

# Practical laboratory classes to improve engagement and achievement amongst engineering students taking first-year mathematics

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**Abstract**—We describe the planning, delivery, and assessment of laboratory classes offered as part of two first-year mathematics courses for engineering students. The laboratory classes, which use practical examples inspired by second-, third- and fourth-year engineering courses, were designed to illustrate the relevance of mathematics to engineering. Once these classes were introduced the percentage of engaged students increased by up to a third, leading to similar improvements in pass rates and median marks.

**Keywords**—*engineering; mathematics; problem-based learning; 21<sup>st</sup> century learning*

## I. INTRODUCTION

Like most universities in New Zealand, Victoria University of Wellington (VUW) is publicly funded with approximately 50% of its budget coming directly from central Government and another 20% or so coming from student fees, which are capped at around 5500 USD/year for domestic students. To ensure both quality and efficiency, Government funding to VUW is contingent on both enrolment- and course completion-targets being met. This means that VUW is under pressure not only to accept large numbers of students who may not be ideally prepared for tertiary study, but also to ensure that those students engage in their studies and perform well enough to complete their courses with passing grades.

The School of Engineering and Computer Science (ECS) at VUW, which offers four-year Bachelor of Engineering degrees in Electrical and Computer Systems Engineering (ECEN), Network Engineering (NWEN), and Software Engineering (SWEN), as well as three-year Bachelor of Science degrees in Computer Science (COMP) and Electrical and Computer Systems (ELCO), faces additional demands from industry groups, which employ large numbers of our graduates and demand that the quality of the degrees received by our graduates remains high. These demands are reinforced by faculty, who are invested in training high quality research students. Thus real or perceived erosion in the quality of the degree program at second-, third-, and fourth-year is effectively prevented.

To meet these competing requirements ECS relies on a requirement of a B grade (70%) average across first-year courses for any student wishing to continue in an engineering degree. This allows enrolment acceptance rates to remain high and provides an explicit incentive for first-year students to achieve

their full potential, while still providing a means to divert weak students so that quality and course completion rates in the engineering degree are not impacted. Students who do not meet the B grade average requirement are encouraged to enrol in COMP or ELCO degrees, which are part of the much larger Bachelor of Science program that is not subject to the same scrutiny as the engineering program.

With these restrictions and incentives in place any course taken by engineering students that consistently gives a significant proportion of sub-B grades becomes a focus of attention. This was the case for two first-year mathematics courses required by engineering students prior to 2014. These two courses, MATH151: Algebra and MATH142: Calculus 1B, presented a persistent stumbling block to engineering students, as shown in Figs. 1 and 2. The MATH151 median mark for engineering students was B- in both 2012 and 2013; results were even lower in MATH142, where median marks for engineering students were B- and C in 2012 and 2013. Pass rates were also concerning, reaching a low of 55% for MATH142 in 2013.

A clue to the cause of this poor performance is present in the proportion of E grades given out in these courses, with as many as 26% of engineering students receiving an E grade in some years. This grade is significant not because it is a failing grade but because it is the lower of two failing grades. An E is below a D, which nominally indicates a mark between 40% and 50%. E grades tend to indicate disengagement from a course, where the student not only under-performs on assessment items but, in many cases, fails to even hand in their assessment items for grading.

These low levels of engagement by engineering students in their mathematics courses prompted several changes to the courses, the first of which began in 2014. Following a curriculum review and diagnostic testing of incoming first-year students that identified critical weaknesses, two new, custom designed courses were introduced specifically for engineering students as replacements to MATH151 and MATH142. These were ENGR121: Engineering Mathematics Foundations and ENGR122: Engineering Mathematics with Calculus. They were designed specifically to improve student engagement by highlighting the relevance of mathematics to engineering, in a similar vein to the Wright State model developed by Klingbeil et al. [1].

