Mathematics for 21st Century Engineering Students

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Abstract*: We survey current Australian trends in course organisation, on-line and on-site support and mathematics remediation strategies for an increasingly diverse student body.*

1. Introduction

Mathematical developments lay at the heart of recent advances in engineering, biomedical science, commerce, and information technology. Students in these areas need mathematical education but their backgrounds, abilities and attitudes vary widely. Mathematics and statistics educators are attempting to engage an increasingly diverse student body. The Carrick Institute for Learning and Teaching has funded a project to examine mathematics for 21st century engineering students. Engineering is chosen as representative of a rapidly evolving technological discipline with a diversifying student body.

Engineering, like many other professions, has evolved significantly in the past couple of decades and is constantly changing to meet the needs of society. The engineering curriculum is adapting to provide students with an adequate foundation to enter the profession. Over the same period the student body has also changed significantly with an increase in the overall proportion of the population attending university, an increase in the number of international students and an increasing number of students in paid employment (Dobson, 2007).

Many Australian universities face similar challenges but they tend to work independently to develop individual strategies. The project includes a timely national review of mathematics teaching and learning strategies for engineering students.

2. Research Strategy

The Advisory Committee comprises approximately equal representation from both the Engineering and Mathematics disciplines. There are representatives from 15 Australian Universities (from all states), the Defence Science and Technology Organisation, Engineers Australia and the Australian Council of Engineering Deans. The Advisory Committee is consulted regularly.

As a first step to identify current practice in the teaching and learning of mathematics to engineering students, a literature review was undertaken. Members of the Advisory Committee were requested to bring to light any unusual or outstanding practice. An extensive literature search was also undertaken by the Research Assistant, beginning with the proceedings from engineering and mathematical education conferences and searching educational journals, proceeding where these documents were to lead. The review included international current practice.

The Helping Engineers Learn Mathematics (HELM) project in the United Kingdom was identified as an example of good practice. PB visited Loughborough University to speak with HELM directors, to visit the Mathematics Learning Centre and to view their teaching aids.

A questionnaire was designed to explore the themes identified by the Advisory Committee, partly guided by the literature review. The questionnaire was designed in a qualitative format in an attempt to prevent the conveyance of any preconceptions of common practice and in the hope of allowing institutions to highlight any interesting practices currently in use.

Thirty-two universities were identified as offering Bachelor of Engineering degree programs. Appropriate representatives from both the Mathematics staff and the Engineering staff were identified and requested to complete the questionnaire or to redirect it to an appropriate nominee.

Case studies will be carried out on Australian universities exhibiting prima facie evidence of outstanding practice in the teaching of mathematics and statistics to engineering students.

A National Symposium on Mathematics Education for 21st Century Engineering Students is to be held on 7th December 2007, in conjunction with the Annual Conference of the AAEE. The symposium is to take place at RMIT Access Grid Room (AGR), linked to several external groups in other states.

3. Preliminary Findings

3.1 Literature Review

The literature review identified four prominent innovative methods used in the teaching of mathematics to engineering students; problem-based learning (PBL), the multi-disciplinary approach, computer based methods (CBMs) and strategies that specifically address student variability. Nirmalakhanda *et al* (2007) claim that the more students participate in their learning, the greater are their learning achievements. Active learning is “learning by doing” rather than the traditional lecture format.

Advanced CBMs and PBL are most frequently claimed to be effective forms of active learning. Many authors reason that CBMs stimulate interest and enhance comprehension (e.g. Brenner *et al*, 2005, Mtenga and Spaingour, 2000, Naimark, 2002 and Colgan, 2000). Nirmalakhanda *et al* (2007) and Duran *et al* (2007) give empirical evidence. Morgenroth *et al* (2002) also argue that CBMs help students enter the profession, as most industries are now reliant on computers.

