SYSTEMATIC DEVELOPMENT OF A FIRST YEAR ENGINEERING MATHEMATICS MODULE

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Abstract
Teaching tertiary mathematics to engineers is a worldwide issue. This paper discusses a systematic and structured approach to developing a first year engineering mathematics module based on the best current pedagogical practices, innovations and resources. All relevant didactic aspects are covered. The guiding paradigm is active learning both in class and out of class.

A development plan is presented and the progress of the module, which is now in its second year, is discussed. Designing and implementing a successful module included: fully understanding the potential student learning problems; researching and applying the best practices in teaching tertiary mathematics; utilising the available resources.

Keywords
Engineering mathematics, declining mathematical skills, active learning, motivation, content, teaching, learning, assessment.

Introduction
Engineering education reform is being considered, planned or embraced by many universities around the world. The CDIO Initiative (www.cdio.org) is an international organisation which is promoting such change. Crawley *et al*. [1] describe the comprehensive methodology that this initiative has developed for redesigning engineering degree programmes and the philosophy underpinning the need for change in engineering education. This need for change is being fuelled by stakeholder feedback; employers want proficient engineering graduates who can hit the ground running. Essentially, engineering graduates should understand how to conceive, design, implement and operate the value-added products and systems associated with their discipline – hence CDIO.

The School of Mechanical and Aerospace Engineering at Queen's University Belfast (QUB) has been a collaborator in the CDIO initiative since 2003 and is well underway in a process of reforming its existing engineering degree programs and, in the case of its new Product Design and Development (PDD) degree, a programme has been developed and built with the CDIO principle, syllabus, standards and methodology at the core.

There is only one mathematics module scheduled in the new Product Design and Development degree programme. This one module is scheduled in the first semester of the first year and therefore has to ensure that the students are adequately prepared with the prerequisite skills that they need for all the other scientific and analytical modules on the degree programme. The success of this module is therefore paramount to their overall progress.

In a CDIO teaching environment a key consideration is to ensure that any mathematics module can integrate with the rest of the course and espouse the same learning strategies inherent in the other more design orientated modules; this is essential if the students are to stay motivated and engaged. The best way to achieve such goals is to carefully examine each of the pedagogical aspects inherent in successfully teaching mathematics to engineering students and endeavour to realise all the best practices and innovations.

This paper discusses the systematic development of such a mathematics course. It defines the key areas of interest and sets out the approach taken. Initially, it was of paramount importance to clearly understand the problems to learning faced by the students in order to tackle the other pedagogical issues associated with such a curriculum design challenge.

Teaching Engineering Mathematics – A Generic Problem

In the UK, it is now widely accepted that since the early nineteen-nineties there has been a real decline in the mathematical capabilities of students entering a wide range of university degree programmes.

A report by the London Mathematical Society [2] clearly identifies this problem and suggests ways of "*tackling*" it. A report published by the Engineering Council [3] presents evidence of a "*serious decline in students' mastery of basic mathematical skills and level of preparation for mathematics-based degree courses*". It encourages universities to be fully aware of the problem and recommends diagnostic testing on entry to mathematics-based degree courses and that additional mathematics support is provided for the students. This support can take the form of supplementary lectures, additional assessed modules, lower level transition modules, mixed-ability teaching, streaming, computer-assisted learning and support centres.

Work by Lawson [4] provided clear evidence that that there has been a marked decline in proficiency in certain mathematical skills amongst students entering university. One example states that in 1997 only 54% of students with mathematics A-level grade C, tested at the start of their university studies, could correctly identify the graph of the cosine function. In 1991 all comparably qualified students could do this.

As part of the UK Government's strategy for improving the UK's productivity and innovation performance, a report was commissioned [5] which subsequently "*Identified a number of serious problems in the supply of people with the requisite high quality skills*" noting that "*there have been significant falls in the numbers taking physics, mathematics, chemistry and engineering qualifications*". For university courses it recommends that: *"Improving the relevance and excitement of science and engineering courses to students is linked closely to improving the relevance of these courses – in terms of skills and knowledge taught – to employers. Updating the nature and content of the course to reflect the latest developments in science and engineering can be achieved both through having lecturers who can draw on recent experience of work environments other than Higher Education Institutions (HEIs), and through explicit changes in course content"*.

