UNIVERSITY OF WATERLOO

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February 26, 2018

To Whom it May Concern:

The Faculty of Mathematics endorses the February 2018 Final Assessment Report for Applied Mathematics, Computational Mathematics, Combinatorics and Optimization and Pure Mathematics.

Let me again express my appreciation for the efforts of your office, the Math Undergraduate Office, the program directors and the departments have invested in the preparation for the final assessment report.

As previously discussed, the outcome of the reviewers' visit had many problematic aspects. In particular, the reviewers' report had factual errors, and it opines on matters outside the scope of the review (and therefore for which no information was provided).

Despite this, the Office of Academic Integrity, the department heads and program director responsible for these programs have tried to extract as much useful insight as can be gleaned from the report. I find the final assessment report for these programs and the implementation plan to be thoughtful and completely appropriate under the circumstances.

Sincerely,

Stephen M. Watt, Dean
Faculty of Mathematics

MC, 200 UNIVERSITY AVENUE WEST, WATERLOO, ON, CANADA N2L 3G1

Final Assessment Report
Applied Mathematics, Computational Mathematics, Combinatorics and Optimization, Pure Math (BMath)
October 2018

Summary of the Program Review:
In accordance with the University Institutional Quality Assurance Process (IQAP), this final assessment report provides a synthesis of the external evaluation and the internal response and assessments of the Applied Mathematics, Computational Mathematics, Combinatorics and Optimization and Pure Math (BMath) programs delivered by the Faculty of Math. A self-study (Volume I) for each program was prepared and submitted to the Associate Vice-President, Academic. Each self-study presented the program's description and learning outcomes, an analytical assessment of the program, and program data, including a standard data package prepared by the Office of Institutional Analysis & Planning (IAP). Appended to each report were the course outlines for all the courses in the program, and the CVs (Volume II) for each full-time faculty member associated with the on-going delivery of the program.

Two arm's-length external reviewers were selected by the Associate Vice-President, Academic from Volume III: Dr. Michael Lamoureux, Professor of Mathematics, University of Calgary; and Dr. Mary Pugh, Professor of Mathematics, University of Toronto. In addition one internal reviewer, Dr. Michael Dixon, Professor of Psychology at the University of Waterloo was selected by the Associate Vice-President, Academic.

They reviewed the self-study documentation and then conducted a site visit to the University on July 18-19, 2016. The visit included interviews with the Associate Vice-President, Academic; Dean of the Faculty; Faculty Associate Dean of Undergraduate Studies, Chairs and Directors of the Departments, Faculty members, staff and meetings with a group of current undergraduate students.

This final assessment report is based on information extracted, in many cases verbatim, from the self-study, the external reviewers' report and the program response.

Program characteristics:

Applied Mathematics (Applied Mathematics/Biology Option, Applied Mathematics/Earth Sciences Option, Applied Mathematics/Economics Option, Applied Mathematics/Physics Option, Applied Mathematics with Engineering Electives, Scientific Computation/Applied Mathematics)

Applied Mathematics focuses on the development of a variety of differential equation-based models. These yield mathematical and computational descriptions of dynamic phenomena: from the motion of ocean waves, to the control of aircraft flight, to the volatile price of stock options. The Applied Mathematics plan builds on the fundamental courses in calculus and linear algebra and offers a variety of core courses in ordinary differential equations, partial differential equations, and computational mathematics. These courses, along with an introduction to physics, provide a foundation for modeling across a wide range of domains.

Combinatorics and Optimization (Combinatorics and Optimization, Mathematical Optimization, Mathematical Optimization – Business Specialization, Mathematical Optimization – Operations Research Specialization)

Combinatorics is the study of discrete structures. Since computers work with discrete objects, this subject is becoming increasingly important in our digital age. Optimization is the problem of minimizing or maximizing functions subject to a set of constraints.

The department offers two undergraduate Honours programs, namely a program in "Combinatorics and Optimization" and a program in "Mathematical Optimization". The first Honours program emphasizes both subjects equally. It is natural to teach both topics together as Combinatorics and Optimization are complementary subjects. Problems in Combinatorics have an Optimization counterpart and combinatorial tools are needed to solve discrete optimization problems. The second Honours program (Mathematical Optimization) provides a strong foundation in the field of optimization. That program has two options, namely, Operations Research and Business; the latter one is tailored to Math Business students.