CBMs are often enhanced when used in conjunction with other innovative methods. They are argued to be particularly effective with a PBL approach (Duran *et al*, 2007). PBL is seen to be particularly effective in small groups; the PBL classroom environment mirrors many workplace situations (Smith et al, 2005). These findings do not however render traditional teaching methods redundant. Nirmalakhandan *et al* (2007) quantitatively show the effectiveness of integrating physical and computer models with the traditional theoretical model, showing that combinations of teaching methods help to tap into the different learning styles of students.

MATLAB is widely believed to be the most effective software in the teaching of mathematics to engineering students (Kent and Noss, 2000, Mtenga and Spainhour, 2000 and Waldvogel, 2006). It is seen to be particularly effective due to its ease of use (data is input in a familiar form) and its wide use in the engineering profession. MATHCAD and POLYMATH are also highly regarded for similar reasons (Brenner *et al*, 2005 and Morgenroth *et al*, 2002).

Avitabile *et al* (2005) showed that lateral integration of learning materials across subjects may be taken further to a vertical integration model, where material used in earlier subjects is revisited later, interweaving learning experiences and concluding with a final year project in Dynamical Systems.

It is clear from the review that the most effective engineering mathematics subjects are part of a well-designed engineering curriculum that enables students to understand the relevance and see the development of concepts over the entire course. It is crucial to address the increased student variability and to take into account differing learning styles. Easily accessible student support systems are also key to an effective engineering mathematics subject.

3.2 Questionnaire

The questionnaire was sent to both the Engineering Unit and the Mathematics Unit at the 32 universities identified as offering a Bachelor of Engineering program. 27 universities responded, including 13 who provided responses from both disciplines.

While we requested discussion of more advanced mathematical subjects traditionally taught by engineering staff, such as Signal Processing and Control Systems, all respondents referred only to the subjects taught by mathematics staff. The responses therefore refer to first and second year enabling mathematics courses. During site visits two people commented that engineering staff had been reluctant to identify their subjects as being predominantly mathematical due to perceived threats of the transfer of subjects to the mathematics and statistics unit, even in traditional engineering subjects.

3.21 Changes to the student body

Overall, women outnumber men in Australian higher education - this is also true in science, engineering and technology (SET) subjects; over the past five years there has been an increase in the number and proportion of women. The expansion in SET is made up mostly of international students, the proportion of domestic students having decreased (Dobson, 2007). Students are increasingly working part- or full- time during their studies. There has also been an increase in external students.

When asked about the changing demographics of engineering students, questionnaire respondents identified an increase in international students and a couple mentioned an increased number of students in paid employment and an increase in female students. Eleven respondents stated that they had noticed no change. Comment was also made about the changing expectations of students and the move to the student as consumer, taking a more active interest in ensuring that expectations are met.

In response to the question, "Have there been changes to the academic backgrounds of students entering engineering degree programs?", most universities stated a decline in mathematical preparation. However three universities stated that no dramatic changes had been noticed.

Many attributed the decline in mathematical ability to a lowering of entry standards to engineering degree programs; the majority of universities have removed the higher level high school mathematics prerequisite. Many universities also now offer alternative entry routes through TAFE and Foundation Year studies; these students were also identified as less mathematically able in general. Concern was also expressed by a number of respondents about changes to the high school mathematics and science syllabus and differences in syllabus between states, with particular concern about the standard of mathematics from Queensland high school students. Worryingly these concerns are supported by the findings of Barrington and Brown (2005), Barrington (2006), Barry and Chapman (2007), Belward *et al* (2006), Mullamphy *et al* (2007) and Engineers Australia (2007).

One respondent felt that mathematically and scientifically well prepared students were still coming from high school, but fewer are attracted to science or engineering programs. Further, he expressed a need for this problem to be addressed.

3.22 Adapting the teaching of mathematics to 21st century engineering students

Universities have employed various methods to address the decrease in mathematical preparation. Many institutions , including Victoria University, the University of Western Australia and the University of Technology Sydney offer bridging courses. These tend to be intensive three to four week courses which run before semester one of first year, usually concentrating on calculus. Bridging courses are often not compulsory; most are offered free of charge, although some must be paid for (normally through the HECS system). Some institutions have incorporated a pre-calculus course into first year for all students.

