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Identification of generic errors for effective formative feedback in Energy Studies thematic area of Mechanical Engineering

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Abstract: The paper describes the findings from a CETL funded project for the identification of generic errors made by undergraduate students within the thematic area of energy studies in an accredited Mechanical Engineering programme. The idea came from the author's own experience of teaching in the above thematic area when he observed that the mistakes and errors that the students usually make have some recurrence. Also, the mistakes committed within this subject area are very much theme focused.

A systematic qualitative investigation was carried out on the student works available within module boxes. Usually the number of student works kept in a module box is square root of n, where n represents the total number of scripts in a cohort. Four different modules spread over three academic levels (Levels 3,4,5) and for three academic years were available and considered for data collection. Altogether the number of student works that were available was 185. The methodology involved the standard qualitative categorisation approach where the scripts were scrutinised and re-scrutinised in an attempt to identify the commonality of mistakes. After several trials along with critical analysis of the tutor feedback on each individual script, it was possible to identify nine generic errors and mistakes. The frequencies were then counted and data presented in percentages.

Interestingly, the findings from this study have later been compared with errors found in examination scripts (of one energy study module) in later years and a broad similarity has been found. Based on such observation, the author regularly uses the findings to remind students of the generic errors and mistakes and highlights the various ways in which they can be minimsed. The feedback from students has been found to be very positive. The results also highlight that similar templates can be produced for other thematic areas of learning such as 'design' or 'mechanics' within engineering disciplines. Students will greatly benefit from such an in-house list which may serve as a feed-forward template in their future years in the university and beyond.

Introduction

The degree level programme in Mechanical engineering (ME) is a broad discipline and covers many different subjects which are delivered through a number of modules. The undergraduate curriculum spreads over three or four years in English universities and leads to either BEng (H) for MEng (H) qualification respectively. The whole curriculum can be viewed as being made up of four areas of learning namely, Design, Mechanics, Energy studies (ES) and supporting subjects such as Economics, Accounting, Business study etc. The thematic area of ES is a core area of learning for all mechanical engineering and related programmes. During their three or four years in the university, students develop their knowledge in this area by building upon previous year's knowledge. For example, Energy studies for the IMechE (2012) accredited mechanical engineering programme at Northumbria University is taught over three years as EN0101 (Level 4), EN0201 (Level 5) and EN0301 (Level 6). For other programmes such as Mechanical Design and Technology, MDT (discontinued two years ago due to poor recruitment), there were similar modules namely EN0146 (Level 4) and EN0230 (Level 5), which also dealt with Energy studies. Usually, a level 4 module in ES is a pre-requisite for a corresponding level 5 module due to the conceptual building blocks of

knowledge which the students are expected to acquire gradually. The topics within this core area are traditionally termed as 'harder' subjects (Yerushalmi & Polingher, 2006) because they involve highly conceptual theories of Heat and Mass Transfer, Laws of thermodynamics or complicated fluid flow equations (Massey & Ward-Smith, 2006) etc. It is the author's opinion that the deeper understanding of these subjects is accomplished in three stages. They are:
(a) Understanding the fundamental concepts of all of these theories,
(b) Develop the ability to translate these theories into workable engineering principles using mathematical tools and
(c) Be competent in applying these principles into practical engineering problems.

In this context, it is worthwhile to look at the specific UK-SPEC (Standard for Professional Engineering Competence) learning outcomes criteria and compare them with the three stages mentioned above. As can be seen from the IMechE (2012), there are five components of learning outcomes: *Underpinning Science (US), Engineering Analysis (E), Design (D), Economic, Social and Environmental Context (S) and Engineering Practice (P)*. The modules within ES contribute significantly to *US*, *E* and *P* and broadly correspond to stages (a), (b) and (c) respectively.

The fact that fundamental conceptual understanding is the essential pre-requisite for progressing through ES, any 'misconception' or 'lack of understanding' may deter the students in using the knowledge for practical engineering practice. Hence it is very important to identify the errors made by the students so that corrective actions can be taken. Miller *et al*. (2011) conducted a very thorough study on identifying the misconceptions in these subjects using a Delphi study (Streveler *et al*. 2003) on a large sample of undergraduate students in a number of universities in the USA. They developed an assessment instrument, the Thermal and Transport Concept Inventory, which can be reliably used to identify a dozen poorly understood concepts. One of the characteristics of these misconceptions is that they are very 'robust' and 'hard to change' and may even stay with the learners after graduation (Chi, 2005). With rapid advancement of science, this 'lack of understanding' may act as a big hindrance for engineers to adapt to the changes in emerging technology. The author of the present paper would like to extend further that the deeper understanding also remains incomplete unless the other stages identified in the previous paragraph (stages b and c) are equally developed.

