Developing Engineering Expertise within Numerical Methods

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INTRODUCTION

The learning processes that support the development of expertise are particularly salient as undergraduate engineering education lays the foundation upon which expert engineering practice can be built [1]. There are a number of ideas within the literature which give structure to this development. For example, the nature of expertise can be described in terms of models of the learner, stages of skill acquisition, and the progression from novice to expert [2], and, if there is disparity between knowledge and skills taught in a college and those needed by a professional engineer then re-alignment can be made using modification of in-school activities [3], cognitive apprenticeship [4], reflective practicum [5], and active learning strategies [6]. Perhaps a more direct approach [1], and the one used here, would be to use two key ideas. The first is the importance of structuring knowledge in a domain around key concepts and principles of the field to facilitate students' abilities to access and transfer knowledge to new and novel problems. The second is the central role of motivation in enhancing students' level of performance in educational settings. The first of these implies the encouragement of deeper learning by the students, which is in line with a growing focus on deeper learning principles in higher education [7,8]. In structuring knowledge in a domain around key concepts and principles, notice should also be taken of the findings of the authors [9] who have now come to the conclusion that induction rather than deduction may be the best strategy for teaching. The remainder of this paper is concerned with first, a brief discussion on how expertise may be developed within a, numerical methods for engineering module, a description of how it was implemented, and, an experiment to determine if there was any substantive improvement in student deeper knowledge and skills.

1 EXPERTISE DEVELOPMENT

It is not the intention here to spontaneously create experts from undergraduate students as expertise takes significant time to develop, for example ten years [10]. People who have considerable expertise, approach problems by considering the whole problem prior to attempting specific methods [11], and, they classify problems based on deep features, such as general principles that govern the correct solution rather than shallow features such as the relationship between objects in mechanics. A typical way for experts to approach the solution of a problem is to use basic principles by first noting important features of the problem, deriving a second-order interpretation of the general principles which were not explicitly stated in the problem and then developing general solution plans. This could be summarized as the non-expert reasoning backwards from the solution goal to the information in the

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problem whereas the expert reasons forward by developing a representation of the whole problem and using it to generate a problem solution [12].

It is our intention to provide learning experiences that are consistent with what is known about the development of expertise. That is to say that the experiences provided during the module will contribute to the maximum possible extent to the growth of expertise. Therefore it is the intention to design and sequence learning experiences, sometimes called, "effective learning experiences" [1], which will promote greater quantities of knowledge and component skills. Obviously, deeper approaches to learning and a closer integration of knowledge and skills place quite a significantly higher cognitive demand on students than the more traditional shallow approach. Hence there is a distinct need to raise motivation within students. Several authors have provided summaries of practices likely to enhance motivation including the authors [13,14]. The authors of [13] emphasizes that students need to perceive the value of the learning experience, students need to have the expectation that they can create and execute a plan to succeed at a given learning task, and, be aware that the learning environment set by the instructor supports their learning. The author of [14] summarizes important points concerning the role of motivation in learning, and guidelines for designing effective instructional environments. First, to attain higher levels of both personal and institutional interest, more cognitive engagement is needed and, instructors should include stimulating, interesting tasks, activities and materials including some novelty. Secondly, let the students have as much personal control of their own learning as possible and behavior, so instructors should provide feedback that focuses on the processes of learning, including use of strategies, effort, and the general changeable and controllable nature of learning. Thirdly, it is important to let students feel confident and competent about their learning tasks.

2 ENGINEERING EXPERTISE DEVELOPMENT FOR NUMERICAL METHODS

The two key suggestions from the preceding two paragraphs have been used as the basis to revise the delivery of an existing numerical methods module with the aim of producing better understanding and skills. What has been attempted is, '*structuring knowledge around key concepts and principles of the field to facilitate students' abilities to access and transfer knowledge to new and novel problems',* and*, 'improving the central role of motivation to enhance students' level of performance in educational settings'.*