Following on from the Roberts Report [5], another report was commissioned to delve further into the mathematics education in the UK (at Secondary level) [6]. In it, Smith identifies "*a curriculum and qualifications framework that fails to meet the mathematical requirements of learners*" and that "*fails to meet the needs and expectations of higher education and employers*". The report calls for a National Centre for Excellence in Mathematics Teaching and recommends "*incorporation of relevant existing mathematics support activities and initiatives*".

The mathematics problem is not confined to the UK. There is clear evidence that European countries have also experienced this declining standard of mathematical knowledge [7,8,9]. The European Society for Engineering Education (SEFI) discussed this in detail in chapter 2 of a working group report it released in 2002 [10]. In addition, Seldon describes the problem in detail, referencing issues from Canada, the USA, South Africa and Hong Kong [11].

Reflection on the Learning Issues

Race [12] suggests several factors that underpin successful learning (p6-7): the students should be motivated and interested and also appreciate the need to learn a specific topic. Therefore, it is important that a first-year maths course should integrate perfectly with the relevant engineering requirements. In addition, any examples used to substantiate the mathematical theory should be engineering specific to help facilitate successful learning.

In order to conform to the intended teaching and learning methods employed in the Product Design and Development degree programme, it is necessary to incorporate active and interactive learning techniques. The merits of this have been well documented by Chickering and Gamson [13], who suggest that, to be actively involved, students must engage in higher-order thinking tasks such as analysis, synthesis, and evaluation. Penner [14] recommends modifying traditional lectures as a way to incorporate active learning in the classroom. Even simply allowing students to consolidate their notes by pausing three times, for two minutes each during a lecture, will improve their learning significantly [15].

The Kolb Learning Cycle [16] is particularly relevant to the Product Design and Development degree programme in that it suggests a theory of learning where the students use concrete experiences as a basis for observation and reflection and then proceed to formulate an abstract theory, which they can then develop and reapply to enhance their learning experience. The design-build projects and the integrated curriculum promoted in this degree programme facilitate this type of learning and therefore it is extremely relevant that the new maths course follows suit.

Otung [17] discusses this in further detail with regard to engineering mathematics, building on not only the declining mathematical skills apparent nowadays but also on the relevance of a declining mathematical appetite from the students. He argues for a "*minimal-mathematics*" approach to modernize the way first-year students are introduced to the subject and eliminate their perception of an "*unfriendly mathematical gatekeeper*".

Consequently, the preparation and development of the new first-year mathematics module had to consider two areas that could potentially provide serious learning challenges for the students:

1. Motivation: Based on the problems inherent in the transition from secondary to tertiary education and the decline in mathematical skills discussed in the previous section [11,17,18].
2. Content Intensity and Relevance: Many topics have to be taught in a short period of time so that the students can acquire all the relevant mathematical knowledge and experience required. Convincing them of this relevance is essential to the learning process [11,17,18].

However, with regard to teaching engineering mathematics, these problems are not uncommon and indeed are experienced by most engineering schools worldwide. As such, there is a wealth of information available to support and guide those involved in teaching and developing courses in engineering mathematics.

Teaching Engineering Mathematics – Available Support

For university lecturers planning an engineering mathematics course there are many resources and published work to help with the preparation. In the UK, in particular, there has been much investment in developing an excellent support framework.

With funding, progress has already been made in developing a national support framework to ease the transition from school mathematics to university mathematics in a wide range of disciplines, including engineering. This support framework consists of a website, **math**centre (www.mathcentre.ac.uk), which was launched in September 2003, and a DVD disk-set, **math**tutor (www.mathtutor.ac.uk). This free resource is intended to help the many students who find themselves ill-prepared for the mathematical demands of their chosen courses, or who need to revise key topics in school-level mathematics once they reach university. At the same time it is designed to help the staff who teach or support them.

In the UK, another useful web resource is The Higher Education Academy's Engineering Subject Centre, which has a specific site on Engineering Mathematics (www.engsc.ac.uk/er/engmath). The Academy recognises that "*Engineering Mathematics is a key area of all engineering degree courses*", and they specify that "*the changes to the A-level mathematics syllabus mean that many departments and institutions are developing strategies to support their students with their mathematics*".

