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Abstract: *Engineering lecturers report difficulties with student learning of concepts and skills associated with the solution of typical basic mechanics problems. The use of both force and moment equilibrium concepts on free-bodies are basic to all mechanics problems. Despite this it apparently remains a difficult area for a significant number of students, even in later years of their degree. An evidence-based approach has been used to analyse two of the suggested reasons for such difficulties. Both quantitative and qualitative methods have been utilised to establish the role of a student's academic history, and the role of gaps in the student's problem analysis process. Theoretical frameworks were also applied, particularly experiential learning, and an application of the van Hiele taxonomy of geometric reasoning. The results of the application of these frameworks were measured through student survey and students' performance on assessment tasks. Indications are that academic history may not be a good predictor of a student's ability to learn the concepts and skills required. This suggests the need to target specific gaps in their basic maths skills and in their analysis process, and to target our teaching approach to those gaps.*

Keywords: mechanics education, academic history, pre-existing knowledge

Introduction

The use of both force and moment equilibrium concepts on free-bodies are basic to all mechanics problems. An initial step in mechanics design analysis is to conceptually isolate bodies (ie. whole structures, or elements of multi-part structures) from their physical environment and to mathematically analyse how forces and moments affect each individual body. These individual calculations feed into more complex models of the bodies in context and under changed environmental conditions, and allow development of solvable models of structures. These solvable models allow engineers to test how structures will react (eg. flex, stretch, break) under different loading conditions. Hence, understanding free bodies is central to solving problems in mechanics.

Engineering lecturers report difficulties with student learning of concepts and skills associated with the solution of typical basic mechanics problems. Ongoing research by Paul Steif of Carnegie Mellon University and others suggests that students make a range of typical errors including; the inclusion of internal forces, inadequate distinction between force and moment, couples seen as equivalent to a force, direction of force at connections set by the direction of the connecter, and assumption that the force direction is influenced by the presence of an applied load (Stief and Hansen, 2006). Although there is a small but growing body of research into student learning in statics, engineering academics show a tendency to continue to guess at the reasons for these difficulties, and how to solve them.

Typical approaches to addressing students' difficulties with learning basic mechanics are based around individual academics' informal observations of student learning and anecdotal conclusions on an appropriate solution. The literature contains numerous reports of attempts to improve student learning of mechanics (eg. concept mapping - Ellis et al., 2004; tutorial - Ambrose, 2004; online – Donaldson and Sheppard, 2003; textbook – Roylance et al., 2001). However, many innovations appear to be based on anecdotal evidence of the genesis of student learning difficulties, and rigorous evaluation of student learning in response to changed teaching is rare. While observations and experience are useful, an evidence-based approach to understanding how and why students struggle with mechanics promises to provide a firmer basis for deciding to implement changes. This paper reports on an ongoing series of empirical investigations into the inhibitors to student learning of these concepts.

Hypotheses
Based on the first author's experiences of teaching mechanics, a review of the literature and on commonly speculated reasons for students' difficulties with basic mechanics, we developed two hypotheses:

Students struggle with basic mechanics in university engineering courses because of:
1. Academic history - in particular students' insufficient grounding in maths, physics and engineering studies.
2. Approach to problem analysis - specifically gaps in the problem analysis process used by students.

A third hypothesis would be that students struggle with concepts in mechanics due to a lack understanding of the engineering context for the problems. As part of a broader research project, we have been examining the difficulties offered to engineering students through the 'de-contextualisation' of problems, and we discuss the background, method, outcomes and recommended teaching strategies of our research on this hypothesis in a companion paper (Dwight et al., submitted).

We investigated the two hypothesised reasons for students' struggles in mechanics sequentially. That is, we first investigated academic history because it is so often nominated as the main (and most logical) reason that students have difficulties in early

mechanics learning. With the knowledge gained on academic history, we subsequently investigated the impact on learning of students' approach to problem solving.

Academic history

It is generally agreed that a sound mathematics and physics background from school are prerequisite to engineering, and particularly to engineering mechanics. This is because particular concepts from high school maths and physics are thought to underpin or precede concepts commonly learned in the early years of engineering mechanics. For example, specific knowledge that might be required for learning about the application of free-body diagrams includes: the ability to manipulate equations, familiarity with Newton's Laws, and the ability to make abstract representations of physical things. The reason why this background may be missing is that the subjects that teach these topics were not studied by the students at high school. A hypothesis that academic history (ie. study in high school maths and physics) is important to learning mechanics would suggest that students without this grounding would demonstrate significantly poorer performance in engineering mechanics than students who had studied maths and physics at high school.