Computational Mathematics

Mathematical models arise in a wide variety of fields: business, economics, engineering, finance, medicine, science, and many others. The application of computer methods to simulate such models was traditionally called "scientific computation," though the practice has spread far beyond its roots in science to encompass problems arising in all areas of society. The results of such simulations are numerical answers, formulae, data sets, plots, charts, and images that help us to understand the nature of the world around us, and allow us to predict and influence the future.

Developing and analyzing such models involves a blend of mathematics and computer science. It includes issues such as the implications of finite precision arithmetic, the efficiency, accuracy, and stability of numerical computations, the development and maintenance of mathematical software, and the effects of modern developments in computer architectures and networks.

Pure Mathematics

Pure Mathematics comprises a broad spectrum of mathematics. Interests of the Department include algebra, logic, number theory, analysis, geometry and topology, and range from the very classical to the most modern.

Pure Mathematics programs focus on developing students' knowledge and understanding of fundamental areas of mathematics. Our students develop outstanding analytical and problem-solving skills. They are trained to think logically, critically and creatively, and to write clear, rigorous arguments.

There are also a number of joint programs: Joint Applied Mathematics, Joint Combinatorics and Optimization, Joint Pure Mathematics, as well as, four associated minors: Applied Mathematics Minor; Combinatorics and Optimization Minor; Computational Mathematics Minor; Pure Mathematics Minor.

Summary of strengths, challenges and weaknesses based on self-study:

Applied Mathematics

Strengths

- Small class sizes in third and fourth year
- Large number of specialized courses related to research areas of faculty members offered in third and fourth year
- Many students have the opportunity for one or more undergraduate research terms
- Large percentage of strong students
- Co-op program is healthy with good placement rate

Challenges

- Although not seen in the data given, there are indications that enrolment in our Mathematical Physics plan is decreasing as more students choose the Physics version over the Applied Math version
- Students only enroll in Applied Math in second year, however our degree requires that they take one or more first year Physics courses. We need a way to identify and contact potential students earlier in their program
- Diversity of students in our required courses: Applied Math students, Physics students and Math students other than Applied Math. The majority of those enrolled may not be Applied Math students.

Weaknesses

- Overall enrolment is low

Combinatorics and Optimization

Strengths

- The Honours program in Combinatorics and Optimization is unique among North American institutions at the undergraduate level.
- With over thirty full-time professors the department has an unmatched concentration of researchers and instructors in Combinatorics and Optimization

Challenges

- Few high schools and first-year undergraduate students have heard of Combinatorics or Optimization. This is in sharp contrast with other areas of studies such as Computer Science or Business.

Computational Mathematics

Strengths

- The biggest strength of the program is breadth. This is also the most prominent distinction from other programs offered in the Faculty of Mathematics.
- The large number of affiliated members from Mathematics, Engineering, and Science Faculties (over 50 in total), gives a broad exposure of subjects to students. Not many programs on campus have the same scale of diversity
- Students receive training in a broad set of skills that well prepare them for future jobs or studies.

Challenges/Weaknesses

- Recruitment of students can be challenging as it is not always clear how computational mathematics is different from mathematics and computer science.
- All of the undergraduate courses are offered through other departments/schools; hence, the program lacks control over the offering and scheduling of the undergraduate courses.
- The number of computational math students in any of these courses is often quite small. As such, it is very possible for a computational math student to go through the program and never meet any other students within the program.
- The day to day advising of the Computational Mathematics program is run from the Mathematics Undergraduate Office. Unfortunately, this causes a disconnect from the people administering the program, and the people responsible for maintaining the program.

Pure Mathematics

Strengths

- The quality of the Pure Mathematics Major program and the challenge it provides to even the best students in the Mathematics Faculty is one of the great strengths of the program. This is attested by the fact that their students win major external awards and are admitted to the premier graduate schools.
- Pure Mathematics is known throughout the Faculty to have outstanding teachers, with 5 of the 23 faculty members having won teaching awards.

Challenges/Weaknesses

- Due to the small size of the department, they are not able to offer the frequency and variety of courses that might be possible in larger mathematics departments.

- The size of NSERC grants in mathematics limits the number of research opportunities they are able to offer to their students. They generally have more interested and talented students than they can fund.