In 2002 the Higher Education Funding Council for England (HEFCE) funded a three year project called HELM (helm.lboro.ac.uk), Helping Engineers Learn Mathematics. This freely available resource aims to *"enhance the mathematical education of engineering undergraduates by the provision of a range of flexible learning resources"* and *"drive student learning via a computer based assessment regime"*. In addition, the well trialed teaching resources provide an excellent support for preparing an engineering mathematics course.

In January 2005 HEFCE announced the creation of 74 Centres for Excellence in Teaching and Learning (CETLs) to promote excellence across all subjects and aspects of teaching and learning in higher education. One of those CETLs was the Centre for Excellence in the Provision of University-wide Mathematics & Statistics Support (www.sigma-cetl.ac.uk). This CETL is currently building upon Loughborough and Coventry Universities' *"extensive experience and reputations in the support of thousands of undergraduate and postgraduate students, from across the full breadth of these universities, who require some knowledge of* *mathematical and/or statistical methods to fully engage with their programme of study"*. Two of its aims are *"to research and promote enhancement of the teaching and learning of the mathematics and statistics taught"* throughout these two universities and *"to stimulate and encourage growth of similar proactive activity across the HE sector"*.

In 2001 the Learning and Teaching Support Network published three documents focusing on the teaching of engineering mathematics in the higher education community. The first of these [19] identifies the deficits in mathematical knowledge of students entering engineering degree courses and describes many initiatives which increase motivation among students and give them alternative environments in which to improve their mathematics skills. The second [20] focuses on the methods of maths support for students, recommending maths learning centers, drop-in centers, summer schools, computer-based support, paper-based support and student-support websites. The third [21] provides information on diagnostic testing for the students at the beginning of their degree courses.

Due to an increasing need for the mutual recognition of engineering qualifications across Europe, the European Society for Engineering Education has produced a detailed document [10] which recommends an updated engineering mathematics core curriculum for the twenty-first century. This report specifies all the mathematical topics which should form part of a complete engineering degree programme and as such, provides excellent guidelines for course design.

Developing the Engineering Maths Course

The potential student learning and support issue with engineering mathematics was approached with all the relevant information and resources gathered and documented from the previous two sections. The following subsections describe how relevant material was researched and applied to planning and developing the new mathematics course.

Mathematics background of the students

A change in the entrance requirements for the Product Design and Development degree programme meant that the mathematics background of the students who would be taking the new maths course was going to be weak. This has been discussed in detail in an earlier section and substantiated by several authors who provided recommendations on how to deal with this problem [11,17,18, 22]. However, feedback and information gathered from a previous, similar cohort was also available to reliably corroborate the planning decisions with regard to the perceived learning abilities and attitudes of future cohorts.

This feedback helped to directly identify several learning issues and attitudes to mathematics. Fourteen out of the seventeen students surveyed stated that Maths was the subject that was *"presenting the most difficulty"* for them. Their responses to the question, *"what would you suggest to help with this?"* produced several very interesting answers which supported the contentions of Race [12] regarding factors underpinning successful learning: *"less theory that may not be needed"*; *"extra classes with fewer people"*; *"step by step instructions"*; *"slower teaching"*; *"detailed handouts"*. These answers were very useful in forming the basis for planning the new mathematics course.

Learning Styles

Specifically regarding engineering education, Felder and Silverman [23] suggest that the learning styles of the students and the teaching styles of the instructors should be compatible in order to maximise the learning potential of the students. This does not have to apply across the whole course, but should be considered in specific areas where problems exist. The model presented classifies several different kinds of learners and therefore provides students with an understanding of their preferred learning style and lecturers with the ability to design courses that appeal to all learning styles.

Orhun [24] conducted an extensive literature review and study on learning styles and attitudes to teaching and learning engineering mathematics. He concluded that having information on students' learning styles could help teachers adapt their courses to better motivate student learning and could help students become better learners with a more positive attitude to their studies.

With this in mind, a survey was carried out on the aforementioned similar cohort from a previous year, in conjunction with Hermon [25]. The results clearly showed that this cohort preferred a 'hands-on' and 'real-world-relevance' approach to learning. It must be pointed out that the size of the group surveyed meant that the results were statistically insignificant, but it did provide a clue as to the type of student that might enroll for the Product Design and Development degree programme.

