Grade 11 or 12 secondary school classes in Biology, Chemistry, and Physics are presented with an open-ended, real-world problem designed by graduate students. After being trained to work in university teaching and laboratory spaces, student groups are given the freedom to design and execute experiments using university resources. Specifically, students will iterate on their proposed experiments under the guidance of graduate mentors. The program culminates in a symposium where students present a scientific poster outlining their projects to a broad audience of their peers, teachers, and University of Toronto students and faculty. Uniquely, the *Discovery* program is directly integrated into the classroom: programming is designed in collaboration with secondary school educators to complement the existing secondary school science curriculum, and *Discovery*-related deliverables comprise 10-15% of students' final course grade, as decided upon by partner educators. Graduate mentors are recruited to support 1-3 groups of secondary students who work in teams of 2-4 members, although both of these can vary depending on the number of graduate mentor signups and student enrollment within secondary science courses respectively.

1.2. Program Timeline

Discovery follows the Ontario academic calendar and runs during the Fall and Spring terms of each year from October to January and April to June, respectively. Figure 1 shows the timeline of program activity over the course of one semester. Logistic and curriculum planning for the program begins approximately 2 months before the first student visit to campus. This planning phase includes communication with teachers and administrators from partner secondary schools, development and preparation of projects, and recruitment of volunteer graduate mentors.

Each term, secondary school students work on their *Discovery* projects over the course of three visits to University of Toronto laboratory spaces, during which they receive instruction and guidance from volunteer graduate student mentors. This is supported by one virtual meeting where mentors discuss project progress and provide feedback to students before the last experimental visit. These visits are spaced 2-3 weeks apart. At the end of the term, students present their projects at a poster symposium, giving them the opportunity to share their work with peers, mentors, teachers, and faculty.

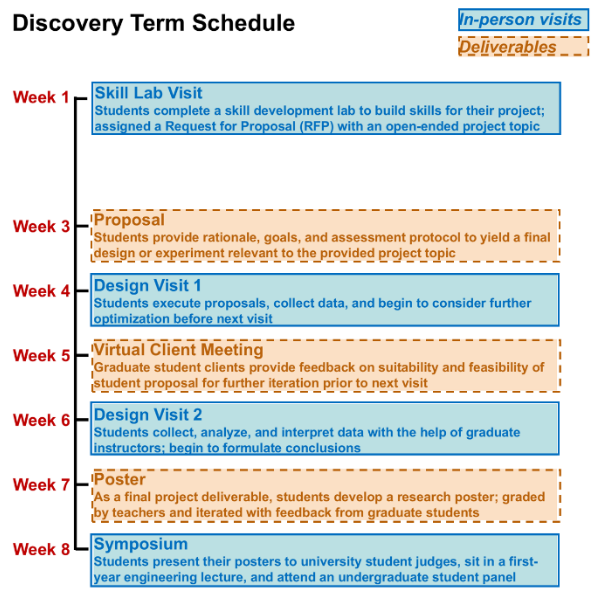

Fig. 1. *Discovery* term schedule. Secondary classes come to the University of Toronto over the course of 3 visits (blue) to execute their *Discovery* projects. Between program visits, students submit deliverables (orange) to graduate mentors for guidance, and to teachers for assessment.

Table 1 outlines an example schedule for the student campus visits. *Discovery* visits begin with mentors preparing the classrooms and lab spaces for the experiments and projects planned for that day. Following pre-lab activities, students move to their teaching spaces to work on their projects for 2 hours. Students regroup for a 1-hour lunch break then resume work on their projects for another 2 hours in the afternoon. This schedule directly aligns with the partner school days.