Summary of key findings from the external reviewers:

Waterloo is very successful at attracting top students from across Canada into its mathematics programs, and thus it can be highly selective in choosing to admit only the most competitive applicants with high grades and excellent achievements on contest exams. Generally speaking, all the programs reflect a strong, traditional approach to mathematical training with foci on central, important topics. However, there are some gaps in the curriculum between the programs that the Departments, as a group, need to identify and fill where appropriate.

Attrition rates seem to be impressively low. The vast majority of students complete their degree at Waterloo, although there is quite a bit of movement between programs before completion (which indicates healthy options available for the students). Reviewers noted that some students moved on to top schools for graduate studies, including University of California Berkeley, Cambridge, Chicago, Columbia, Harvard, MIT, Stanford and Toronto. Other recent graduates of the UW math undergrad programs include a Clay Fellow at Stanford, a Moore Instructor at MIT, a PDF at Princeton, and a winner of the CMS Doctoral Prize which are all very notable accomplishments for the student body.

In addition, most of the faculty members are active in the larger, international research community. They participate in conferences and workshops, organize similar events, collaborate broadly, and are active in organizations relevant to the discipline (e.g. the Canadian Mathematical Society, the Canadian Applied and Industrial Mathematics Society, the American Mathematical Society, etc.). This keeps the faculty at the forefront of current research and scholarship, ensuring the students are taught by professors aware of the latest developments in the discipline.

Program response to external reviewer recommendations:

Recommendations

1. Significant effort must be made to improve the information and advice provided to potential and current undergraduate students in the programs in mathematics, whether that be through online resources and webpages, or in-person advising. The wide variety of math programs offered from these four units should be presented as a cohesive unit that students can enter with confidence. Currently, online information on what programs are available and their requirements is spread across many webpages, presenting a confusing matrix of data for the students to sort through. Some programs are described in various Department webpages, others in the Faculty's webpages,

and many details are explained in University documents. In particular, Computational Mathematics being independent of Departments does not appear in any prominent way in the online documentation. Some information on possibilities and expectations (such as the option to take graduate courses while an undergrad, or to take a minor outside the Faculty) seems to be absent altogether

The Departments state that they do not have the resources to do one-on-one advising with all students. Even if such advising were available, it would have to be complemented by clear, easy-to-understand documentation on proper program information which would allow students to explore their options and formulate their questions. It is strongly recommended program documentation for students be revised and clarified for student use. Such documentation could include student profiles of real (or hypothetical) students including the generic student who came in with top grades and went through the programs with the goal of going to graduate school in math, the ''good at everything" student who came in with top grades and either needed to discern a single focus or chose to focus on two subjects, the "Renaissance/Non-standard" student who came in with top grades and wants to study both computer science and psychology, the "challenged" student whose path through university has had bumps in the road and how they kept on track and so forth. One does see student profiles if one clicks on the "Future Undergraduates" link of the Faculty of Mathematics page but current undergraduates wouldn't be looking there.

Response

With respect to the portion of the recommendation relating to one-on-one advising, we would like to clarify that all four academic units do provide one-on-one advising to all students interested in their programs. In addition to this, there are regular "info nights" to inform students about the possible programs. We believe these measures address that part of the recommendation.

With respect to the portion of the recommendation concerning departmental and faculty websites, there are already processes in place to improve, maintain and update these webpages. For example, Jodi Szimanski (Director, Strategic Communications) is responsible for all faculty level webpages and these have been recently revised to include more information that is helpful for the undergraduate students. As another example, the Pure Math department hired a graduate student for Winter 2017 to overhaul all of the Pure Math related webpages. The responsibility for the pages for Computational Mathematics is held jointly by the Director (Jeff Orchard) and the administrative assistant (Amanda Guderian) and recently (Fall 2015) underwent major revisions. The other two units are similar. We expect that these processes are sufficient to address this recommendation.

2. We encourage the Departments and Faculty to reconsider the program entrance requirements. While the emphasis on contest exams scores (in conjunction with high school grades) has served

the Departments well in selecting highly competitive, performance-focused students who will succeed in the program, it also may bias against creative, mathematically talented individuals who don't necessarily like competition. This does not serve the wider community of potential students who could have a full and productive career in mathematics. We understand that the math competitions and math education outreach are a vital service that the Faculty of Mathematics is providing to Canada and that, as a result, it's part of its branding. We also understand that the mandate of the University is broader than simply trying to train undergraduates who might become world-class research academics. That said, it would likely be healthier if the math competition aspect be significantly downplayed the moment students *arrive* at Waterloo and start the next stage of their lives.