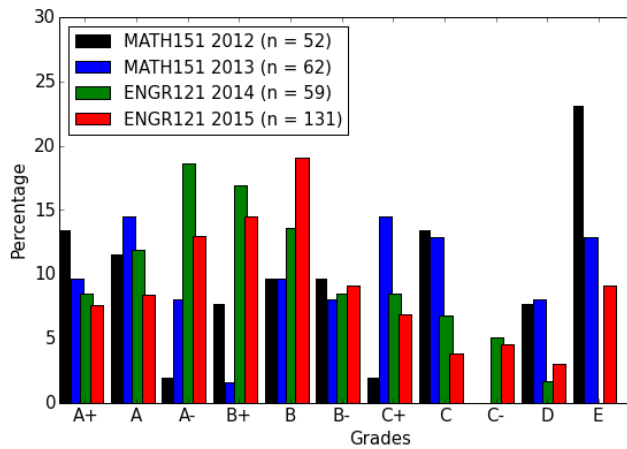


Fig. 1. Grade distributions for engineering students enrolled in MATH151 (2012, 2013) and ENGR121 (2014, 2015).

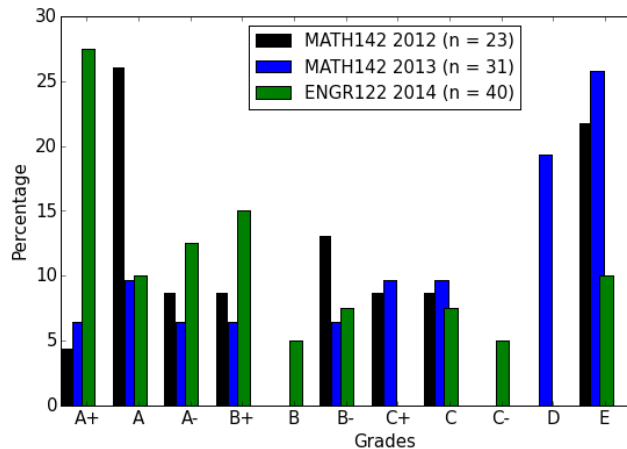


Fig. 2. Grade distributions for engineering students enrolled in MATH142 (2012, 2013) and ENGR122 (2014).

Although ENGR121 and ENGR122 dealt with the same topics covered in the MATH courses that they replaced, lectures were re-written in a collaboration between staff from the School of Mathematics and Statistics (SMS) and ECS to prioritise key theorems and practical engineering applications, while proofs and corollaries were deemphasised. The overall goal was to ensure that essential material was covered thoroughly, with minimal detours into peripheral content. A fourth weekly lecture slot was also introduced, which was reserved for revision of material covered in the previous three lectures and discussion of how that material fitted in to topics covered in tutorials and laboratories.

The ENGR prefixes for the new courses were chosen intentionally for their similarity to other 100-level engineering courses such as ENGR101: Engineering Technology and ENGR110: Engineering Modelling and Design. Using a common course code prefix for mathematics and other introductory courses served to eliminate the mental divide between mathematics and engineering harboured by some of the first-year students. It also highlighted the interrelated nature of courses in an engineering degree, which was contrary to the philosophy employed by the New Zealand secondary school assessment system [2].

A marquee feature of the new mathematics courses was the inclusion of practical laboratory classes to illustrate the relevance and application of techniques discussed in lectures and practiced in tutorials. This change was informed by literature on problem-based learning (PBL) [3,4], which is gaining popularity as a central component of 21<sup>st</sup> century learning [5].

After examining potential causes of low student engagement in the next section of this paper, we describe the planning, delivery, and assessment of these laboratory classes and discuss the resulting improvement in student engagement and performance that was measured. We conclude with a reflection on progress to date and potential next steps in the development of our offerings to first-year students.

## II. CONTRIBUTING FACTORS TO STUDENT DISENGAGEMENT

We believe there were several specific factors contributing to student disengagement in our particular context. Firstly, students struggled to engage with their mathematics courses because they were not uniformly prepared for them by their secondary school studies. The New Zealand secondary school qualification framework, known as the National Certificate of Education Achievement (NCEA), relies on modularised courses that allow students to pick and choose topics for assessment within a subject [2]. Completing assessments earns students credits; once enough credits are earned across three or more subjects, the student is eligible to enrol in university study. A consequence of this flexible approach is that students may gain entry to university as a result of earning credits in a particular subject, say, mathematics, without ever having studied key topics in that subject, such as perhaps differentiation or integration. This means that students do not have a common foundation when they begin their university studies, as a result their first year mathematics courses swing quickly and unpredictably from material that they are familiar with to completely new concepts [6]. Furthermore, the parts of the course that are new or challenging are different for each student.