An appreciation of the students' learning preferences helped prepare the new mathematics course with regard to the didactic strategy employed. A standard learning styles questionnaire is now given to all new students at the beginning of each academic year to facilitate in this regard.

Course Content

Research literature has provided many examples of how other engineering schools are approaching this problem. Indeed, Willcox and Bounova [26] at MIT have provided excellent guidance on key areas to be addressed in order to improve the teaching of mathematics in an engineering context. They identify the mathematical skills required of undergraduate engineering students on a specific programme and also the *"barriers to deep mathematical understanding"*, which the students might face. The crux of their approach is to have a clear list of the mathematical skills that are relevant to the core curriculum involved.

Where the mathematical skills of the new students are extremely weak, Bamforth et al. [27] propose a "pre-sessional" course to help support and retain the students. They include useful information relating to the content and its implementation. Otung [17] emphasises the importance of a "*minimal-mathematics*" content which puts engineering first and mathematics second, to help bolster attitudes and deficiencies.

Didactic Strategies

Cox [28] discusses at length the role that pedagogical theory has to play in teaching mathematics. He concentrates on the practical use of such theory in third level education and provides many references to the latest thinking on the subject.

The strategies involved in teaching, learning and assessment need to be aligned. Cox [29] describes the taxonomies involved in alignment with regard to teaching engineers mathematics and discusses the application of a simple, practitioner-friendly classification of educational objectives.

It is important to note at the outset that the strategy with regard to assessment is the key factor in student learning. Gibbs [30] and Rust [31] both look at this in great detail by focusing on carefully directing student learning both inside and outside the class and designing assessment that supports worthwhile learning. Obviously this all has to be achieved within the context of "*constructive alignment*" as advocated by Biggs [32].

Active learning is a key aspect of a CDIO syllabus and this too can be greatly influenced by the nature of the assessment. Gokhale [33] provides information to assist with active learning and concludes that it can enhance critical-thinking and problem-solving skills, which fit perfectly with the learning outcomes for any mathematics course. Oates *et al*. [34] discuss effective tutorials in tertiary mathematics and describe their collaborative tutorials and peer-tutor schemes that have proven very worthy from a student perspective. Prince [35] discusses the effectiveness of active learning by examining and analyzing a profusion of educational literature on the subject and concludes that there is indeed support for it.

Continuous assessment promotes learning progress, but is resource intensive. Davis et al. [36] get over this problem by successfully applying the HELM resource mentioned earlier in their engineering mathematics teaching. Their student feedback and conclusions support the fact that this can be a very effective and useful resource.

All of this is extremely relevant in the current climate of teaching engineers mathematics, especially with regard to the declining skills problems already discussed. A further resource, specifically regarding assessment in engineering courses, was published by the Engineering Professors' Council in 1992 [37]. This paper discusses all aspects of assessment with respect to efficiency and productivity for the lecturers and improved learning for the students, and as such is extremely useful when preparing new or improved curricula. It also looks at some innovative methods of assessment that have worked in practice.

At the Technical University of Federico Santa Maria in Chile, there have been several specific didactic strategies employed for over sixteen years now to improve the teaching and learning of mathematics to engineering students. This stems from problems due to the mathematical capabilities of students, similar to those described earlier, where it was necessary to deal with the high student drop-out rates.

The most interesting aspect of their work is a "Remedial Program for First Year Engineering Students", which started in 1991 and is described by Urbina *et al*. [38]. This work explains how a special course is provided to cope with the large drop-out rates at the end of the first year of their engineering programmes due to *"very bad academic results"*. A key constituent of this corrective course is an innovative approach to teaching mathematics. This includes information on the structure, the content and sequence of content, and the context to support student learning.

The methodology uses an educational approach based on a short period teaching-learning cycle as described by León de la Barra *et al*. [39]. This guarantees *"immediate feedback and correction for both the student and the lecturer"*, and, due to the small units of content being taught, *"key processes such as motivation, delivery of the lesson, study, learning evaluation, corrections, reinforcement and projection are successfully developed in the time elapsed in a class session"*.

To complement the classroom activities, a cooperative learning procedure is applied to all tutorial and homework [40]. This use of small groups ensures the students work together *"to maximise their own and each other's learning"*.