Response

This recommendation is for something beyond the mandate of the reviewers, and outside of the mandate of the units being reviewed; admissions are handled by the Faculty of Mathematics, and math students enter into the programs under review after their first year of study.

Despite that, it is worth mentioning that the faculty has made a number of changes recently to the way that undergraduate students are admitted. All students are now required to supply a "Admissions Information Form" with their applications. This allow the students to discuss things beyond their grades and competition scores. The Faculty of Math takes these forms quite seriously, and tries to admit students who are "well-rounded" as well as being very strong academically. It has been the faculty's experience that these are the students that are most successful in University.

3. A process should be put in place to continuously update and keep current the courses and curricula in the programs. It was somewhat surprising to these reviewers to see, for instance, that the Pure Math program is almost identical to similar programs from 35 years ago. There needs to be room in the programs for modern advances. Ideally, these course reviews would be done as a team by the three Departments (Applied Math, Combinatorics & Optimization, and Pure Math). In addition, it would be wonderful if there were some sort of teaching credit mechanism by which a faculty member from one department could teach a course that is affiliated with another department. One would want to have some sort of bookkeeping to ensure that over a five year windows, say, that these teaching exchanges are fair and balanced. Also, it would be helpful if there were faculty hires who were joint hires between two departments. While joint hires can be delicate when departments have markedly different cultures and professional expectations, because Applied Mathematics, Combinatorics & Optimization, and Pure Mathematics would normally be all in a single department and so the usual difficulties that joint hires would face should be quite minimal.

Response

The recommendation was made based on incorrect information. All departments have processes in place to ensure that the programs are continuously updated and improved. In particular, all

three departments have an associate chair for undergraduate studies, (Mohammad Kohandel for Applied Math, David McKinnon for Pure Math and Ricardo Fukasawa for C&O). Part of the mandate of these associate chairs is to oversee, update and improve the undergraduate curriculum. They would also identify any gaps within the curriculum and work to remove them. The position of associate chair rotates amount the faculty, and is supported by a curriculum committee. This ensures that the program is always being kept modern, and that multiple viewpoints are always involved. The structure for Computational Math is slightly different, in that the role of the associate chair is done by the Director, in consultation with the undergraduate advisor (Martin Pei), and the role of the curriculum committee is done by the steering committee. All four units have undergone changes, sometimes minor, sometimes significant, on a regular basis as part of this process.

The reviewers were informed that this was the case and given many examples of improvements to the programs. These processes currently work well. As the programs are already doing what the recommendation asked, it is believed that no further action is required to address this recommendation.

In addition, a curriculum committee for the "core courses" has been created to look at those courses that are common to all programs within the faculty. A number of changes have already been made to the calculus stream, and they are currently looking at other core courses. This will be an ongoing committee made up of the undergraduate associate chairs, in addition to other relevant parties.

A more collaborative approach to teaching courses and hiring researchers would be a welcome change, and we are already working on developing processes to make this change possible.

4. On a related matter, a process is needed to identify and cover any gaps in the curriculum. Perhaps because of the division of math into separate departments, there seem to be some holes that are not covered in the various mathematical programs. Geometric PDE's, theoretical PDE's, mathematical probability, some modern harmonic analysis (both pure and in applications), and industrial applications are some examples that highlight the issue. To present the students with a comprehensive mathematics education, it is important to monitor the breadth across all program and ensure important fields are covered.

   Response
   Each department has an undergraduate committee whose purpose is to examine and renew the curriculum in each department. In addition, the Undergraduate Affairs Committee at the Faculty level is charged with the same task at a higher level. We will continue to work on providing the most excellent and broad-ranging courses that we can, given the resource constraints we must work with.

5. The university needs to also consider the issue of renewal of faculty in Pure Math and Combinatorics & Optimization. Both departments appear to be "top heavy", especially the Pure Math department.

