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Assessment of Deep Learning Ability for Problem Solvers*

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Teaching design in engineering is a complex but challenging task requiring the development of numerous attributes by the students. Furthermore, with the increasing diversity of subjects taught in civil engineering less time is available for addressing individual subjects, let alone individual attributes. There is also the tension caused by the need to impart a deeper long-term training for engineering problem solvers while maintaining the short-term training of the essential but straightforward prescriptive design tools and skills. It is shown that it is still possible to develop design courses that train and, more importantly, assess a student's problem solving abilities by implementing assessment schemes that acknowledge and reward higher level learning while still maintaining an element that ensures the basic skills have been mastered.

Keywords: assessment; learning; teaching; engineering design; fundamental principles

INTRODUCTION

THERE IS CURRENTLY much discussion about the sort of training that is appropriate or best for engineering undergraduates. Many highlight the need for training students to be life-long learners [1] who are capable of tackling *real world* open problems in a creative manner. Ribeiro and Muzukami [2] talk of the 'unpredictable obsolescence of much of what is learned at engineering schools' and argue against a system based on the transmission and reception of knowledge. Potential ways to promote this have included the use of realistic designs [3] where the task might be similar to that expected of newly graduated engineers, case studies [4] where students are exposed to a wide variety of issues from actual projects, and problem-based learning in general where it is hoped students take an active responsibility in their own learning [2, 5].

However, despite all the advantages of the deep learning that is fostered by these methods, employers may still want engineers who are able to undertake standard design tasks following the application of relevant codes and standards. While it might be thought that there must be a trade-off between deep learning that prepares for life-long learning and shallow learning that is more appropriate for solving well-posed problems with a single correct solution, this may not always be the case. For example, van Meter and Sperling [6] suggest that student ability at problem solving is enhanced when some tasks become automatic. That is, practice in mathematical calculations, for example, makes the process more automatic and more attention can be paid to other aspects of the problem. This suggests the idea of assessing a design subject in two complementary ways: tests, exams and quizzes to ensure that the fundamental tools are there; and a separate process for the design itself to encourage them to tackle open problems in a creative way. Perrenet *et al.* [5] describe something very similar in an engineering course where direct instruction and supervised practice are used to complement problem based learning in a five-year engineering programme.

One aspect of the teaching process that seems to have been largely overlooked in the recent literature is the role that assessment plays in driving the way students approach the subject, no matter what form of delivery is being used. Ditcher [7] argues that 'students are driven by the external demands of the assessment system'. The effect that this has is not always appreciated. For example, Atman *et al.* [8] reported on a study that compared the design ability of freshman and senior year engineering undergraduates in tackling non-technical real world problems. A number of conclusions were drawn on the way the two groups differed but it is of interest that the assessment criteria were determined *following* the submission of the designs, leaving students with just a vague notion of what was actually required as they worked on their problems. We strongly believe that if students are to be given designs that are intended to foster an ability to tackle messy open-ended real-world problems, then an assessment scheme must be in place beforehand to guide the students towards the sorts of learning outcomes that are being sought. As Vos [9] suggests: 'criteria must describe the learning you *really* want to happen'. A report by the Committee on the Foundations of Assessment

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[10] agrees: 'Students learn more when they understand . . . the criteria by which their work will be evaluated'.

In a previous paper [11], a sequential procedure was described for specifically assessing the student's ability to solve problems. The aim of that paper was to show how university engineering design projects can be structured to encourage the development of the students' problem solving abilities, but more importantly how their problem solving abilities could be quantitatively assessed. Unlike often used assessment techniques where marks are entered for each of the components of the project which may then be weighted and summed [12, 13], this alternative assessment procedure prioritises in sequential order the concepts that govern the ability to solve problems. This is more in line with the taxonomy of Bloom et al. [14] where the cognitive skills are divided into six levels of increasing complexity. It also aligns with the U.S. Engineering Accreditation Commission [15] where the first of the assessment criteria (3a) is: 'an ability to apply knowledge of mathematics, science and engineering'.

In the current paper, three case studies, covering subjects from the first, third and fourth year of a four-year degree course are presented to illustrate the use of the sequential method in assessing deep or higher-level learning. It is shown how a component of the project must be formulated to force the student to tackle the problem solving aspects and how these problem solving aspects can be quantified, not just for the final mark but more importantly so that the student knows what is required at the start of the project. Examples are given of projects with single or multiple goals and an example is also given of incorporating standard methods for assessing knowledge retention with the sequential method for assessing deep learning to produce a balanced design project.