Some respondents state that mathematics subject content for engineering students has become less demanding with many courses containing remedial aspects, an increased emphasis on heuristic ideas, rather than mathematical rigour and greater use of software. The increase in the use of software has also required the removal of some content, although arguably this is also partly due to the changing nature of mathematics.

Many universities are moving towards problem based learning and teaching in context. The benefits of these methods have been widely discussed (Lopez, 2007). Universities employ methods such as small group learning (Victoria University), guest lecturers to demonstrate the relevance of particular mathematics topics (Curtin University of Technology), using engineering problems in mathematics tutorial classes (University of Queensland, Victoria University, *et al*) and the use of software enabling students to gain additional feedback when answering practice questions - CalMaeth at University of Western Australia (Judd, 1996) and Weblearn at RMIT (Fernandez and Fitz-Gerald, 2004).

There has been a significant extension of student support services offered in many universities. Many institutions are now offering increased hours of drop-in mathematics clinics run either by staff or by students – it has been said that a benefit of third or fourth year students running the clinics is that they provide extra motivation to first and second year students as they are able to reiterate, from recent experience, the value of good mathematical foundations in more senior courses.

Students are now able to access most subject and support material from online platforms such as Blackboard and webCT. This appears to be a common method used by universities to address the increasing demands on students (such as part- or full-time work and family obligations) as it allows students to study at times convenient to them. Resources such as video problem solutions (University of Wollongong) have been developed and made available online.

The streaming of first year students is a method increasingly used to address the wide variability of students' mathematical backgrounds when entering university. Most commonly, students go on to take a common second year course. However enabling mathematics subjects are also often tailored to specific engineering disciplines with students taking a common first year enabling mathematics course, progressing to different discipline specific second year courses.

3.23 Software Packages

Unsurprisingly following Lopez's (2007) findings, MATLAB is the most used software package (19/27 responding universities). Excel was the second most popular (10/27) and Minitab third (7/27). Surprisingly only 2/27 responding universities use MATHCAD and no responding universities use POLYMATH. The majority of universities use one or two packages (15/27), but ten universities use between three and five different software packages. Only two universities do not use any software packages in the teaching of mathematics to engineering students.

Some universities have developed in-house software to compensate for a decrease in mathematics and statistics staff, to reduce the marking burden of the remaining staff and to allow students to study at times convenient to themselves (Keady and Fitz-Gerald, 2006). These are explored further in site visits.

3.24 Curriculum Development

With few exceptions, Mathematics and Statistics staff teach only subjects that are 100% mathematics in content. First and second year enabling mathematics subjects are often taught to all science students in large lecture groups. One institution identified an enabling subject taught half by mathematics staff and half by physics staff. It was frequently mentioned that the number of enabling mathematics subjects has been decreasing over the past 10 years to make way for more "soft skill" subjects. Despite this and the observed decrease in incoming students' ability, the enabling mathematics subjects are still expected to provide the same foundation mathematics. As previously discussed, respondents to the questionnaire made limited reference to third and fourth year.

The majority of respondents stated that enabling mathematics subjects for engineering students are designed by mathematics staff in consultation with engineering staff. However, this appears to vary from very informal consultation which is the responsibility of the mathematics staff member to formal committees encompassing all engineering subject teaching with representatives from all the university's engineering disciplines, industry, students and the mathematics department involved in curriculum design. Most commonly, engineering staff develop a list of key topics and inclusions, either with or independently of mathematics and statistics staff, after which mathematics and statistics staff develop a curriculum around these guidelines.

Once the curriculum is in place it appears that the mathematics department is largely responsible for overseeing the teaching and learning. Some institutions referred to an interdepartmental committee that meets on an ad hoc basis, some to regular informal dialogue between departments. A couple of institutions referred to a First Year Director of Engineering who deals with administrative tasks, but is not responsible for interdepartmental liaison. Only two institutions referred to a formal committee that meets on a regular basis.