A second barrier to engagement was an over-reliance on lectures to teach large classes of first-year students [7]. Students struggle to participate when their learning needs are not being met. Unfortunately, the one-way flow of communication from educator to students facilitated by lecture theatres does not easily allow for academics to cater to students who need additional assistance or who are ready for extension work. The varied experience of students during their secondary school studies means that first-year university classes in New Zealand are becoming more diverse, not less, hence disengagement due to ineffectual lectures is not a problem that we expect to diminish with time.

Finally, student surveys suggested that first-year students often had inaccurate expectations of what an engineering degree involved. Fueled by aggressive marketing featuring robots and mobile phone apps built and coded by third- and fourth-year engineering students, first-year students were not prepared for the cerebral nature of their university studies [8]. In particular, they struggled to see the relevance of mathematics courses to their chosen degree. The fact that engineering is not taught explicitly as a subject at secondary school no doubt contributed

to a general lack of awareness of what engineering is amongst university freshmen.

These factors should be understood in the context of the NZ Government and VUW's shared mandate for continued growth in engineering recruitment. To meet this requirement VUW has a relatively open entry policy which exacerbates the challenge faced by ECS to cater to an incoming student body with a wide range of academic levels [9]. The demand for larger, more diverse class sizes to meet increased institutional and market demands places a greater emphasis on introducing new teaching methods that counter the traditional lecture model.

### III. LABORATORY CLASS DESIGN

Our primary method to improve engagement amongst engineering students in their first-year mathematics courses was to introduce a series of practical laboratory classes based on PBL [3], the main features of which are [4]:

- Learning is student-centered, i.e., students make choices about how and what they want to learn.
- Learning occurs in small student groups and promotes collaborative learning.
- Teachers are facilitators or guides or coaches.
- Problems form the organizing focus and stimulus for learning.
- Problems are a vehicle for the development of authentic problem-solving skills.
- New information is acquired through self-directed learning.

PBL was chosen as a guiding philosophy as its aim is to give the students educational situations where they can apply their knowledge to problems in an active manner. PBL was also selected for its ability to cater to a diverse group of learners, and for allowing teaching staff more individual connection with students. Although this differs from the traditional mode of demonstration and acquisition often experienced in more conventional lectures and laboratory sessions, it is similar to situations professional engineers may regularly encounter when they take on new clients or assignments. As such, PBL was viewed as a good model for training future engineers.

Importantly, the practical laboratories were not designed to completely replace the lectures, tutorials, assignments and exams that were already present in the courses, instead, they were introduced to complement them. In this sense we were able to apply a mixed learning environment that covered various different methods of instruction so that students could have greater opportunities to encounter a method that related to their learning style. Adding practical laboratories also allowed us to introduce topics to students that they would not otherwise see during their first year of tertiary study, while helping to navigate threshold concepts [10] from the first-year mathematics curriculum. Sections below discuss the delivery, planning and selected examples of content and assessment of the laboratory classes.

#### A. Delivery

Laboratory classes were held in a 42-seat computer work room with significant floor space at the front of the lab where students could gather to be briefed or perform their practical experiments. In line with the principles of PBL, this environment was conducive to students forming small groups to learn together and to choose between different learning modes, for example, working through problems using pen and paper, manipulating data via a PC, or setting up physical experiments on the floor to test their hypotheses.

Three streams of classes were necessary to satisfy timetable and seating constraints. Classes lasted for two hours, with fifteen minutes used at the start of each class to brief the students on their learning objectives and to discuss the examples and concepts that students would encounter during the laboratory. These briefings were essential to creating a safe learning environment in which students felt comfortable taking risks to maximise their learning.