To help in the structuring of the knowledge and to give immediate and easy access to the knowledge, a system replacing the tutorials and computer laboratories of the traditional course, centered on the computer algebra system *Mathematica* was devised, where all files necessary for the course (lecture notes, additional learning materials, databases, computer codes, reports, etc.) are available concisely, using notebook (.nb) files and placed on the course management system Moodle. This part of the new approach could be thought of as pseudo-web-based teaching. The traditional two-hour lecture per week was retained. The tutorial and laboratory materials were re-written with worked examples and small projects much more closely related to key concepts of the mathematics of numerical methods, fluid mechanics, heat transfer and vibration theory. The system was designed whilst keeping in mind the expected audience, page design, and usability [15], as well as its interconnection with the face-to-face lectures. The learning abilities of the students, in addition to their knowledge acquired from pre-requisite modules, were taken into account. Also, thought was given as to where the students would learn, and, ensuring they had access to computers when required. For page design, Moodle makes it easy to navigate from one learning material to the next. Consistency was used regarding fonts and layouts to help avoid frustration and make the scanning of information easier. The concepts and topics were organized to help the learner find key facts quickly and assist in comprehending critical topics. So called "chunking of information" was used where small sections of information were isolated to help the students retain the information better. It is known that people can retain large amounts of information if the information is presented in a well-organized fashion with the topics segmented [15].

As this new part of the course is, in the main, a self-study medium, interaction of the learner with the course contents becomes more important than found in other teaching forums. The learner has to interact with the content of the course as opposed to the instructor. This content engagement is critical and the learning experience is greatly enhanced when exercises and/or activities are incorporated [15]. This is exactly what this new system is used for here and, there is almost continual active learning when using this system. Animation, simulations, small quizzes and tests, are all written using *Mathematica* notebooks.

There is a “Root” (Fig. 1) system to help the student navigate through the many information files, together with a primitive, but developing “Find” option. Students also have a comprehensive “Help” option, where all *Mathematica* functions are fully described together with very useful examples. Communication currently is usually by email, chat-line or SMS with the participants fully capable of sending messages to individuals or to groups of other participants in addition to the instructor.

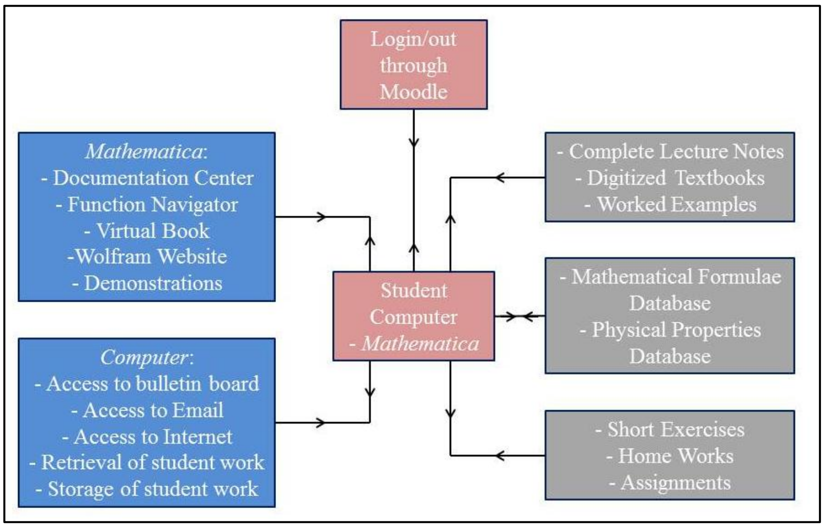

Fig.1 Student interaction with new learning system

To help with the motivation of the students, it was recognized that students had to be prepared to use the new system. This was in part instructional on how to use the system, but also inspirational ,in that the students were given information concerning the advantages of self-learning and raised their consciousness regarding letting them see that engaging in this activity could be fun, sometimes easier and definitely educationally rewarding. The system was designed to have meaningful events and relationships to engineering professional life. The exercises, homeworks and assignments were designed with the thought that they should be distinctive and memorable and that the pace of learning was neither overwhelming nor underwhelming. Today’s students, like society in general, have a need for instant gratification. Therefore, the first tasks in the learning process were given special consideration. The learner was carefully told of the context of the task, how it fits into engineering in general, they were given the hint of the challenge, and also of the resulting feeling of achievement when finished.