The majority of respondents stated that mathematics and statistics curriculum for engineering students has not been altered in response to the changing requirements of employers. Of the institutions that did identify such changes, one institution has increased the probability and statistics content to half of a second year unit and three institutions teach industry specific software to each engineering discipline. A few institutions stated that mathematical and statistical content has been reduced in response to industry requirement for engineering students to learn increased soft skills.

3.25 Assessment

All mathematics and statistics subjects taught to engineering students are assessed in part by a written exam. Of the 27 responding institutions, no institution assesses mathematics and statistics subjects wholly by a written exam. The written exam comprises between 50% and 80% of the final grade, continuous assessment is used for the additional component.

The continuous assessment most commonly comprises quizzes or assignments, individual or group weekly assignments to be handed in at class each week, weekly class or on-line quizzes, a major individual or group project or assignment, and two or three tests throughout the semester. The benefits of continuous assessment are widely discussed as allowing for simple misconceptions to be identified and corrected and to build students' confidence.

3.3 Site Visits and Telephone Discussions

Additional information was gleaned from more extensive discussion, both on site visits and through telephone discussions. We have been working closely with the Australian Association of Deans of Engineering on the Carrick-funded project, "*Rethinking Engineering Education*", and have participated in some of their site visits.

3.31 Organisation

As universities increasingly attempt to attract students and reduce attrition, the need to provide a good "service" to the "consumer" (student) is taking priority. In particular the need to address the transition to university, either from High School, from another country or back to study for mature students, is being increasingly recognised. Projects such as the University of Queensland's "The First Year Experience" (Burnett, 2006), the University of Sydney's "First Year Experience" (http://www.itl.usyd.edu.au/FYE/) and "strengthening the first-year community" at Griffith University (http://www.griffith.edu.au/landt/) attempt to aid this transition.

Curtin University of Technology have developed the "Engineering Foundation Year" (EFY), the effectiveness of this project was recognised through the 2006 Carrick Institute award for The First Year Experience. The EFY was developed for students to gain experience and knowledge in engineering fundamentals, enabling skills, learning skills and professional practice. Sponsorship from industry allowed the development of the EFY Studio, which mirrors the layout of an open plan office, with small project meeting rooms and clinic rooms where students can obtain advice and assistance.

Mathematics comprises 25% of first year study and is identified as a crucial enabling skill for engineers to conduct technical work. The EFY highlights the benefits of collaboration between units in the development of enabling subjects. Throughout the process the Dean of Teaching and Learning has acted as an impartial arbiter organising joint committee structure and student feedback sessions. Mathematics subjects were designed during a series of meetings held by the EFY Committee and engineering mathematics co-ordinators. These meetings enabled both parties to gain a common understanding of the aims for engineering mathematics; it was agreed that some of the abstract content would be removed. Students are offered support at drop-in clinics in the EFY Studio by a resident mathematics tutor, available for 4 hours a week. Engineering mathematics now gets excellent student feedback (93% positive in 2007).

3.32 Innovative teaching and learning

It is a difficult task to engage, educate to a common level, and demonstrate the relevance of mathematics to increasingly diverse student body. Many respondents have said that this task has become increasingly difficult due to the reduced numbers of mathematics and statistics staff and the reduction of mathematics subjects from the syllabi of most engineering degree programs.

The University of South Australia (Colgan, 2000) and the Australian Defence Force Academy (Barry and Webb, 2005) run first year courses that incorporate the use of MATLAB. As there are few textbooks which incorporate the use of MATLAB at first year level, both institutions have developed their own supporting resources for students. Both courses combine active and passive learning in an attempt to further engage students and highlight the relevance of the foundation material to the engineering degree program. Engineering problems, which contribute to the final grade, must be solved by students both in groups and individually. Students must gain an understanding of the problem, convert it to a mathematical formulation, design MATLAB code to analyse the problem and write a professional report to a fictitious supervisor. Both subjects have had positive staff and student feedback and have been seen to develop an assortment of engineering skills. The collaboration required between the departments in developing the courses has also been seen to have a positive effect in encouraging more interaction between units. The University of Wollongong has developed a series of online tutorials for students to introduce them to MATLAB (Baafi and Boyd, 2001).