Table 1: Sample *Discovery* visit schedule (Chemistry)

Time	Student Activity	Mentor Activity
8:00-9:00 AM	Arrive to campus; breakfast	Set up equipment and reagents in teaching lab
9:00-10:00 AM	Pre-lab lecture by Chemistry mentors	
10:00 AM-12:00 PM	Work period in teaching lab	
12:00-1:00 PM	Lunch	Lunch; set up teaching lab
1:00-3:00 PM	Work period in teaching lab	
3:00-3:30 PM	Students leave	Cleanup and debrief

1.3. Project Curriculum

During the first visit to campus, students participate in introductory lectures to provide the necessary theoretical project background. Students subsequently complete a hands-on “Skill Lab” protocol that introduces them to the equipment and experimental techniques that will be available to them throughout their projects. The Skill Lab is designed to enable students to acquire the technical competencies required for their project. For example, the protocol may teach students micropipetting techniques and how to perform calculations for proper reagent measurements and experimental consistency. During the first visit, students are also provided with a “Request for Proposal” (RFP) document that outlines the real-world motivation for the problem to be investigated during the semester and defines the open-ended research objectives that will be investigated. Following the first visit, students respond to the RFP by developing a research proposal that outlines their individual group hypotheses and experimental designs. Graduate mentors review the proposals and provide feedback before students execute their proposed experiments during the second and third on-campus laboratory visits.

1.4. Motivation for Developing New Program Projects

The continuous development of new *Discovery* projects is essential for accommodating an increasing number of program participants and maintaining program relevance within evolving STEM curricula. However, designing new inquiry-based projects presents significant challenges for graduate students who volunteer as mentors, as they need to balance curriculum development time with their research and other commitments (e.g., courses, teaching assistantships, etc.). Additionally, while graduate mentors often have some undergraduate teaching experience, different instructional approaches must be considered when developing learning materials for secondary school students. For example, skills that undergraduate students would be assumed to possess—such as use of micropipettes or spectrophotometry—may be entirely new to secondary students, necessitating additional integration of skill-based instruction and practice into educational materials. Such unforeseen gaps between graduate student instructor expectations and secondary student competencies prior to *Discovery* can lead to diminished experiences for both students and volunteers.

With the objectives of streamlining *Discovery* curriculum development and better preparing graduate mentors for secondary student instruction, we have developed a standardized template to serve as a guide for mentors when designing new *Discovery* projects. While graduate mentors are encouraged to incorporate their own areas of interest and expertise, the template provides an overview of project aspects that need careful consideration but may otherwise be overlooked. To further aid project design, the template provides criteria to define successful project implementation and ensures consistency in experience across all three subjects.

1.5. Project Template

The template outlines critical project components for streamlining project ideation, development, and planning as graduate mentors design new *Discovery* curricula. These considerations will not only allow graduate mentors to define experiments that students can perform during programming but also incorporate the practical considerations that must be planned for a successful inquiry-based learning experience and ensure consistency across the experiences of the difference STEM disciplines.

The template is divided into prescribed and open-ended components of *Discovery* projects. The prescribed components (i.e., the Skill Lab protocol and RFP) are elements of the project that all students will utilize in the same manner and should be designed to provide students the competencies and resources needed to successfully complete their projects. The prescribed activities represent the primary opportunities during campus visits for students to acquire new skills. Therefore, graduate mentors must carefully consider what technical competencies will be required and how they should be taught.

The open-ended components (e.g., the proposal, experimental design, etc.), on the other hand, should be designed to provide students the freedom to independently investigate parameters of interest and develop critical thinking competencies. The open-ended or inquiry-based components should allow students to propose and test different experimental conditions, fostering independent investigation, problem solving, and critical thinking, thereby aligning with the mission of the *Discovery* program. While designing the open-ended components, graduate mentors must identify the potential experimental parameters that students could independently investigate during Design Visits.

Consideration of the open-ended components can further facilitate the design of the prescribed materials. For example, if it is expected that students may choose to modify and explore specific parameters (e.g., reagent concentration) within their projects, the Skill Lab might be designed to demonstrate how those parameters could be modified and analyzed under different conditions. Moreover, careful consideration of the parameters of interest selected by students allows for graduate mentors to anticipate materials needed for *Discovery* Design Visits, or to disclose in advance potential experimental constraints (e.g., maximum stock concentrations of reagents) to students and educators prior to submitting their Proposals. Figure 2 outlines both the prescribed and open-ended components of the project template for *Discovery* in blue.