One convenient way to measure the understanding of a learner's knowledge is through summative assessments and the final grades. However, this mode of assessment, although widely and conveniently practised for ES subjects, fails to evaluate the process of learning (Black *et al*. 2002). Only a careful scrutiny by experienced faculty members of the errors and mistakes made by the students can show the extent of the student's level of understanding. The objectives of the present paper are to present the findings from a project to explore the generic patterns of such errors so that a 'data base of subject specific mistakes and errors' can be created. A list of such 'mistakes and errors' can be used by the tutor to provide feedback (Higgins *et al*. 2001) or act as a feed forward (Duncan, 2007) template for future years. Also, a reliable list developed in-house may help the lecturers to provide focused tutorial help and optimise the time sharing between topics.

Methodology and Results

As part of the quality assurance process at Northumbria university, module boxes for all modules are securely stored for at least past three years. Each module box must contain a sample of student work for all types of assessments such as assignment, laboratory reports and examination scripts. The number of scripts for which records are kept is square root of n, where n represents the cohort size. If the cohort size is less than 50, then at least 7 representative samples are kept. The sample is selected by taking equal number from the top and the bottom quartile and the rest from the middle range. The years for which module boxes were available are the academic years ending in 2005, 2006, 2007 and the total number of student works available for this study was 185. The modules considered were all in the ES area as mentioned below.

- EN0101: Energy and the Environment (Level 4, ME)
- EN0201: Energy Conversion Systems (Level 5, ME)
- EN0301: Energy Management Systems (level 6, ME)
- EN0230: Technology for Engineering (Level 5, MDT, now discontinued)

In the first instance, all of the tutor comments (395 in total) were written up by a graduate student in a spread sheet. Then the author, who himself is a subject specialist and taught some sections of all of the above four modules, scrutinized the student works to find out why marks were deducted by comparing against model solutions available in the module boxes. Author's scrutiny resulted in additional 200 data points in the form of comments in author's own words. All of these data (totalling 595 at this stage) were then analysed by following the framework approach (McDowell *et al*. 2010; Pope *et al*. 2002) of Grounded theory as is commonly employed for qualitative data analysis. In a nutshell, the comments were read and re-read over and over again and several themes of 'errors and mistakes' started to emerge after familiarisation with the bulk data. After several iterations, it was possible to group all the 'meaningful data' under nine generic categories of error. The total number of data (i.e., various errors and mistakes) was 560 for which frequencies were calculated. Thirty five data were rejected for various reasons such as being vague, ambiguous or irrelevant. At that stage, the author had detailed discussion with another more experienced colleague who was also of the opinion that the categorisation was meaningful. More discussion on the choice and implications of the error categories are discussed later in the paper. The nine error categories are shown in Table 1 and the frequency and percentage of the generic mistakes are given in Table 2.

Table 1: The nine categories of errors and mistakes

Category	**Description of the error**
A	Not understanding the fundamental concepts
B	Unable to engage in short follow-up discussion of problems
C	Not understanding the physical problem clearly or not reading the question carefully
D	Using wrong units and wrong equations
E	Calculation error
F	Error carried forward
G	Wrong assumptions
H	Fails to show steps
I	Reported wrong answer

Table 2: Frequency and percentage of errors and mistakes in each category

Error type	A	B	C	D	E	F	G	H	I	Total
Count (n)	188	36	70	67	77	54	38	12	18	560
Percent (%)	33.6	6.4	12.5	11.9	13.7	9.6	6.8	2.1	3.2	99.8*
*Does not add up to 100, due to rounding off to one decimal point.										

Further note on data and sources of bias

Since the data were collected from random representative samples they are likely to be free from any bias. Also, the entry qualification of students during those three years was the same (280 UCAS points or equivalent for ME and 260 for MDT) suggesting uniformity of students' academic merit. However, it is possible that the student works which were kept in the module boxes may have 'more written' comments than 'normal' due to the fact that these are subject to external scrutiny during Internal Periodic Review or Accreditation Visits. However, this was an advantage to the study rather than a bias. The work which was meant to be done by the author himself was already available thanks to the tutors who at that time were unaware that such a study would ever be conducted.

It may however be argued that the additional 200 data points collected by the author himself may have been subjected to personal bias. To avoid this as much as possible, the author did not scrutinise the other 395 data points in the spread sheet collated by the graduate student before writing his own comments on the student works.

Rationale, Implications and Suggested Corrective Actions for Errors

The nine categories of errors and mistakes identified in this study arose from various considerations. The fact that the subjects within ES comprise difficult scientific principles (Streveler *et al*. 2003), the errors due to conceptual misunderstanding are likely to be very significant and is also reflected in Table 2. While some of the other errors (such as E, H and I) may be generic to any other mathematical subject, the implications may be very different in the context of ES. Columns two and three in Table 3 below, summarises the rationale and implications for the choice of various categories and column four gives an outline of possible corrective measures.