Lastly, there was an attempt to alleviate some of the disadvantages of working in relative isolation and the subsequent development of bad habits. In an effort to counteract these, meetings, in student groups of not more than 30 in number, were called when thought necessary and not less than one per week. During these informal meetings, which were student centered, every student was encouraged to talk about problems, successes, ways of working, etc. If a problem with a student falling behind arose, a teaching assistant was asked to help rectify any problems.

3 EXPERIMENT

To investigate the effectiveness the new developed approach to teaching and learning numerical methods in engineering, a controlled experiment applying a pre-test- post-test control group design was conducted [16]. The subjects had to undertake two tests, one before the module started (pre-test) and one after the module was completed (post-test). The effectiveness of the teaching and learning was then evaluated by comparing the scores between subjects in the experimental group (A), i.e. those who were taught using the new approach, and subjects in the control group (B), i.e. those who were taught using the traditional approach. The new approach consisted of a two-hour lecture plus as long as a student liked using the materials on Moodle. The traditional approach consisted twelve weeks of a two-hour lecture, a two-hour tutorial and a two-hour computer laboratory session each week

3.1 Experimental hypothesis

Six constructs were used to measure performance of the teaching and learning. Each construct was represented by one dependent variable. The experimental hypothesis was stated for the dependent variables as,

'*The learning effect in group A is higher than in group B, either with regard to the performance improvement between pre-test and post-test (relative learning effect), or with regard to post-test performance (absolute learning effect). The absolute learning effect is of interest because it may indicate an upper bound of the possible correct answers depending on the type of teaching and learning (A or B)*'.

3.2 Method

A pre-test−post-test control group design was applied. The design involved subjects from groups taught in two sequential semesters. The groups had already been taught modules in Engineering Mathematics and Vector Analysis in exact content and time-wise replication, and a distribution of their combined results for these two modules is shown on *Fig. 2*

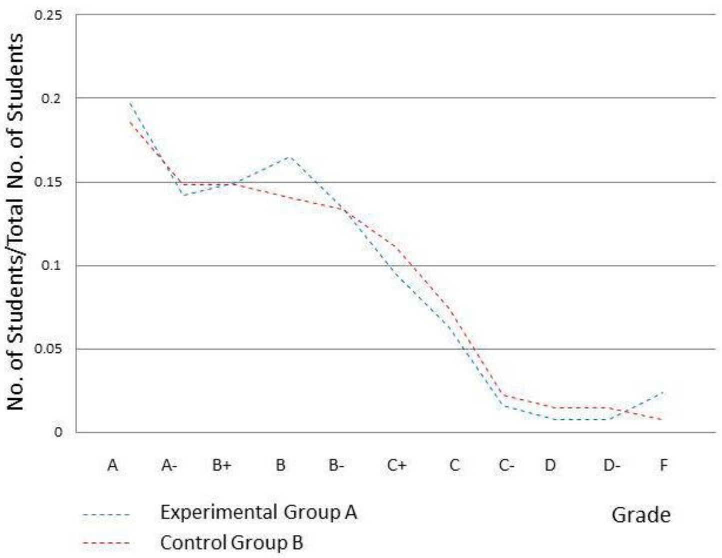

Fig. 2 Normalized distributions of combined marks for groups (A) and (B).

As can be seen, the distributions of the two student cohorts are reasonably similar in their mathematical abilities, and the correlation coefficient was calculated as 0.91. The mean results for groups (A) and (B) were 65.4% and 64.9%, respectively, and the standard deviations were 8.6% and 10.1 % respectively.

The students did not know that the post-test questions were identical to the pre-test questions, nor were they allowed to keep any of the examination questions. The personal characteristics of each group are summarized in *Table 1*.