At the University of Adelaide we are lucky enough to have a large proportion of students from outside Australia (25% in the engineering faculty) and this has an effect on the teaching method and material. With such a large overseas contingent it would be inappropriate to focus courses on local engineering standards or codes of practice, so while these are used in the design the emphasis is clearly on teaching the fundamental principles and in problem solving. We want the students to learn to think, to learn to learn, and to learn the fundamental principles [11]. Students are then set design problems, parts of which are deliberately outside the scope of national standards and codes to encourage and enhance their ability to learn to learn and to problem solve. Finally, a part of the course towards the end teaches them to design according to the code or standard to get them accustomed to following codes even though it is felt that their training for this can best be obtained from industry where practising engineers have this expertise and the rookie engineer can rapidly obtain this skill from them.

FIRST YEAR ENGINEERING, PLANNING AND DESIGN

All first year students (approximately 400 each year) take an introductory engineering subject that involves a series of lectures and a group project. The lectures include modules on engineering history and ethics, economic principles, decision-making theory, environmental sustainability, social considerations, project scheduling, creativity, and the issues of working in teams. In the group project, students work in small teams (6–8 students) supervised by an academic. The projects are generally non-technical, although over the course of the semester many students will have to become familiar with some technical aspects of the solution they propose. In some ways it is not the final solution that is important but how the problem is tackled, and the lectures are designed to assist by providing students with some of the skills necessary to work effectively in the team environment. Furthermore, an open problem with an infinite number of solutions is required and it is believed that it is better if the topic is outside the academic's skill zone so that they cannot drive the solution in a particular direction. As an example, the following is an extract from the design brief handed to students by one of the authors:

Background to engineering, planning and design project

Each natural disaster brings its own unique problems for non-government aid organizations. However, these non-government organizations have to develop generic plans that can cope with all types of disasters so that they can react quickly. An aid organization, Students Support Without Frontiers, has advertised for a tender for the development of a generic disaster relief plan. Your consultancy, in competition with numerous other consultancies, is developing a preliminary plan. The consultancy that wins the tender will then be funded to develop a detailed plan.

Students research the problem, formulate a plan, and prepare a single group report, all in the space of ten weeks. The assessment technique, which is an example of the sequential assessment procedure for a project with a single goal, used for this project is shown in Table 1. Columns 2 to 6 list the sequential objectives in ascending order of priority and the rows show the grades that the objectives achieve. Although the background research undertaken by the students is important, what the marking scheme promotes is the use that they make of their findings. A shallow regurgitation of material is poorly rewarded and may even fail. The higher marks are reserved for those who are able to apply what they have found to the problem in a creative and well thought out way. It should be noted that the McBeath Action Verbs (create, design, explain, rate, challenge, defend and question) [16] that are relevant to these higher marks are associated with Bloom's higher learning cat-

Table 1 Engineering planning and design assessment

Grade (1)	Collection of important information, not quantity but diversity (2)	Synopsis of important information, reasons why important (3)	Categorisation of concepts within problem and reasons for categorisation (4)	In depth analysis and reasons (5)	Original approach with reasons (6)
HD > 85	Yes	Yes	Yes	Yes	Yes
D 75–84	Yes	Yes	Yes	Yes	No
C 65–74	Yes	Yes	Yes	No	No
P 50–64	Yes	Yes	No	No	No
F 40–49	Yes	No	No	No	No
F < 40	Not extensive	No	No	No	No

egories (synthesis, evaluation and valuation) and this is seen as a justification for the method. It can also be seen in Table 1 that the quality of the presentation of the report does not by itself warrant a set number of marks or even a grade. However, it can be used to set the final mark within the ranges listed in column 1.

The students are given the assessment procedure of Table 1 at the start of the project as part of the design brief and, hence, can tailor their approach accordingly. Generally speaking, each objective has to be achieved in sequential order. For example, the synopsis in column 3 cannot be achieved unless important information in column 2 has been attained. It has been found that the weak students may try to address each objective or column but more often than not in only a shallow fashion, hence, each objective has to be attained in depth. The importance of the students giving *reasons* is shown in columns 3 to 6. It is only when the students attempt to give reasons for certain behaviours that the depth of understanding of the student can be gauged. That a certain behaviour occurs and is recognised is important, however, an attempt by the student to explain through reasons why that behaviour occurs is much more important and can be used to gauge the depth of understanding.