Figure 3 shows a whiteboard sketch from one of these briefings. Here green text is model data for a report, while red text represents comments from the students regarding presentation of that data. This interactive evaluation allows an instructor to model best practice and clearly define success criteria, while giving the students an opportunity to synthesise their learning. Briefings were also used to give feedback to students on previous laboratories and to invite feedback on the current topic. This allowed experiments to be tweaked in response to student needs, abilities, and prior experiences facilitating a student centred approach.

To assist in small group learning a combination of undergraduate and postgraduate tutors was used to interact with and guide students through the laboratories. These tutors were drawn from both SMS and ECS, which meant that students were able to receive specialist coaching with the concepts and the applications that they were studying. As well as facilitating learning, tutors also played a part in increasing engagement through their personalised interactions with individual students. For this reason, tutors were encouraged to roam through the work room and proactively interact with students. Engagement and learning were also positively affected by encouraging students to work in pairs during their laboratory classes, which allowed peer teaching [11] and collaborative learning [5] to take place.

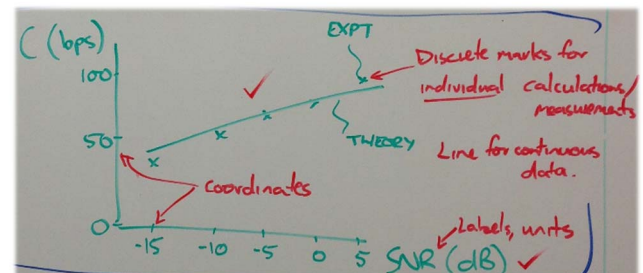


Fig. 3 Whiteboard sketch from an ENGR121 laboratory, 2015.

#### B. Planning

In line with PBL principles, problems for the laboratory classes were taken from topics studied in second- and third-year

courses in the Bachelor of Engineering program and were used to illustrate the mathematical concepts covered in lectures. Although the complementarity between lectures and laboratories was intentional, the timing and order of concepts in the laboratories was kept different to that of the lectures, in order to encourage students to consider their university studies holistically, rather than with a siloed or compartmentalised mentality that is implicitly encouraged by the modular assessment used in New Zealand High Schools [2]. Each laboratory topic was covered over a fortnight in two laboratory classes, giving students an extended period to contemplate the application being studied. To cater to various learning styles, printed notes and instruction sheets were prepared to complement the experimentation and discussion in laboratories.

Tasks within each laboratory were split into three categories, dubbed “core”, “completion”, and “challenge”, which corresponded roughly to the “knowledge”, “understanding”, and “application” levels in Bloom’s revised taxonomy [12]. This structure allowed exercises to be scaffolded, so that new knowledge was introduced in bite-size chunks that students could easily relate to their past experiences. Challenge tasks were designed to be open-ended, requiring additional insight or research outside of the laboratory classes; in other words, they encouraged students to acquire information through self-directed learning [4]. This structure generally works well as it caters to students’ differing backgrounds and abilities: students with more experience have the opportunity to extend their learning by completing “challenge” exercises, while other students are not unnecessarily overwhelmed by advanced, time-consuming tasks.

### C. Laboratory Content

Academics from ECS were canvased for potential laboratory topics that were relevant to their graduates in the latter stages of their degrees. Eight topics were chosen in all, allowing each mathematics course to be complemented by four laboratory topics. Dedicated support from technical staff allowed circuit boards, robots, and code snippets to be prepared that served as real-world props to illustrate content from the mathematics curriculum, as shown in Figs. 4 and 5. Three examples of laboratory topics, along with the principles they describe and their relevance to the engineering majors offered by VUW are given here.

#### 1) Robot navigation

Pairs of students were given a two-wheel, battery-powered robot that they could program to travel at different speeds, shown in Fig. 4. They used kinematic equations to find the acceleration and maximum velocity of their robot based on measurements made with a ruler and stop watch, before repeating their calculations using differentiation. They also calculated uncertainty estimates for each of their measurements. Knowing the rate of acceleration, which was assumed constant to simplify the analysis, and the maximum velocity of their robot, students calculated the angle and time required for their robot to intercept a second vehicle, travelling at a known velocity on a given heading.