Table 1. Personal characteristics

Characteristic	Group (A) ($n = 124$)	Group (B) ($n = 149$)
Average Age (years)	21.5	20.6
Percentage female	52%	49%
Majors	Chemical, Electrical, Mechanical, Civil Engineering	Chemical, Electrical, Mechanical, Civil Engineering

Two things especially were of concern to this experiment: the opinion of both groups of web-based learning was not high, indicating perhaps that the pseudo-web-based teaching being offered to the experimental group (A) may not be well received; secondly working with others seems to very important to each group, indicating again that possible isolation when using the course management system approach must be guarded against. During the experiment, data for two types of variables were collected, that is four dependent variables to capture fundamental concept knowledge (C.1, …,C.4) and two dependent variables which capture skills concerning the module (S.1, S.2). The dependent variables are constructs used to capture engineering expertise as gained from the teaching and learning of the module. Each construct was measured through an aggregate of 3 questions. The nature of the questions asked for each construct is given in *Table 2*.

Table 2. Experimental variables

	Knowledge concerning fundamental concepts of:
C.1	Ordinary and partial differential equations.
C.2	Fluid mechanics in relation to numerical methods.
C.3	Heat transfer in relation to numerical methods.
C.4	Vibration theory in relation to numerical methods.
S.1	Demonstration of computational skills when solving partial differential equations.
S.2	Demonstration of computational skills to visualize results during the post-processing stage.

Standard significance testing was used to investigate the effect of the treatments on the dependent variables C.1 to C.4 and S.1 and S.2. The null hypotheses were stated as follows,

$H_{0,1}$: There is no difference in relative learning effectiveness between experimental group (A) and control group (B).

$H_{0,2}$: There is no difference in absolute learning effectiveness between experimental group (A) and control group (B).

For testing hypotheses $H_{0,1}$ and $H_{0,2}$ an appropriate test is a one-sided *t*-test for independent samples [17]. It is well known that the *t*-test operates under the assumption of normal distribution of the variables in the test samples and the absence of outliers. On testing it was found that normal distributions of results could not be assumed and the results for each lay within the range of $\pm 2\sigma$ for each of the tests. It has been stated [16] that *t*-tests are in fact quite robust against the violation of the normality assumption but strongly influenced by outliers. Given what has been just described, it was felt that *t*-testing was appropriate here.

4 RESULTS

4.1 Inferential statistics

In the following, the results of statistical hypotheses testing are presented for each hypothesis individually.

Table 3 shows for each dependent variable separately the results of testing hypothesis $H_{0,1}$ using a one-tailed *t*-test for independent samples. Column two of this table gives the value of Cohen's d, column three the degrees of freedom, column four the *t*-value of the study, column five the critical value for α = 0.10 that the *t*-value has to exceed to be statistically significant, and column six provides the associated *p*-value.

The most striking of these results is the large Cohen's d values for the dependent variables S.1 and S.2. A statistically significant level and practical significance was achieved for both of these dependent variables. For the dependent variable C.1, which was concerned with fundamental concepts involving partial differential equations and ordinary differential equations, the result was less emphatic, but also statistically significant and of practical significance. The result for the dependent variable C.2 shows a very low value hence no significant result can be claimed here, and, while the dependent variable C.3 result shows a slightly statistically significant result. The dependent variable C.4 does not support the direction of the hypothesis.

Table 3. Results for ‘performance improvement’

Group (A) versus Group (B)					
Variable	d	df	*t*-Value	Crit. $t_{0.90}$	*p*-Value
C.1 (ODE,PDE)	0.68	271	5.597	1.2846	0.0000
C.2 (Fluid Mech.)	0.06	271	0.494	1.2846	0.3108
C.3 (Heat Transfer)	0.30	271	2.469	1.2846	0.0070
C.4 (Vibration)	-0.03	271	-0.247	1.2846	0.5975
S.1 (Skills, PDEs)	1.12	271	9.219	1.2846	0.0000
S.2 (Skills, Visual)	0.94	271	7.737	1.2846	0.0000

Table 4 shows for each dependent variable separately the results of testing hypothesis $H_{0,2}$ using a one-tailed *t*-test for independent samples. Again the values for the Cohen’s d are large for the dependent variables S.1 and S.2, showing that a statistically significant level and practical significance was achieved for these dependent variables. While the dependent variables C.1 and C.3 do not show a high statistical significance, they do support the direction of expected absolute learning effect with practical significance, i.e. showing a medium effect size. The dependent variables C.2 and C.4 do not support the direction of the hypothesis although the Cohen d values are reasonably small.