1.6. Success Criteria

Key considerations for curriculum development involve the assessment of project feasibility to ensure alignment with the program's schedule and logistical constraints. Each *Discovery* project consists of structured laboratory sessions with work periods defined by time and space. Experiments must be feasible within a single program day, typically divided into a three-hour morning session and a two-hour afternoon session (Table 1). To maximize utility of time within the teaching labs, time-sensitive steps should be carefully planned to avoid conflicts with breaks and transitions between activities. Furthermore, experimental procedures should be designed to fit within a single laboratory visit, with the second visit serving as an opportunity for refinement or replication. Skill Lab activities are structured to train students to engage in the necessary lab safety practices and essential techniques within a single session. This ensures students can successfully and safely execute their experiments during laboratory visits.

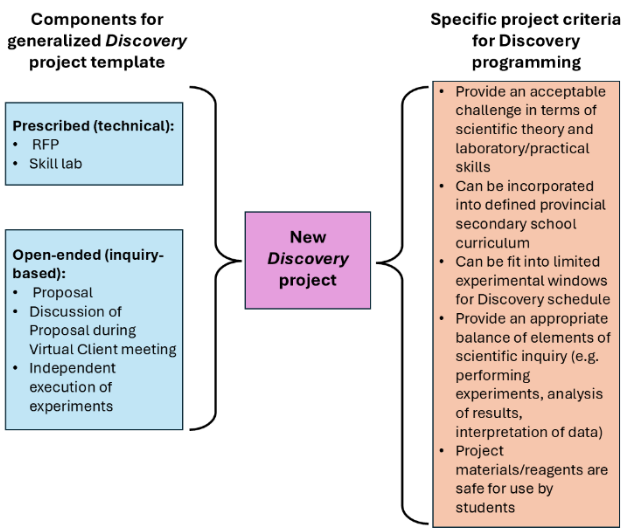

Fig. 2. Template for *Discovery* projects (blue) along with criteria specific for programming (orange).

Other critical considerations in project design are safety, sustainability, and cost-effectiveness. Selection of project materials should prioritize affordability, reliability, and ease of use, while also ensuring compliance with safety standards. Experiments should be designed to use safe, non-toxic, and environmentally friendly chemicals wherever possible, allowing for easy handling by students with minimal risk and reducing hazardous waste generation. All experimental procedures should follow best practices for chemical handling, proper waste disposal, and the use of personal protective equipment to maintain a safe laboratory environment. Whenever possible, experimental protocols should be streamlined to minimize unnecessary steps, extended incubations, and reliance on specialized equipment. A safety-conscious and cost-efficient approach not only ensures the sustainability of the program but also facilitates its expansion to accommodate more students and *Discovery* school partners.

Finally, each project should provide an appropriate balance of the elements of scientific inquiry with clearly defined student learning outcomes. These outcomes should encompass the technical skills students will acquire through performing experiments and collecting data. They should also include the scientific concepts students will explore through background research and the critical thinking skills they will develop through formulating hypotheses, independently analyzing data, and interpreting results. By maintaining a balance between hands-on experimentation and data-driven inquiry, *Discovery* projects provide students with a comprehensive research experience that mirrors real-world scientific investigation. In alignment with the template components (prescribed, open-ended) and with the elements of inquiry, projects must provide an acceptable challenge for students in terms of both theory and practical knowledge for optimal learning outcomes. Figure 2 illustrates the template and the proposed criteria (in orange) for new *Discovery* projects.

2. Application of Template and Success Criteria for Developing New Program Projects

A new project developed by graduate mentors for Fall 2024 Chemistry programming serves as an example of a generalized template for *Discovery* projects. The new Chemistry curriculum was initially conceptualized by drawing inspiration from an online science fair project that outlined the creation and testing of shampoos [14]. The *Discovery* Chemistry team developed a project for Grade 12 students, working in groups of 3-4, to formulate and optimize unique organic shampoos derived from sustainable sources, and compare their proposed formulations to a store-bought or commercially available control. The programming content for the Chemistry project consisted of an RFP document for teachers and students to provide a real-life context to the project, supported by a one-hour lecture introducing key concepts. This was followed by a Skill Lab protocol for students to complete, a Chemistry Background document on relevant theory and terminology for students, as well as a two-part Proposal for students to submit for feedback from graduate mentors.

2.1. Defined Template Component

During the first student visit to campus, Chemistry students were required to complete the experiments outlined in the Skill Lab protocol. This protocol provided detailed steps for creating two pre-defined shampoo formulations and performing 4 different experimental procedures to characterize the shampoos created by students. Table 2 outlines the main components of the Skill Lab for the new Chemistry project. The Skill Lab protocol permitted students to develop practical competencies within the laboratory setting with guidance from graduate mentors.