The use of metacognitive questions to augment the "short cycle" teaching and learning has also been shown to have a benefit compared with standard approaches to teaching and learning, and this is described in a further paper by León de la Barra *et a*l. [41].

The Engineering Mathematics Course Development Plan

Having identified the potential learning issues, and equipped with all of the information, support, advice and best-practice available form the extensive review described in previous two sub-sections, a strategic plan was adopted to prepare the first ever Mathematics for Product Design module. As time and resources would be an issue, it was important to adopt a realistic curriculum development plan: The key parts were:

1. Precisely mapping the mathematical skills and content required for the Product Design and Development degree programme. This involved meeting with all the staff involved in teaching modules on this course to ascertain their mathematical requirements and prerequisites.
2. Integrating and signposting the relevance of this module with the other modules on the Product Design degree course and indeed to the product design profession itself.
3. Integrating relevant worked examples form other modules.
4. Deciding on the best textbooks to recommend for the module. The guiding axiom that the books must promote active learning sessions and also contain relevant engineering problems was the main focus.
5. Ensuring there was scope for active and interactive learning embedded in the module. This included embedding the "Short Period Teaching-Learning Cycles" [39] and also information gathered from the MathCentre website and the HELM resources.
6. Considering different continuous assessment techniques beyond the usual examinations.
7. Considering computer assisted learning and assessment (HELM).

Discussion

When tasked with developing a brand new mathematics module for a new breed of Product Design student with a minimal mathematics background it was important to fully understand the basic learning issues and challenges involved. Feedback and a survey of students with a similar educational background provided a valuable insight into their basic needs and preferences when attending an engineering maths class and also their probable learning styles. However, more information was needed.

Research into the worldwide problem of successfully teaching mathematics to engineering students revealed a wealth of information, support, advice and resources to call on. From government reports to educational papers, from online resources to freely available hardware and software, from Centres of Excellence to Subject Centres, the help facility was, and is, extensive.

Information gathered from these resources helped not only to decide and plan what to teach in the new module (the syllabus), but also corroborated the key paradigm that forms the backbone of the Product Design degree programme, which is experiential learning. Therefore the plan to adopt and adapt active and interactive learning techniques was indeed warranted.

Research clearly shows benefits in teaching, learning and assessment practices that are student-centred; therefore it is necessary to be fully aware of the background and abilities of all new students. Several approaches were adopted based on previous work; these were diagnostic testing at entry and a learning styles inventory; the latter indicated a particular predominant processing preference. This information provided clarity with regard to developing the module content, the teaching methods and also effective assessment criteria. Emphasis was specifically placed on developing innovative and continuous assessment techniques that had a well proven record, based on the reality that assessment potentially affects learning more than teaching.

The content of the maths module was chosen because it was totally relevant to the specific degree programme; published work has shown this to be most beneficial and emphasised that this important fact must be conveyed to the students. Simple interviews with all the academic staff involved in the Product Design and Development degree program helped identify exactly what mathematics skills were required. It was considered essential, that the mathematics module would be conducted at the outset of the degree programme, so as to equip the students with the necessary mathematical skills prior to undertaking the other scientific subjects within the programme – a course of action verified from other publications.

The key challenges with regard to motivating the students and clearly explaining the relevance of the module were successful in that the module is now in its second year and the average attendance for both years has exceeded 75%. An evaluation strategy modified the module for the second year and consequently improved the average summative assessment results by over 10%. This was due to a change in the assessment methods to include more coursework, homework and an experimental peer marking scheme.

Conclusions

- When designing a mathematics module for first year engineering students it was important to understand the learning challenges involved in relation to the potential mathematical skills and learning preferences of the students.
- Many useful resources were used to help with teaching this engineering mathematics module.
- Recent reports and publications have shown that motivating engineering students for mathematics is becoming more of an issue and a key factor that influences their learning potential. This was found to be true in this case.
- To motivate the students, relevant content was chosen that applied the mathematical theory to real engineering problems. In addition, the module was designed to integrate with the other first year modules.
- Active and collaborative teaching methods were used, which were closely aligned with the assessment strategy.
- The assessment strategy endeavoured to maximise learning by promoting learning outside as well as inside the classroom. Peer marking was used to help improve learning.

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