THIRD YEAR REINFORCED CONCRETE DESIGN

The sequential assessment is applied to a third year reinforced concrete course where the class of 45 to 50 students design a new reinforced concrete frame and then retrofit the frame for increased loads to strengthen and stiffen it. The first part of the course shown in Table 2 covers the most difficult component, which is the analysis and design of reinforced concrete columns. The students learn to design reinforced concrete columns from first principles by developing their own spreadsheets that allow any column cross-section to be analysed. This ensures that the students obtain a full grasp of the concepts that control the structural fundamental behaviour of reinforced concrete. Their understanding of the *fundamental principles* and their (possibly) shallow learning is tested through two 90-minute quizzes that cover closed form problems done under exam conditions.

The students have then to use the fundamental principles to consider a new retrofitting technique that is outside the scope of existing standards and which is presented as an open ended problem so that they can use their imagination. The results are submitted as hand calculations, spreadsheet analyses and a typed report In the hand calculations and spreadsheet analyses the students apply the fundamental principles to this new retrofitting technique. As the mathematics of this component have already been assessed by the quizzes, the lecturer does not have to scrutinise this component in detail but only ensure that certain principles have been covered. In the typed report, the students have to discuss and critically review the outcomes of the hand calculations and spreadsheet analyses, giving reasons throughout and this is used to assess their ability to solve problems.

Having covered the most difficult component of the course in the column design (Part 1 in Table 2), the second part of the course then has the students work on the design of reinforced concrete frames. This half is closer to a standard design although there is a small component that requires the beams to be stiffened, which lies outside current standards and is presented as an open problem to allow some originality of thought. The assessment also includes quizzes, hand calculations, spreadsheets

Table 2 Reinforced concrete design timetable

Week number in 12 week semester											
1	2	3	4	5	6	7	8	9	10	11	12
		Quiz 1			Quiz 2					Quiz 3	
Part 1: Column project							Part 2: Frame project				

and typed reports. It can be seen that the course covers the full design package as may be required by a consultant, but also incorporates problem solving, which is central to a university education.

The column retrofitting component in the first part of the course is presented to the students as follows.

Column retrofitting component A client, consisting of a government housing and bridge department, has offered for tender a contract for the assessment of a new technique for the static and seismic retrofitting of reinforced concrete structures by bonding either steel, aluminium or carbon/glass fibre reinforced polymer (FRP) plates to their surfaces.

The contract was offered as this is a new form of construction that is not covered by existing codes of practice. Your consultancy/contracting firm has been lucky enough to win the contract under extreme odds even though there is no one in your firm familiar with the technique. The aim is to:

- Provide an engineering assessment of the potential performance of this new technique for retrofitting reinforced concrete columns. The engineering assessment is to be based on analyses of the existing test data and numerical simulations using fundamental principles, as this new form of retrofitting is not covered by national codes of practice.
- From your analytical assessment of the technique and further parametric studies, you will need to advise your client on whether: to use the technique; not to use the technique; further testing or further analyses are required; which approach is best, etc.

The students are required to hand in *engineering hand calculations* of any length and that are well annotated, *spreadsheets* for calculations that are repeated, and a *typed report* of a finite page length. The typed report must not contain components of the lecture notes nor of the hand calculations but should give the results of any calculations such as in parametric studies. In particular, the typed report allows the student to show their depth of understanding or originality by discussing the outcomes and by giving reasons and suggestions. In effect, the typed report is used to determine whether the student gets a Distinction or High Distinction.

The assessment procedure is given in Table 3. If the student does a parametric study that shows variations, then that will only get a Credit. If the student gives structural engineering reasons for the variations and explains them in such a way that suggests a deep understanding then this will achieve a Distinction. If an original approach is developed or if an original reason is deduced or for any other originality, (and this does occur), then the student is worthy of a High Distinction. An excellent presentation that does not display understanding may only achieve a Pass or Credit. An original approach poorly presented, but understandable, would still achieve a Higher Distinction.

Table 3 Assessment of RC column retrofitting project

Grade	Characteristics
HD 85–100	As for a Distinction but some original approach through reasoning
D 75–84	As for a Credit but shows a depth of understanding through reasons
C 65–74	Easy to follow straightforward basic calculation according to the Code and without reasons
P 50–64	As for a Credit, however some basic errors that suggest a lack of understanding
F < 50	As for a Credit, however major errors in understanding

FOURTH YEAR HONOURS RESEARCH PROJECT

The final year research project in an engineering university degree is really the ultimate course in assessing the student's abilities in problem solving as it directly tests all three facets of problem solving: the ability to think, to learn, and to grasp and extend fundamental concepts. It is, therefore, in many ways the most important course in which to apply the sequential priority approach. The assessment procedures described below have been developed for a final year research course where a total class of approximately 60 to 80 students is divided into groups of four students to tackle an engineering research problem. The course accounts for a quarter of a year's work for each student and, hence, the project is equivalent to a full year's work for an individual student; accordingly the outcomes should be just below that expected from a student doing a Master by research. Obviously if less overall time is available, the expectations should be reduced.