Method
For the testing of the first hypothesis related to academic history, the performance in a number of mechanics-based quizzes in the early years of the degree were correlated against the student's final year school results program.

Analysis of the correlation between a new student's academic history and their performance in both an 'Entry' quiz and a mid-term 'Mastery Skills' quiz following seven weeks of university study in mechanics was undertaken.

Results and Discussion
The raw results for Entry quiz and Mastery Skills quiz and results of applying a T-Test are presented in Table 1 compared against particular sets of academic backgrounds (ie. final year physics and maths).

Considering the Entry quiz, there was differentiation of those who had done physics or maths extension (higher level maths). Students who had studied final year physics scored around 13 percentage points above students who had not, and students with maths extension averaged 10 percentage points above those without. Surprisingly, those who had done engineering studies scored no higher than the average, suggesting that engineering studies conferred no advantage for this quiz.

Results in the Mastery Skills quiz provided a slightly different view from findings obtained from analysis of the Entry quiz. In the Mastery Skills quiz those who had not done physics did not stand out as performing differently to those who had undertaken final year studies in physics. However, those who had done either maths extension or

Table 1: Quiz results at 1st year week 1 & 7 compared with academic history

Academic History*	Entry quiz (week 1)	Mastery Skills quiz (week 7)
Engineering Studies (n=77/252)		
with (average mark %)	61%	75%
without (average mark %)	56%	67%
T-Test Probability	0.06	0.0006
difference (0.05 significance)	No difference	Significant Difference
Physics (n=179/252)		
with (average mark %)	61%	70%
without (average mark %)	48%	67%
T-Test Probability	0.0000	0.24
difference (0.05 significance)	Significant Difference	No difference
Maths Extension (n=128/252)		
with (average mark %)	62%	73%
without (average mark %)	52%	66%
T-Test Probability	0.0001	0.0015
difference (0.05 significance)	Significant Difference	Significant Difference

*   Note that these results are for the Higher School Certificate (HSC) undertaken by students from schools
    in NSW Australia. Their result is the basis on which entry to Australian Universities is determined.

engineering studies were differentiated and achieved an average score 7% higher than
those who had not done maths extension, or not done engineering studies.

These results suggested that having studied maths extension conferred a consistent
advantage in first year engineering mechanics tests of between 7 and 10 percentage
points. Having studied final year school physics or engineering science was a less
consistent predictor of successful performance.

Having identified that academic history appeared to have some statistically demonstrable
effect on quiz results in basic mechanics, we were curious to discover whether this was
an effect that persisted into the later years of the degree program. Analyses of student
performance in a second year mechanics subject against students' academic history in
maths and engineering studies are presented in Table 2. There was no significant
difference in performance on the mid-term exam by students with and without
engineering studies, or with or without maths extension at school. Interestingly, school
academic background appears to no longer explain or influence performance.

Table 2: Mid-term results in 2nd year mechanics compared with academic history

Academic History	n	Mid-term exam (week 6)
Engineering Studies		
with (average mark %)	42	36%
without (average mark %)	99	33%
T-Test		0.12
difference (0.01 significance)		No diff
Maths Extension		
with (average mark %)	93	35%
without (average mark %)	48	33%
T-Test		0.23
difference (0.05 significance)		No diff

During our analysis of first year students' performance in the Entry quiz, we examined in detail student responses to each of the quiz questions. We were attempting to gain further understanding of academic history and its influence on student performance. We conducted statistical analysis of student's marks for each of the questions in the Quiz according to student academic history. While there were some significant differences attributable to academic history, the more striking finding was that a range of different types of errors were identified, but they were not particular to academic history. The group of students as a whole were largely united in failure for some questions and easily completing others. In Table 3, we list the fundamental skill that each of the questions in the Entry quiz relied on and was designed to test (ie. Question five required students to make a direct application of $\Sigma F=ma$) and the average mark achieved by students for each question. As is apparent from Table 3, the first year student group demonstrated substantial problems in making an analogy between a problem and how it might be usefully represented, and in interpreting $\Sigma F=ma$ and the concept of velocity relative to acceleration. Not as problematic, but still of concern were the student groups' demonstrated difficulties in the fundamental skills of free body diagram, direct application of $\Sigma F=ma$ and in the utterly fundamental capacity to manipulate equations.