This laboratory was inspired by the field of mechatronics, which is taught explicitly in subsequent years of the ECEN major. It intentionally used Arduino-based robots, as that

platform was familiar to the students as a result of assignments in some of their other first-year courses. Most importantly, the laboratory provided practical illustrations of abstract concepts such as differentiation, trigonometry, and uncertainty, which are all part of the first-year mathematics curriculum.

#### 2) Mobile phone communications

Students used the speedtest.net app to measure data transfer rates on their mobile phones. Given assumptions about bandwidth and channel gain, students then calculated the minimum channel capacity and signal-to-noise ratio (SNR) of the channel between their phone and the nearest communications tower. The second part of the laboratory

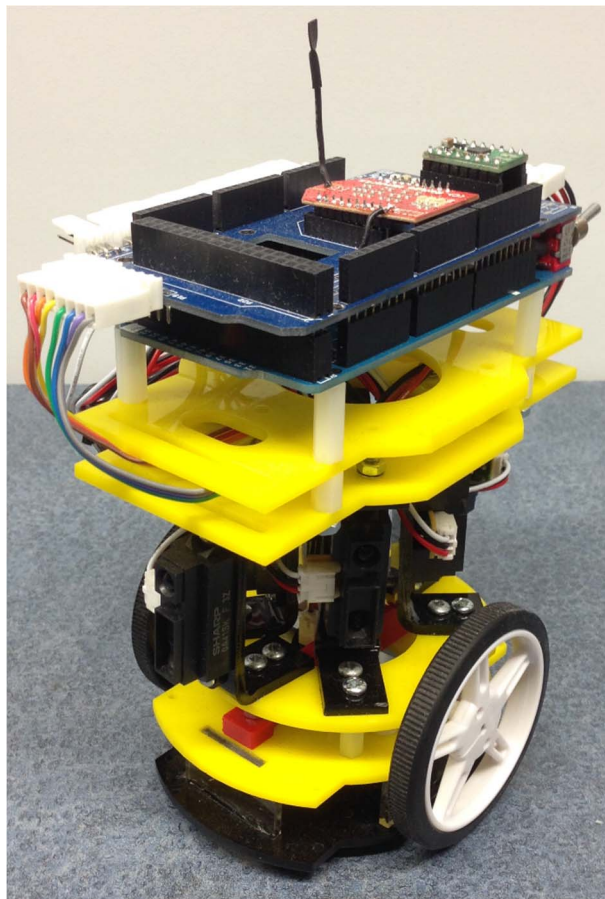


Fig. 4. Battery-powered “minion” robot used to illustrate concepts such as differentiation, uncertainty, and trigonometry.

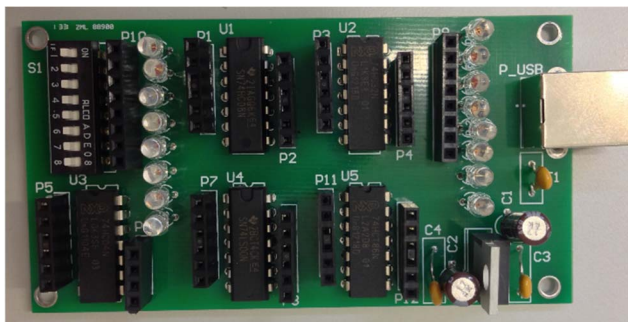


Fig. 5. Printed circuit board containing digital logic integrated circuits and light-emitting diodes that can be connected in various configurations. These boards were used to demonstrate principles of boolean logic.

involved running Python code to simulate and plot the bit-error rate (BER) of channels with different SNRs.

Content for this laboratory was simplified from material in third- and fourth-year communications and networking courses, which form part of the NWEN and ECEN majors. Exercises were chosen to give students experience manipulating complex numbers, which are a traditional area of weakness for first-year students. The mathematics of logarithms was also explored.

### 3) Algorithmic complexity

Students were given java implementations of several sorting routines, along with instructions for how to run each routine on provided data sets. Students recorded the time taken by each routine to sort each data set in order to estimate the efficiency of the different routines. They then compared their experimental ranking to the theoretical efficiency of the algorithms, expressed using big O notation. This laboratory gave an introduction to algorithmic analysis, which is a second-year topic in the SWEN major. It showed practical applications of polynomials, exponential, logarithms, and limits.