The course is well structured to keep the students motivated and on track. The main outcomes are a literature review and a short presentation in the first semester, followed by a poster presentation, thesis, and conference presentation in the second semester. The assessment of the literature review, which counts for 10% of the mark, is similar to that shown in Table 1, but shown again in Table 4 with the three facets of problem solving. The students are required to collect important literature relevant to their project. Of importance in columns (2) and (3) is not the quantity but the diversity of the information collected. Hence page after page of references would be frowned upon. Furthermore, if that is all they do, they will fail. What is important, is what the students do with the information they have collected. We are now in the realm of *Learn to Learn* in columns (4) and (5). Each publication has already been broken down into its important components in column (3), it is now categorised in column (4) and in terms clearly shown to be relevant to the research project in column (5). All the time, the students are expected to give reasons and to demonstrate their understanding. Having now collected the information and broken it down into forms relevant to the research project, the students can now use the information and in many ways make it their own in columns (6) and (7), which is now in the realm of *Learn to Think*. Column (6) covers their own in-depth discussion or analysis of the facts they have collected. The students should be encouraged to give their own reasoned opinions, follow their own paths even though they may appear to be unusual; in essence, to use their imagination, and if something original comes out of it then they may have entered the domain of a High Distinction in column (7).

The assessment of the final thesis or report carries most of the course marks (75%) and is, therefore, the most important. The problem with the thesis assessment is that it can be taken personally by the students' supervisor. To avoid this, the thesis is assessed by the supervisor and independently by two other lecturers, one of whom has expertise in the discipline of the project. Most of the final mark will come from the independent lecturers, and if there is a large discrepancy with the supervisor's mark then this is discussed and the discrepancy resolved.

Table 5 is used to assess the research itself and is an example of an assessment with numerous major goals. Students have to write their theses such that non-experts in the subject can assess the categories in Table 5 so that this component of the assessment can be done by all three assessors. Furthermore, if an approach is novel, this information has to be clearly set out in the thesis. The assessor is not expected to try to deduce what the students were thinking. The literature review is reassessed at the end of the project using Table 4. Most research projects use some sort of Methodology such as finite element analyses, genetic algorithms or simply existing equations. Furthermore, most research projects also entail some sort of Parametric Study in trying to find a solution that includes testing.

The upper grade from each of the *Major Items* in Table 5 should give a good indication of what the overall grade should be. Other issues that might affect the final mark are given in Table 6. *Presentation* is important but should not affect the grade but the mark within the grade assuming that the thesis is understandable. The research may already have been graded in Table 5, but it is also worth considering the *Depth of Research* in Table 6. Furthermore as the research is done by groups of four, the *Width of Research* is also important. Even though the grades are shown in the top row in Table 6, this table is only meant to adjust the overall grade from those in Table 5. Also of

Table 4 Assessment of literature review

	Fundamental Principles		Learn to Learn (reasons)		Learn to Think (reasons)	
Grade (%) (1)	Collection of literature (2)	Synopsis of literature (3)	Categorization of literature (4)	Relevance of literature (5)	Their own in-depth discussion (6)	Originality of thought (7)
HD > 84	Good	Yes	Yes	Yes	Yes	Yes
D 75–84	Good	Yes	Yes	Yes	Yes	
C 65–74	Good	Yes	Yes			
P 50–64	Good	Yes				
F 40–49	Good					
F < 40	Poor					

Table 5 Thesis assessment: Part 1—Assessment of research component

Major items Grade (%)	P 50–57	P 58–64	C 65–74	D 75–84	HD 85–93	HD > 94
Methodology Methodologies such as FEA, computing, statistical, ANN and GA packages, and existing equations	Use of existing methodologies		Minor logical development of methodology	Interesting logical development	Exciting logical development of existing methodologies that leads to a significant new approach	
Parametric Modelling Modelling such as experimental tests, computational, and mathematical equations to determine the effect of a variable	Reasonably planned	Carefully planned	Logical extraction of major influences from study	Logical in depth discussion of influences and reasons for trends	Logical discovery of influences that lead to a novel approach or explanation	
Literature review						