Table 4. Results for ‘post-test improvement’

Group (A) versus Group (B)					
Variable	d	df	*t*-Value	Crit. $t_{0.90}$	*p*-Value
C.1 (ODE,PDE)	0.24	271	1.975	1.2846	0.0246
C.2 (Fluid Mech.)	-0.11	271	-1.280	1.2846	0.8992
C.3 (Heat Transfer)	0.24	271	1.975	1.2846	0.0246
C.4 (Vibration)	-0.09	271	-0.741	1.2846	0.7703
S.1 (Skills, PDEs)	0.64	271	5.268	1.2846	0.0000
S.2 (Skills, Visual)	0.71	271	5.844	1.2846	0.0000

5 DISCUSSION

There was, at the beginning of the new system’s development process, an amount of scepticism and inertia which had to be overcome, probably due to the non-awareness of what such a system may contribute and a certain reluctance to change what was already working reasonably well. However, it was clear that new technologies and approaches could bring new opportunities and it was on this basis that progress was initially made. Also it was recognized that today’s students respond positively when using technology, that is, they seem more interested and engaged in what they were doing. A third reason, and an important one, was that it was felt that the subject, numerical methods, could no longer be divorced from computer programming. When computer programming is involved, the learning process becomes much more personalized after the initial beginner level, and the question arose as to how to efficiently provide the student with an environment to accommodate the need to explore different ways to achieve a given outcome, and to have time to reflect and research around and beyond an outcome.

The empirical studies presented in this paper investigated the effect of changing a numerical methods for engineering module to develop engineering expertise. The performance of the students was analysed with regard to six aspects, i.e., knowledge concerning fundamental concepts of, ordinary and partial differential equations (C.1), fluid mechanics (C.2), heat transfer (C.3), and vibration (C.4) as well as computational skills involving partial differential equations (S.1) and visualisation (S.2). The results show, quite conclusively that that the experimental method of delivering the module in the revised way led to enhancement of the skills acquired by group (A) as compared to group (B). It is clear when students are allowed to explore and learn at their own pace, and, with the opportunity to have as much hands-on activity as they wished for, computational skills become stronger.

The results for the performance of relative and absolute learning effectiveness between the experimental and control groups did not show as conclusive results as for the computational skills. For the fundamental concepts related to differential equations (C.1) significantly better scores were obtained by the experimental group but similar learning was received by both groups for the fundamental skills concerning fluid mechanics (C.2.) and vibration (C.4), showing that new material prepared for the experimental group had no effect, and perhaps reversed the hoped-for trend. For fundamental heat transfer concepts (C.2) the trend was correct and for relative learning effectiveness the results were statistically significant. It is clear that more work has to be done in structuring knowledge around key concepts and principles of the various fields of interest to improve these results. As the course is now on Moodle, development is planned for more audio, video modes of communication as well as the inclusion of much more digitised multiple-choice tests to help the students check on their progress and expand their curiosity. Lectures, explaining difficult concepts will soon be available “on-line” so that students can view explanations as many times as they feel necessary.

5.1 Threats to validity

There are three main classes of threats to the validity of this study, i.e. construct validity, internal validity and external validity.

Regarding construct validity, the isolation of the concepts of differential equations, fluid mechanics, heat transfer and vibration may not always be possible, so making the distinctions held in this work too simplistic. Internal validity is the degree to which conclusions can be drawn about the casual effect of the independent variable on the dependent variables. Potential threats can include selection effects, non-random student loss, instrumentation effect and maturation effect. The selection effect was to some extent alleviated by comparison of previous mathematical results of the two groups. In addition any differences in ability between groups were captured by collecting pre-test scores and by measuring the level of experience of students. There was no drop-out of any kind before the pre-test or before the treatment. Most students thought that enough time was given for each of the tasks, so alleviating an instrumentation effect, and any maturation effect was minimized by not informing students that they would be completing the same test for the post-test as that given for the pre-test. All pre-test papers were re-collected after the pre-test.