Table 3: Errors: Rationale, implications and corrective measures

Error category	**Rationale/ Root cause**	**Implications**	**Corrective measures**
A. Not understanding the fundamental concepts	Nature of the subject Many sub-divisions possible Tutor's evaluation - may be subjective	Impact future learning and professional practice Gross reduction in mark	Students need thorough reading and solve tutorials Tutor to highlight the basic concepts in the lecture, tutorials and labs
B. Unable to engage in short follow-up discussion of problems	Basic theory leads to many corollaries which are equally important for engineering applications. Students must develop this ability.	Essential for understanding practical engineering applications but often ignored. Learner not being able to bridge fundamental theory and engineering principles.	Students must not avoid studying descriptive topics in detail. Tutor to emphasise the importance and highlight significance by relating theory to practice
C. Not understanding the physical problem clearly or Not reading the question carefully	ES problems are sometimes too long and students lack the ability to extract right information from the bigger physical situation.	Essential for engineering practice. ES problems are always complex and associated with other processes.	Students to practice many tutorials by themselves. Tutors to supply plenty of tutorials of variable challenge.
D. Using wrong units and wrong equations	The role of units (such as kg, ^{o}C) can be very tricky in ES and students must develop the understanding of how the interplay between units affect different quantities.	A very common source of error and may lead to wrong or misleading answer and interpretation. May contribute to significantly poorer grade.	Students to solve tutorial problems. Tutors must not avoid setting challenging problems to focus this aspect.
E. Calculation error	Correct results are vital for engineering systems. Simple error and is caused by too much dependence on calculators	Often trivial. May have very serious consequence by leading to different physical meaning if the numbers are wrong.	Students to solve problems in few steps. Interpret the physical meaning of final answer/ result.

Error category	Rationale/ Root cause	Implications	Corrective measures
F. Error carried forward	Engineering problems are inter-connected and students must develop the competence of getting it right at every stage.	May have serious consequence in real life and may lead to completely wrong result.	Students to look at intermediate results and interpret physical meaning. Tutor to highlight the possible effect by fictitious scenario.
G. Wrong assumptions	Practical engineering problems are so much connected with other systems that it is essential for students to develop the ability to make judicious assumptions.	May lead to seriously erroneous solutions. Poor grade in exams.	Students to solve tutorial problems and engage in relevant laboratory work. Tutors to highlight these issues.
H. Fails to show steps	A recurrent mistake found in significant number of scripts. Students' habit of avoiding writing and too much use of calculators.	It matters more if the final answer is wrong and the tutor has no clue about the actual level of error. Poorer grade	Students to solve problems in few steps and write them down. Tutors should highlight this point.
I. Reported wrong answer	Ambiguous question? Students not reading the question or failing to understand the problem	Fairly trivial and may not reduce grade significantly.	Students can easily avoid these by reading the question carefully.

Discussion

The systematic exercise carried out during this project has several useful implications some of which are shown in Table 3. From lecturer's point of view he/she would be able to provide more structured feedback to students in addition to their numerical grades. With a checklist like this, the teachers can easily provide useful formative feedback (Bertolo *et al*. 2012; Irons, 2008) very quickly which may help to reduce staff workload. This would also help students concentrate on the topics where they are weak or where they need more help. They can then seek help from tutors in the tutorial classes on such matters. It may also be possible to identify specific topics within this subject area that are more 'difficult' (from students' perspectives evaluated by frequency of occurrence) than the others. This would allow the tutors to spend variable amount of tutorial time so that the difficult topics may be delivered more effectively and efficiently. It will also highlight whether there is a need to design any laboratory experiment on the more difficult items. Once identified, students can also engage themselves in rectifying their errors and clarify their understanding. The laboratory components of the modules can significantly help in the reduction of errors in category G.

Error categories A and B which represent two-fifths of all errors, may be sub-divided into many categories and is essentially subject specific. For example, if a similar study were conducted on Mechanics which is also a highly mathematical subject, the fundamental building block concepts would be completely different and would have different sub-divisions. The author has also experience in teaching Mechanics for a number of years, and feels that ES are likely to have the highest number of conceptual errors compared with other thematic areas in mechanical engineering. The data base created by the Colorado educational research group (Streveler *et al*. 2008) may be consulted for the sub-categories. In terms of marking, it is the tutor's assessment of how much a student should be penalised for making mistakes in this category, but most teachers would agree that the penalty is likely to be high. This is often subjective but a threshold level of 'pass' or 'distinction' may be decided *a priori* for examination scripts. The tutor should also be proactive in tackling these issues wherever they appear during the year and perhaps a bit of repetition on conceptual building blocks throughout the semester would benefit the learners. Error category B may also be directly interpreted as the learner's inability to relate *Underpinning Science (US)* to *Engineering analysis (E)* (IMechE, 2012).