	Asst. Prof.	Assoc. Prof.	Full Prof.
Applied Math	4 (17%)	7 (30%)	12 (52%)
C & O	3 (11%)	6 (22%)	18 (67%)
Pure Math	2 (9%)	4 (17%)	17 (74%)

Assuming that the time to tenure/promotion is 6 years and that the professorial career is 35 years, then one could expect 17% of the faculty to be assistant professors. In practice, one would want higher numbers than this. Junior faculty are vital for bringing in new fields, new ideas, and for shaking up the status quo (however much senior faculty might resent such disruption). Not all assistant professors get tenure. Also, strong departments will have hired so well (and supported their hires so well) that some assistant and associate professors will move to even better departments. While such losses are unfortunate to the department, they are a sign of good taste in hiring and vigour - the departing faculty member will, no doubt, have invigorated the department while they were there and will, one hopes, have left with nothing but good things to say about the department they left.

Response
As should be expected, all departments are always willing and eager to hire strong candidates. In fact, all three departments hired in 2017. In addition to these hires, the faculty is attempting to hire a junior URC as an exceptional hire. The candidate under consideration has strong ties to all three departments. The departments will continue to hire excellent and energetic junior faculty members to all three departments, as resources allow.

6. While we did not meet with any lecturers, the research faculty felt that lecturers need to be more fully integrated into departments so that they can be full participants in the delivery of the programs. For the lecturers to properly prepare the students for upper level courses, likely they need to do more than just teach first-year courses -- it might be appropriate for them to also teach the upper level courses. This would help address concerns raised about the mismatch between what is being delivered in first year courses, and what professors are needing their students to master before entering the upper years of the programs. Also, it would help if lecturers have a primary departmental affiliation. Having a departmental affiliation would, one hopes, allow them to be more fully aware of what students will need to know after their first year. Some of the research faculty expressed concerns that some of the first-year courses are not open to innovation. Running a large first-year course is a complicated, delicate job and it's easy to imagine that once the course coordinator has "figured things out" that he/she would prefer to let the machine run without change. This is the easiest thing to do but it doesn't allow for pedagogical

innovation or for the introduction (or elimination) of topics or the redistribution of focus on topics. Further, because there seems to be a tradition of providing lecture notes for courses, rather than having students read a textbook, there's a risk that whoever writes the notes sets the tenor of the course. Experienced lecturers will lecture in an independent manner from the notes, providing their own vision and allowing the notes to serve as an additional resource, but inexperienced lecturers may not do so --- this makes having lecture notes instead of a book somewhat risky.

Response

There are currently ongoing discussions between the Dean, Associate Dean Undergrad and the various academic units on how to best involve lecturers within the Math Faculty. This discussion has been going for more than a year now. It is hoped that a resolution will be found within the next year. This, though, is ultimately the responsibility of the Dean, and not within the control of any of the units under review.

7. Some concrete decision needs to be taken on the Computational Math program. Specifically, either promote it, or close it down. There seems to be a great opportunity for an exciting math program that could lead to outstanding careers for students. This would be in computational math, modeling, data analytics, and related industrial careers that merge math skills with cutting edge computation. Yet we see little enthusiasm by current participants and little effort to advertise and promote the program. Without an effort by the Faculty of Mathematics to properly grow this endeavour, perhaps resources should be re-allocated elsewhere. We recognize that the program is probably not expensive to run and that the graduate portion of the program may be valuable --- it should at the very least be easy for current students to know about this program. For example, it is listed under "programs" on the "future undergraduates" page of the Faculty of Mathematics but is not listed under "majors, minors, and specializations" on the "current undergraduates" page.

   Response

   The Computational Mathematics undergraduate program has been growing substantially over the past few years. The number of students enrolled has increased approximately 40% per year since 2015. The topic was discussed between the Director of Computational Mathematics and the Dean, and it was mutually agreed that the undergraduate program fulfills an important role in the Faculty.

   The Computational Mathematics program has already undertaken some initiatives to promote its undergraduate program. In early November 2016, Computational Mathematics held a career panel consisting of past graduates of the Computational Mathematics program. These alumni talked about what they got out of the program, as well as where they are now in their career. The panel was very well attended by undergraduates (about 80 students) and will help promote the undergraduate program. Given its success, the Centre plans to hold more events like this one.

   The Computational Mathematics Steering committee will continue to discuss other ways to promote the undergraduate program.