### D. Assessment

Informal, formative assessment involved class conversations held during the briefings at the start of each laboratory class. These conversations allowed instructors to identify areas that needed additional explanation or work in lectures. Furthermore, they were used to plan the content of subsequent laboratory topics.

Summative assessment was by means of formal written reports submitted one week after the second laboratory class on a topic. Students were encouraged to use a template with sections for the Aim, Method, Results, and Discussion associated with each topic. This template was common to four first-year engineering and mathematics courses, which served to further increase the coherence of the first-year engineering student experience.

Written reports were used as assessment for three reasons: firstly, to reinforce learning by requiring students to translate the mathematical concepts they had explored into written english. Secondly, to encourage deeper insight into mathematical concepts, by encouraging students to reflect on their learning before they wrote their report. Thirdly, to develop students' written communication skills, which can potentially be neglected in technically demanding degrees such as Engineering.

Reports were marked by tutors on a scale from one to ten. Reports that contained most of the required work completed with a moderate number of errors were awarded a mark of seven or eight out of ten, while particularly strong reports that offered good insight into the material covered were given nine or even ten out of ten. Marks below six out of ten were rarely assigned; instead, an unsatisfactory or "U" grade was given and the student was encouraged to resubmit a more complete laboratory report. This helped students to gauge the standard expected at university and to adjust their performance accordingly.

This marking system worked very well for tutors who were studying engineering themselves, as they were universally familiar with it from their own experiences of undergraduate

courses. On the other hand, tutors with a mathematical background typically struggled with the imprecision of such a scheme, preferring instead to report a strict tally of the number of questions answered correctly compared to the total number of questions in the laboratory. As a result of these differences in background and experience, bi-weekly meetings were held between tutors and academic staff to moderate marks and discuss problematic reports.

## IV. RESULTS

The grade distributions in Figs. 1 and 2 show that student achievement improved dramatically in the new mathematics courses that contained laboratories. Median marks increased from B- and C for MATH151 and MATH142 to B and B+ for ENGR121 and ENGR122. Pass rates improved from 55% and 79% for MATH151 and MATH142 to 88% and 98% for ENGR121 and ENGR122, respectively. Most importantly, the proportion of E grades, which is an indicator of low engagement, dropped from 14% to 0% for the algebra course and from 26% to 10% for calculus. These results demonstrate that mathematics courses are no longer a barrier to students achieving a B average in their first year.

Student feedback from teaching surveys indicated that these laboratories are well received. Appreciation for the briefings at the start of the laboratory sessions is a recurring theme, while students also value individual interactions with their instructors. Furthermore, use of real-world examples makes the laboratories relevant to students' own past experiences, encouraging them to participate in their courses and effectively engaging them in their studies.

## V. REFLECTION

Creating dedicated courses for engineering students that used practical, relevant applications to illustrate key mathematical concepts in a laboratory setting led to immediate improvements in student engagement, as shown by the reduction in E grades recorded in Figs. 1 and 2. Student achievement improved as well, as shown by the improved median grades in Figs. 1 and 2. We cannot say with certainty that this increase in median grades is due solely to students' improved understanding of mathematical concepts, as a team dilution effect resulting from the introduction of group-based laboratories or a shift in the emphasis of the assessments from theoretical to practical understanding may be responsible for this change. However, preliminary results based on the first cohort of students to complete the new mathematics courses suggests that the increase in the proportion of students engaging with and passing their mathematics courses in first-year is not mirrored by a corresponding decrease in the proportion of students passing their second-year engineering courses that depend heavily on first year mathematics content. In fact, engagement and pass rates in second year engineering courses have stayed relatively constant between cohorts, despite an increase in class size.

Student satisfaction scores also increased for the new courses: course- and teaching-surveys completed by students show that they particularly appreciated the briefings at the start of each laboratory class and the interactions that they had with their classmates, tutors, and academics. Finally, cohort surveys taken twice a year [13] showed that mathematics courses were

no longer considered to be “the most difficult” courses for students once ENGR121 and ENGR122 were introduced.