One common corrective action mentioned in column four of Table 3 suggests that the students need to spend more time on tutorials where they would be asked/encouraged to solve problems by 'themselves'. The current tendency amongst many academics including the author's own institution to provide complete solutions to tutorials may not be a good idea. The author has serious reservation against this practice, in particular, in the context of ES modules. Since deep understanding is essential for these subjects, it is often counter-productive if detailed solutions are provided to students. The following two quotations are frequently heard from students doing ES.

'.. If I understood the problem, I could do that easily.'

Or (student saying to tutor):

'.. when you solve it in the class, it doesn't seem difficult at all! But when I try, I often struggle and don't get to the point (about) where to start..'

The first step in solving a real life engineering problem is to translate the physical situation/process to a manageable level such that available engineering principles can be applied with confidence. To do this, the practitioner needs a deeper understanding of the whole system to be able to make judicious assumptions. Hence it is essential that the learners and tutors alike give proper attention to the error categories C and G. There may be some possibility that ambiguity in examination question or English language proficiency of students may have contributed to the error C.

Simple and trivial errors such as categories E, H and I can be easily avoided and would help students get higher grades. Most tutors would be reluctant to penalise the students heavily for such mistakes unless these trivial errors lead to a completely wrong direction. For example, a calculation error in flow *Reynolds number* (indicator of flow instability) may lead to *turbulent* flow whereas the flow is actually *laminar* (Massey & Ward-Smith, 2006). Some fictitious test cases may be designed by the tutor to highlight these factors.

It is worthwhile to note here that the author has conducted smaller scale scrutiny of errors made by the students in the unseen examination scripts for module EN0201 (Level 5) during the last two academic years. Interestingly, broadly similar percentages (of all errors) were observed as shown in Table 4 below.

Table 4: Comparison of error types for subsequent years

Error category	**% of errors** **n = 560 (original study)**	**% of errors (year 2009)** **n =178 (EN0201 exam scripts only)**	**% (year 2010)** **n = 220 (EN0201 exam scripts only)**
A	33.6	37.1	39.1
B	6.4	3.4	3.2
C	12.5	14.6	15.9
D	11.9	15.1	16.8
E	13.7	12.9	9.1
F	9.6	11.2	7.7
G	6.8	2.2	1.4
H	2.1	2.8	5.9
I	3.2	0.6	0.9
Total (%)	99.8	99.8	100

The above table must be interpreted with caution due to a number of factors. Firstly, the data samples for 2009 and 2010 were obtained from unseen examination scripts only whereas the original study comprised assignments and laboratory reports in addition to examination scripts. Secondly, the data in the original study were taken from modules in three different levels, whereas the data for 2009 and

2010 relates to just one Level 5 module only. Perhaps this explains why there is an increase in error categories A (fundamental concepts) and D (wrong units and equations). The reduction in G is possibly due to the fact that students did not need to make assumptions during unseen examinations to an extent that is common in assignments which always incorporate some open-ended components. A reduction in category I may be due to the current feed forward template which was made available to the students. However, without a rigorous analysis like the original study, it is not fair to make any definitive remark about the observations or forecast any trend. Perhaps, what is useful is that there appears to be a broad similarity of the various errors and mistakes over the years.

Conclusions and Future Work

The findings from this study are regularly used by the author in at least three modules spread over three years of study. The error list is made available to the students through the eLP and the general feedback from students about this list is very positive. The vast majority of students (more than 80%) commented that the error list had been 'very useful' against 'useful' and 'not useful' based on the cumulative survey of about 250 respondents over the last four years. The following three studies may be conducted as a continuation of the present work.

It is not known whether this feedback or feed forward template does really help students to avoid repeating the errors. To establish this, a systematic case control intervention study similar to (Duncan, 2007) needs to be undertaken.

The fundamental conceptual error (Error category A) needs to be analysed and subdivided into various components. A rich volume of work is already available (Miller *et al*. 2011; Nelson *et al*. 2007) and may help as a good guideline. However, it needs to be recognised that the teaching and learning culture between US and UK university systems are very different and so are the learning processes of students. It would be very interesting and useful to investigate the similarities and differences between UK students and those in the US.

A thorough investigation similar to the one presented in this work may be conducted by taking information from the module boxes from the past three years and analyse the results to see if there is any statistically significant variation over time. With the rapid change in technology which impact students' learning styles as well as tutors' delivery patterns, it is possible that the common errors and mistakes that students make, do also change with time. The entry requirement for engineering students is also steadily increasing. So a thorough re-evaluation would be useful.

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