Table 2: Lab components aligned with technical competencies students are intended to develop through project experience during the Skill Lab.

Chemistry Skill Lab components	**Student competencies**
Creation of two pre-defined shampoo formulations	• Use of micropipettes • Measurement of liquid volumes • Preparing formulations
Characterization of shampoos: • Cleaning power (how much dirt can shampoo remove?) • pH (would the shampoo be compatible with the scalp?) • Foaming behaviour (would the shampoo be marketable, considering consumers prefer a shampoo with high foaming behaviour?) • Dirt dispersion (cleaning efficiency; how much dirt remains in the foam phase?)	• Preparation of dilutions • Independent handling of reagents and organization of experimental samples • Recording observation, analyzing results, and formulating hypotheses

Relevant skills included the use of micropipettes, independent handling of reagents and organization of samples, and the preparation of formulations and diluted solutions for experiments. Completion of the 4 characterization experiments provided students with the foundation they would require for completing their projects, as students performed these tests using their own proposed shampoo formulations. The 4 experiments were designed with a specific question in mind regarding shampoo performance, as seen in Table 2.

2.2. Open-Ended Template Component

Following completion of the Skill Lab, students developed their Proposals based on their initial observations, with guidance from graduate mentors. The Proposal was completed in two parts and was designed to integrate critical elements of scientific inquiry (analysis, interpretation of results, design of experiments, etc.) and foster independent thinking and problem solving amongst students. In Part 1, students outlined the project background and responded to guided questions designed to help plan their experiments, refine their hypotheses, and consider key variables. Following the first experimental visit, students completed Part 2 of the Proposal, where they defined specific experimental conditions to test. This two-step process allows students to iteratively refine their approach, select the appropriate methods to test their hypotheses, and ensure their experimental design effectively addresses their research question of interest. This inquiry-based component of the *Discovery* project reflects the CEAB (Canadian Engineering Accreditation Board) attributes 2 and 4 on problem analysis and design respectively as students develop and analyze their proposed solutions to real-world problems [15] and importantly aligns with the four broad areas of scientific investigation within Ontario's secondary science curriculum [16]. Table 3 outlines key activities and competencies for students to gain from the Proposal.

Table 3: Two-part *Discovery* Proposal coupled with key activities and development of critical thinking competencies related to scientific inquiry.

Chemistry Proposal	**Student competencies**
Proposal Part 1	• Application of Chemistry background theory • Partial interpretation of Skill Lab results • Preliminary conceptualization of hypothesis for project
Proposal Part 2 (Feedback or guidance provided by graduate mentors)	• Analysis of data and interpretation of complete results from Skill Lab • Conceptualization of hypotheses for project and design of experiments for final visit • Identification of key variables (independent, dependent, controlled) • Selection of appropriate methods • Independent execution of experiments

Together, the Skill Lab and Proposal provide a structured template that combines both prescribed and inquiry-based components to provide students with a comprehensive, hands-on learning experience (Tables 2 and 3). The prescribed component includes the Skill Lab, RFP, and a preparatory lecture, all of which establish the foundational knowledge and technical skills necessary for experimentation. The Proposals make up the inquiry-based component which serves as a foundation to guide students in developing a clear experimental plan.

3. OUTCOMES OF NEW PROJECT IMPLEMENTATION: EVALUATION OF SUCCESS CRITERIA

Our team approached the delivery of the new Chemistry project by continuously monitoring student progress and identifying areas for future improvement to be made to the project during the semester of programming. Over the course of this first project iteration, our team proactively developed interventions to support student progress. These interventions aimed to address challenges associated with delivering new *Discovery* projects, particularly for graduate mentors engaged in full-time research, with varying levels of laboratory experience among both mentors and secondary students. At the end of each *Discovery* visit, student team progress was discussed during a debriefing amongst graduate mentors, and necessary interventions to support the project completion were developed. Interventions taken to support students during Chemistry programming in Fall 2024 are discussed below.