The engineering mathematics courses were generally well received by faculty from both ECS and SMS, to the point where a third engineering mathematics course, ENGR123: Engineering Mathematics with Logic and Statistics, was commissioned in the same mould of ENGR121 and ENGR122, specifically for students studying SWEN and NWEN. ENGR121 will also be opened up to COMP students for the first time in 2017. This means that ENGR121 enrolments have increased from 59 in 2014 to 259 in 2016 and a projected 400+ in 2017.

In light of this rapid increase in enrolments in ENGR121, some changes can be recommended for the engineering mathematics courses going forward. Firstly, the briefings at the start of each laboratory class that were deliverable by a single person when there were only three parallel streams of students in a course become untenable when twelve or more parallel streams are required, as was the case in 2016. Moving laboratory classes to a larger venue is an option; an initial step in this direction saw laboratory classes held in two neighbouring computer workrooms simultaneously, giving a combined seating capacity of 72 per stream.

Another alternative is to record briefings and make videos available to students via blackboard or YouTube, either before or at the start of each laboratory class. Although this flipped classroom approach [14] ensures that all students receive the same information, it removes some of the opportunities for interaction that allow students to ask questions about their work and to give informal feedback on their progress. Our preferred option, which preserves the opportunities for continuous feedback between students and their instructors, is to use experienced tutors as well as academic staff to give briefings at the start of laboratory classes.

One of the biggest changes to the laboratory classes after the first year that they were run involved the summative assessment methods employed at the end of each laboratory topic. While the completion of formal written reports had a positive impact on the written communication skills of the cohort by the end of the year, members of the engineering faculty expressed concern at the length of time required to complete each report. They argued that it was quite possible for students to spend more time writing reports than practicing mathematics, which defeated the purpose of introducing revamped mathematics courses.

To address these concerns the laboratory assessment was modified to allow students to write down key results directly on their instruction sheets. Requirements for formal written reports were removed from three of the four laboratory topics in each course, greatly reducing the take-home component of student workload and allowing them to spend more time exploring the mathematical concepts present in each topic. Concerns about students’ written communication skills were addressed by changing some of the assessments in ENGR101 and ENGR110 to better target these areas.

Looking forward, the learning model pioneered in ENGR121 and ENGR122 could quite conceivably be adopted in courses offered by other Schools that cater to engineering

students. Already a physics course offered by the School of Chemical and Physical Sciences to engineers has been renamed to take advantage of the ENGR course prefix. This is a relatively painless change to make, which goes some way to convincing students that all of their courses are relevant for their chosen degree. However, the much larger tasks of streamlining lecture content to avoid non-essential material and using carefully selected examples from the engineering curriculum in practical laboratories to illustrate core concepts, which were both implemented in ENGR121 and ENGR122, require significant effort and investment on the part of the Schools offering these courses. In the case of VUW, engineering is a growing program situated in a funding environment that rewards growth, hence such changes can be contemplated; however, this may not be the case at other universities.

## VI. CONCLUSION

We have successfully introduced practical laboratories inspired by engineering pedagogy into first-year mathematics courses that previously relied predominantly on lectures to enthuse and motivate students. The laboratories use PBL to introduce students to engineering topics that they will encounter later on in their degree and to illustrate the relevance and interconnectedness of mathematics to their studies. The self-directed nature of the PBL tasks gave students a sense of ownership over their work, which led to their improved participation in and engagement with their courses. As a result of these changes, we have seen student perceptions of mathematics improve dramatically. Students are now achieving better marks and are more aware of the relevance of mathematics to their degree.

The steps called for in our approach require significant resources and a collaborative commitment from various Schools involved with the courses, which means that it may not be suitable in all contexts. Nevertheless, the emphasis on growth in the New Zealand context in general and at VUW in particular mean that the number of our first-year engineering courses following this approach has already doubled to four, less than three years after the first changes were made. PBL specifically is now also being used to inform course changes across the gamut of first year engineering courses at VUW, as well as in several second-, third-, and fourth-year engineering courses. The positive results that we have experienced evidently make a strong argument for continued investment in our approach.

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