8. In our discussions with the research faculty, there was great concern about the New Resource Allocation Model (NRAM) that is being implemented. For example, the Applied Mathematics department is in a precarious position vis a vis engineering. Engineering programs at other universities have created their own courses, with their own course codes, in which they present mathematical material. They then changed their program requirements so that they no longer require a particular course that is taught by the mathematicians and, instead, required their own course. It is our understanding that the Applied Math department has made great efforts to staff first year math courses for engineering students and so they are, naturally concerned, about whether the NRAM will encourage engineering departments to try and play the types of games that have been played at other universities. And, of course, because of the three-department structure any such behaviours would disproportionately affect the Applied Math department which has been acting for the common good by sending its faculty members to teach courses that are focussed on students from an outside faculty.

   Response
   There was no actual recommendation here, so no response is needed.

9. As a final note, the innovation goals of the university need to be better addressed in the programs. While the co-op programs, and online course development are a notable and worthy contribution to innovation, it would be outstanding to see the introduction of professional skills training for the students. This could include courses that work on presentation skills, project management, team management, use of technology in mathematical work, a math modelling course in AMATH for use in industry, and so on. Experiments in novel teaching methods, experiential learning, and entrepreneurial activities should be actively promoted by the Faculty for delivery in its programs.

   Response
   The co-op program includes substantial professional skills training for students, and our departments' courses already include presentations, project and team management, technology, and mathematical modelling. All units under review are constantly examining their teaching methods, and we will continue to teach our students in the best way possible, using both novel and tried-and-true techniques.

Implementation Plan:

	Recommendations	Proposed Follow-up	Responsibility for Leading and Resourcing (if applicable) Follow-up	Timeline for addressing Recommendation
1.	Improve information and advice provided to potential and current undergraduate students, whether that be through online resources and webpages or in-person advising.	Revamp of the Math Websites to improve communication with current and potential students	Jodi Szimanski (Director of Communications and Research Alliances)	December 2018
2.	Reconsider the program entrance requirements; put less emphasis on contest exam scores.	More focus on the "Additional Information Form" so that the faculty is considering more than just marks.	Serge D'Alessio (Associate Dean – Admissions & Outreach)	Completed
3.	Implement a process to continuously update and keep current the courses and curricula in the programs.	To be studied by the respective curriculum committees.	Undergraduate Associate Chairs (for departments), Director (Centre of CM)	Ongoing
4.	Implement a process to identify and cover any gaps in the curriculum.	To be studied by the respective curriculum committees.	Undergraduate Associate Chairs (for departments), Director (Centre of CM)	Ongoing
5.	The University needs to consider the issue of renewal of faculty in Pure Mathematics and Combinatorics and Optimization.	Both departments, as well as Applied Math, hired in 2017	Stephen Watt (Dean of Math)	Completed
6.	Fully integrate lecturers into the department including affiliating a lecturer to a particular department.	Ongoing discussions between unit heads and Dean of Math	Francis Poulin (Associate Dean - Undergrad)	December 2018

7.	Make a concrete decision regarding the Computational Math program; either discontinue the program or put more effort into promoting it	Ongoing discussions between Director of CM and dean	Jeff Orchard (Director of CM) and Stephen Watt (Dean of Math)	December 2018
8.	Reviewers' recommendation is actually a comment on NRAM with no suggestion for follow-up	Not applicable	Not applicable	Not applicable
9.	Innovation goals of the university need to be better addressed by the programs such as through implementation of professional skills training.	Continue to teach students in the best way possible, using both novel and tried-and-true techniques.	Undergraduate Associate Chairs (for departments), Director (Centre of CM)	Ongoing

The Department Chair/Director, in consultation with the Dean of the Faculty shall be responsible for monitoring the Implementation Plan.

UNIVERSITY OF WATERLOO

Date of next program review: 2022

Date

Signatures of Approval:

Kathryn Hare (PM) Feb 28/18 (AM) March 5/18

Chair/Director Date

(C&O) (CM) 6Mar'18

~~AFIW Administrative Dean/Head (For AFIW programs only)~~ Date

2018-02-28

Faculty Dean Date

Feb. 22, 2019

Associate Vice-President, Academic Date
(For undergraduate and augmented programs)

Associate Vice-President, Graduate Studies and Postdoctoral Affairs Date
(For graduate and augmented programs)