External validity is the degree to which the results of the research can be generalized to the population under study and other research settings. Two possible threats have been identified: student representativeness and materials. The students participating in the experiment were all students of an engineering discipline and it can be expected that the results of the study are to some degree representative of this class of students. However as they were undergraduates and not seasoned professionals, this assumption should be treated with some caution. As regards the materials, their size and adequacy may vary depending on students’ previous knowledge.

6 CONCLUSIONS

The results of this work are very promising when it comes to the improvement of the students’ computational skills. Much improvement was found when writing and analyzing computer programs concerned with partial differential equations and in producing post-processing visualization. The latter had the additional advantage in motivating students. However, the same decisive improvement was not found for the teaching and learning of fundamental skills. The results here were patchy, with at times negative results found between the two groups. In the future more audio, video and self-testing materials will be made available, including recording of lectures so that students can isolate difficult concepts and view explanations as many times as they require.

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REFERENCES

[1] Litzinger, T. A., Lattuca, L. R., Hadgraft, R. G. and Newstetter, W. C. (2011), Engineering education and the development of expertise, *Journal of Engineering Education*, Vol. 100, No. 1, pp. 123-150.

[2] Smith, K. A. (1987), Educational engineering: Heuristics for improving learning effectiveness and efficiency, *Engineering Education*, Vol. 77, No. 5, pp. 274-279.

[3] Resnick, L. (1988), Learning in school and out, *Educational Researcher*, Vol.16, No.9, pp.13-20.

[4] Collins, A. (1987), Principles for a theory of cognitive apprenticeship. Paper presented at American Educational Research Association Annual Meeting, Washington, D.C.

[5] Schon, D. A. (1983), The reflective practitioner: How professionals think in action, Basic Books, New York.

[6] Johnson, D. W., Johnston, R. T. and Smith, K. A. (2006), Active learning: cooperation in the college classroom, Interaction Book Company, Edina, Minnesota.

[7] Dabbagh, N. (2003), The intersection and alignment of learner-centered instructional strategies in on-line learning and their implication using course management systems, Presentation at NLII Next Generation CMS, Tucson, AZ.

[8] Weigel, V. (2002), Deep learning for a digital age: Technology's untapped potential to enrich higher education, Jossey-Bass, New York.

[9] Felder, R. M. and Silverman, L. K. (1988, 2002), Learning and teaching styles in engineering education, *Engineering Education*, Vol. 78, No. 7, pp. 674-681.

[10] Anderson, J. R. (1982), Acquisition of a cognitive skill, *Psychological Review*, Vol. 89, pp. 369-406.

[11] Chi, M. T. H., Feltovich, P. and Glaser, R. (1981), Categorization and representation of physics problems by experts and novices, *Cognitive Science*, Vol. 5, No.2, pp.121-152.

[12] Ho, C. H. (2001), Some phenomena of problem decomposition strategy for design thinking: difference between novices and experts, *Design Studies*, Vol. 22, pp. 27-45.

[13] Ambrose, S. A., Bridges, M. W., DiPietro, M., Lovett, M. C., and Norman, M. K. (2010), How learning works: Seven research-based principles for smart teaching, Jossey-Bass, San Franscisco, CA.

[14] Pintrich, P. R. (2003), A motivational science perspective on the role of student motivation in learning and teaching contexts, *The Journal of Educational Psychology*, Vol. 95, No. 4, pp.667-686.

[15] Vai, M., and Sosulski, K. (2011), Essentials of Online Course Design: A Standards-Based Guide (Essentials of Online Learning), Routledge.

[16] Adair, D., Jaeger, M., and Stegen, J. (2011), A comparison of two approaches when teaching object-orientated programming to novices, *International Journal of Engineering Education*, Vol. 27, No. 5, pp. 1-10.

[17] Sheskin, D. J. (1997), Handbook of parametric and nonparametric statistical procedures, CRC Press, Boca Raton.