One challenge that quickly emerged regarding the delivery of the Chemistry project was the time required for students to complete the Skill Lab protocol. This is likely reflective of lack of previous student experience. To enable students to complete the Skill Lab and focus efforts on designing and executing independent experiments, graduate mentors prepared diluted solutions from students' shampoo stocks to facilitate the completion of characterization tests during Design Visit 1. Once students completed all characterization tests at the end of Design Visit 1, graduate mentors prepared the novel shampoo formulations proposed by students. This preparation permitted students to investigate two parameters of interest by modifying their stock formulations accordingly (example: decreasing pH by adding vinegar; effects of surfactant concentration) and allowed students to complete the characterization tests of their choice to examine effects of modifying their selected parameters. This approach reduced the time students spent on creating the shampoo stock but still allowed students to further develop laboratory skills such as pipetting and creating dilutions by modifying their novel formulations to different conditions.

While students are expected to complete the experiments outlined in the Skill Lab during the first day of programming, the Chemistry team also developed contingencies within the programming package that supported students through the new project in between *Discovery* visits. For example, rather than having a single Proposal to submit for feedback from graduate mentors, Chemistry students were asked to submit a two-part Proposal. This was done to accommodate students who did not complete the Skill Lab within the first visit. Although students returned to complete the Skill Lab (prescribed project component, Table 2) during the subsequent visit, the first part of the Proposal allowed for students to critically apply background theory and develop preliminary hypotheses, which falls under the open-ended project component (Table 3). Thus, this contingency was designed to provide a balance of both prescribed and open-ended components within our proposed project template throughout *Discovery* activities. The specific interventions and contingencies created for the delivery of the new *Discovery* project are illustrated in Figure 3. Following the completion of *Discovery* programming in the Fall 2024 semester, the curriculum and delivery of the new *Discovery* Chemistry project to students were evaluated by a participating secondary school chemistry teacher (and co-author of this paper).

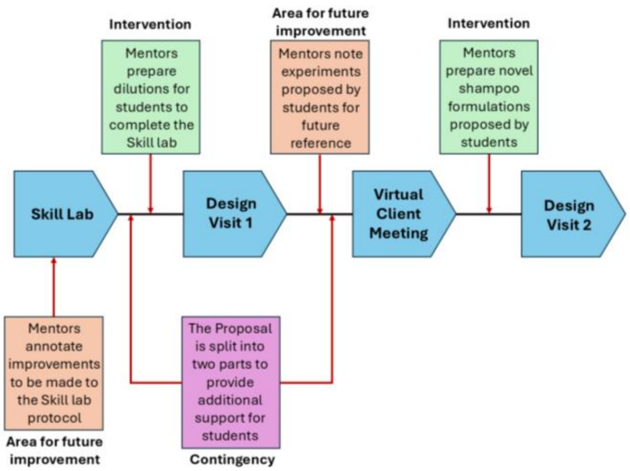

Fig. 3. Illustration of interventions (green), contingencies (purple) and areas to note for future improvements or reference (orange) taken by graduate mentors during delivery of a new Chemistry project in the *Discovery* program (key activities in blue).

Relevant proposed criteria for educators were evaluated in terms of whether the project aligned with each criterion. Justifications were provided for the assessment of each criterion. Table 4 provides the outcomes on the proposed success criteria for the development and implementation of the new Chemistry project. This was shared amongst graduate mentors who were involved in developing the new project to note recommended future improvements to the project curriculum.

As observed in Table 4, the new Chemistry project delivered in Fall 2024 met most of the relevant proposed criteria for new *Discovery* projects, except for fitting within two-hour experimental windows. This shortcoming is primarily attributed to variability in the time required for student teams to complete experiments, rather than the project being unsuitable for secondary students in general. Considering that evaluation of the success criteria identified an issue with time for students to complete activities, the Skill lab within the prescribed template component should be modified to reduce the number of intended competencies for students.