The move to PBL in engineering subjects in some institutions has forced a re-examination of the teaching of mathematics to better align with teaching style of other subjects and again to highlight the relevance of mathematics to engineering. Victoria University now uses a PBL approach in all engineering subjects. Mathematics is taught to engineering students in small groups (20-30 students in a class), there are no large group lectures. Students have three hours interactive class time per week and one hour working on a group project which is an engineering problem related to the topics covered in the three hour interactive class time. The Mathematics Department also offers drop in clinics two days a week. Staff feel that students are more engaged in the foundation mathematics courses than they have been in previous years and the collaboration between the departments in designing the engineering problems has opened the channels for communication. At the University of Queensland a first year mathematics for engineering students subject incorporates a group project in which students explore a relevant mathematical topic of their choice, produce a poster and give a short presentation. This allows students to develop an appreciation of the inter-disciplinary nature of mathematics and the development of communication, team-work and research skills. This small project has been noted by staff to increase students' interest in mathematics (Worsley, 2007).

Some institutions have developed software which allows students, or in some cases forces them (with assessments before students can progress to the next stage), to practise mathematics with feedback on errors. CalMaeth (Dynamical Teaching Solutions software interfaced with Mathematica) at the University of Western Australia (Judd, 1996) and Weblearn interfaced with Maple at RMIT (Fernandez and Fitz-Gerald, 2004) provide diagnostic feedback to students when attempting practice questions, recognising common errors and allowing the provision of further explanation and suggested reading. CalMaeth also rates incorrect answers by degree of severity. For assessed tests, both software programs allow for generating variations of questions for each student to avoid plagiarism. CalMaeth also allows staff to keep track of students' progress, individual statistics may be viewed and summary statistics created. This allows staff to identify areas in which all students require additional assistance. Both software packages have had excellent staff and student feedback.

The University of Wollongong has developed video solutions with voice-over explanation, which attempt to illustrate the thought process in the solution to mathematics questions in a way that written solutions cannot. Video solutions were made available to all students on webCT (in reduced Mac and Windows compatible files) and listed according to mathematical content. A student questionnaire at the end of the course showed that it was the weaker students who tended to make use of these resources and felt that they were helpful. Analysis of grades showed that the average grade of those who used the resources increased from a fail to a pass grade (Aminifar *et al*, 2007).

4. Conclusion

Mathematics educators are attempting to address the numerous challenges faced in the teaching of enabling mathematics to engineers, in a number of innovative ways. The key challenge is the decline of mathematical preparation of students entering first year and the increased variability of their knowledge. This is compounded by the decreasing numbers of mathematics staff, with increased pressure to produce research and the decrease in mathematics enabling subjects in engineering degree programs. Software such as Weblearn and CalMaeth appear to be effective in providing additional practice with feedback for students without further burdening limited staff with extra marking. Learning resources such as video examples also provide students with 'virtual staff assistance'. The major advantage of these resources is that they are available to students to access at their convenience.

Mathematics subjects that have been designed through the collaboration of mathematics and engineering units are more likely to be effective. Joint ownership of curriculum design is particularly important when different branches of engineering, that regard different mathematics topics as essential, are being serviced within a limited number of mathematics subjects. As found at ADFA, collaboration in the development of one unit can open the door for future communication. The benefit of an objective arbiter may clearly be seen in the design of the EFY at Curtin University of Technology. The Dean of Teaching and Learning played a crucial role in organising joint curriculum committees and fostering closer relationships between units in the initial planning stages, but has also maintained momentum after the implementation of the courses, organising regular student feedback.

Many universities are developing similar learning resources for mathematics - software packages, online resources, software handbooks, etc. It would be beneficial to have an online forum in which these resources may be exhibited or shared. This would provide mathematics educators with an easily accessible database of trialed methods and allow discussion of benefits and disadvantages.

Mathematics subjects for engineering should be collaboratively designed with commonly agreed, clear goals from both the mathematics and engineering units. Many students need additional support accessible online and through maths clinics, preferably run by selected third or fourth year students.

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