Table 6 Thesis assessment: Part 2—Issues affecting final mark

Major Item / Grade (%)	P 50-57	P 58-64	C 65-74	D 75-84	HD 85-93	HD > 93
Presentation: Just adequate to: clearly explained, good cross referencing, good illustrations where required, structure of report easy to follow, lot of effort gone into presenting charts, diagrams and figures.						
Depth of Research:	Shallow issues/understanding as in elementary text books			Complex issues that are explained clearly to demonstrate a depth of understanding		
Width of Research: following schedule based on groups of 4 otherwise adjust accordingly	Could have been done by 1 person.	Could have been done by 2 persons.	Could have been done by 3 persons.	Substantial enough to require a research team of 4. Much too diverse to be tackled by one person. Hence the requirement of a research team and major contributions from all members.		
Student Initiative Supervisor only: Areas where the supervisor did not specifically define the research steps, eg if the supervisor thought of an idea/interpretation, how did the student develop it.	Did what they were told to do		Some initiative shown	Capable of logically pursuing a path and developing their own approaches.	Their initiative came up with unforeseen approaches	Their initiative came up with unforeseen approaches that have future potential

importance is the *Student Initiative,* which can only be assessed by the supervisor. For most research groups, Table 6 has little or no effect but is usually used in only exceptional cases.

Having gone through Tables 5 and 6, the assessors should now have a good idea of the grade for the thesis. Table 7 is probably the most important in the assessment and is the final step in the process and should only be done by the supervisor and the assessor who is also an expert in the field. A distinction is made between research projects in *Established Fields* and those that are *Pilot Studies* as the latter are recognised as a very important research tool that may have fewer directly applicable outcomes. *Established Fields* are defined as where the problems in the research field are known so that the originality is mainly in the development of solutions to these problems. *Pilot* or *Blue-Sky Studies* are defined as where the originality is mainly in the identification of the problems in the research field and the development of solution paths such as the groundwork for new modelling techniques.

Table 7 is based on what can be done with the research and in particular what the supervisor would be willing to do with the research, with the supervisor's reputation in mind. Let us consider the *Established Fields*. If the supervisor would genuinely take the contents of the thesis and from only the contents write a journal paper for an international archival journal with the supervisor as one of the authors, then this research is worth the high end of a High Distinction. As a further example, if the research is not of a high enough standard to be published in a journal, but the supervisor is genuinely willing to present it at an international conference then it is worth a Distinction, and so on. A similar approach has been applied to *Pilot Studies* but with a slight reduction in expectations.

CONCLUSIONS

Much work has been undertaken designing engineering courses that are relevant to the profes-

Table 7 Thesis assessment: Part 3—Grading of thesis

Item Grade	P 50–57	P 58–64	C 65–74	D 75–84	HD 85–93	HD 94–100
Established Fields	Bare minimum	Department report.	Local conference.	International conference.	Local non-archival journal paper.	International archival journal paper.
	Nothing original	Data collection, parametric study	Some originality	Original and interesting	Substantial originality	Outstanding originality
Pilot or Blue-Sky Studies	Bare minimum.	Department report.	Local conference.	Average international conference.	Good international conference.	Good international conference.
	Nothing original	Data collection, parametric study	Some originality	Identified new research areas to propose new research approaches.	Identified new research areas to propose and partially develop new research approaches.	Identified new research areas to propose and substantially develop new research approaches.

sion and attractive to students. The use of realistic design projects, case studies and problem or design-based learning have all been promoted as ways to achieve these often contradictory goals. It appears that less thought has been given to the means of assessment and yet it is generally acknowledged that the assessment process drives student learning. Examinations and quizzes are appropriate for assessing how well the basic knowledge and tools necessary for design have been mastered, and the need for these should not be underestimated. However, the assessment of complex, open-ended designs requires a quite different approach and one that rewards deeper learning and the creative application of the basic skills.

The assessment that is appropriate for design should not be rewarding submissions where the bulk of the effort has been put into superficial aspects such as the overall presentation. This may lead to unsatisfactory learning outcomes where in a problem based learning (PBL) subject 'earning credits in PBL appears to be much easier than passing the subject course examinations' [5]. This is not to say that presentation is not important; in the current marking scheme presentation can vary the mark by 10–15%, but this is not what students should be directing their real efforts to. The scheme that has been developed emphasises to students at the start of the design the need to research their topic thoroughly and to use what they have found in a way that demonstrates deep understanding and, if possible, creativity or critical judgement. It also gives the academics marking the submissions a clear description of what is required and this can only assist in producing reliable marks across a wide range of markers [17]. We believe that this approach has changed the way students approach design problems, and has changed it for the better.

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