Table 4: Proposed success criteria evaluated by a collaborator using the new Chemistry project as an example

Proposed criteria for new *Discovery* projects	**Criterion met (indicated by ✓)**	**Justification**
Project provided an acceptable challenge for students in terms of scientific theory or knowledge	✓	Concepts/theory of complex organic molecules such as surfactants, implications in environmental research
Project provided an acceptable challenge for students in terms of practical laboratory skills	✓	Use of pipettes, measuring pH enabled this criterion to be met
Project provided an appropriate balance of both prescribed and inquiry-based components	✓	Skill Lab provided steps for completion of experiments in sufficient detail and student had very wide range of ingredients to use for novel formulations
Project could be incorporated into defined provincial secondary curriculum	✓	Project considered as extension of Chemistry acids and bases and organic chemistry units [16]
Project could be fit into 2-hour experimental windows		Time to completion varied amongst student teams
Project provided an appropriate balance of elements of scientific inquiry	✓	Students given chance to design and conduct own experiments and analyze interpret results

Upon reflection, other improvements that could be made to the new Chemistry project would be having graduate mentors prepare the pre-defined stock shampoos for use in the Skill Lab, and not prepare formulations, which was initially an activity intended for the prescribed project component outlined in Table 2. This adjustment would allow secondary students to focus on formulating their own novel shampoo(s) during subsequent Design Visits, rather than spending excessive time on stock preparation. While this new project still provided an appropriate balance of key components for the proposed *Discovery* project template (and open-ended aspects), implementing this practice would reduce time spent on completing the Skill Lab and allow for multiple rounds of formulation design for students. Moreover, to allow for continuous improvement of the new *Discovery* project in the long-term, graduate mentors kept a physical master copy of the Skill Lab protocol to annotate any changes or modifications to be made during programming. Additionally, mentors documented the types of experiments that student teams proposed in the independent inquiry-based component of their project for future reference while preparing feedback for students prior to the Virtual Client Meeting. Figure 3 highlights important notes on the project taken by graduate mentors for future improvement or reference during key *Discovery* events (Skill Lab, Virtual Client Meeting).

When reflecting on the role of *Discovery* within the broader context of IBL, this program provides secondary students and educators with graduate mentor course facilitators and laboratory resources for inquiry-based learning opportunities. Therefore, the *Discovery* project template and its success criteria provide further support for graduate mentor success in this IBL environment [5], [9], [10], [11], [12], [13]. Since inquiry-based learning can be demanding in terms of time and resources [5], we anticipate that providing a project template for graduate students may further enhance pedagogical development of graduate mentors as previously demonstrated by *Discovery* program outcome analysis [11], [12], [13], and further enable effective implementation of student IBL project experience [9], [10].

4. CONCLUSIONS

Herein, we described a newly designed standard template that provides a structured approach for graduate mentors in the *Discovery* program to develop inquiry-based learning projects for secondary students. The template consists of prescribed and open-ended components with defined criteria for programming. Both the template and success criteria can be generalized for new projects across all *Discovery* subjects (Biology, Chemistry, Physics) and will promote consistency of learning experiences across all participants.

A new Chemistry project delivered in the Fall 2024 semester was used as an example to outline the project template as well as the criteria. The outcomes of the content and delivery of this new *Discovery* project were evaluated against the proposed success criteria. The newly developed project was found to meet all but one of the criteria. An area of improvement regarding how the project fits into limited experimental windows was identified. We highlight specific interventions taken by graduate mentors to address challenges that emerged during programming with a new project, as well as contingencies that were integrated into the Chemistry curriculum before project delivery to support student learning throughout the semester. We also identified critical documents for graduate mentors to reflect and identify improvements or reference for future offerings. We anticipate that providing a template and criteria for new *Discovery* projects, combined with careful oversight by graduate mentors throughout the semester, will expand the current repository to suit an increasing number of program participants. While we only evaluated one new project over its first semester of programming, we expect that the proposed criteria can be used to evaluate the same project over multiple semesters to identify key areas for continuous, iterative improvement and can be adapted to projects developed for other *Discovery* subjects. Student feedback from the Fall 2024 semester will be analyzed once received. Importantly, future studies will involve the analysis of student feedback and performance to determine whether the template and success criteria for new *Discovery* projects will provide similar learning outcomes for students compared to previously iterated project curricula.

Acknowledgements

The authors would like to thank the entire team of graduate mentors for their contributions to the program, and for facilitating the delivery of the new *Discovery* project. The authors are grateful for the continued support from laboratory facility managers at the University of Toronto’s Faculty of Applied Science and Engineering, who generously provide the teaching spaces and equipment for *Discovery* programming. The authors would like to acknowledge financial support provided by NSERC PromoScience Grant #577316-2022.

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