Table 3: Results in each question of Entry quiz by fundamental skill tested

Fundamental skill tested	Average mark	Problem?
Q1. Interpretation of meaning of $\Sigma F=ma$	83%	No
Q2. Inexplicit use of concept of moments	94%	No
Q3. Application of free body diagram or $\Sigma F=ma$	47%	A bit
Q4. Analogy between problem and its useful representation	13%	Yes
Q5. Direct application of $\Sigma F=ma$	63%	A bit
Q6. Interpret $\Sigma F=ma$ and velocity relative to acceleration	34%	Yes
Q7. Capability to manipulate an equation	58%	A bit

The reasons for the results reported in this section are of course complex and subject to numerous influences. Our hypothesis that students' academic history was the main factor hindering mechanics learning yielded a complex set of findings, however, based on the measures and analysis reported above a student's academic history was not a consistent predictor of performance in basic mechanics, although maths extension appeared to confer a predictable advantage. Further, the results from student performance in second year mechanics showed that the influence of academic history became statistically insignificant as students got further into their program. We discovered that the first year student group shared poor performance for some key skills that underpin mechanics analysis (eg. manipulation of equations, application of free body diagram). These findings suggested that, rather than identifying and streaming students by their academic history, we would be better served by assisting the full student group to improve their skills in targeted basic areas. Our complex and provocative findings on the first hypothesis encouraged us to embark on investigating our second hypothesised reason for student learning difficulties in mechanics: approach to problem analysis.

Approach to problem analysis

A key aspect of engineering problem-solving is "the ability to isolate vital information from a visual representational context" (Sharp et al., 2004). We suspect these are overlooked skills, and the realisation of such fundamental skills may lie behind the limitations observed in students' problem-solving abilities in mechanics. The importance of the ability to isolate vital information from a visual representational context is further elaborated in the field of mathematics education research. Research in this field includes a body of knowledge relating to spatial thinking or geometry concept knowledge which is termed van Hiele's Taxonomy. According to Sharpe et al (2004), van Hiele proposed that to be able to isolate important information from the context of the problem (i.e. extract the relevant information and leave the rest behind) and use it to problem solve requires strong concept knowledge. This approach to unpicking an engineering problem can be represented by reference to the levels of the van Hiele Taxonomy. This Taxonomy is particularly useful because the first three levels of understanding are testable by what students can observably do (ie. their actions). Van Hiele's Taxonomy states the early stages of geometric understanding as (Sharpe *et al.*, 2004):

i.   Visualisation: Look at the whole without consideration of individual components (ie. do these look like trusses, does this look stable, is this a cantilever).

ii. Analysis: Picking out particular components of the image that have meaning. Establishment of properties and characteristics (ie. is it rotating, is it static, what stresses are involved).

iii. Informal deduction: Using and inter-relating things already known to deduce relationships and draw informal conclusions (ie. stating consequence without proof, interpreting and predicting with free-body diagrams).

Much problem solving in engineering mechanics relies on skills that fall within the description of 'informal deduction'. However, proponents of the van Hiele's Taxonomy suggest that students be encouraged to make 'analysis level' statements before moving on to 'informal deductions'. This approach establishes the habit of a structured approach to sequential problem analysis, where students are encouraged to look (at the object) before they leap (to a deduction). Observations made by the first author (RAD) teaching a 3rd year design subject suggest that, persisting into Year 3, students second guess what the informal deductions are to be (which formula should be used) and then make sure the formula fits. Faced with an 'open ended' design problem, students often outline how they are going to use one particular analysis or another but cannot explain what use that will be in solving the problem.

The van Hiele Taxonomy provided a structured way to understand and explain some of the steps in mechanics problem analysis and solving. Our hypothesis that difficulties students experience in learning about mechanics were attributable to flawed problem analysis would suggest that it would be useful to screen for flaws in geometric reasoning ability. Such screening would potentially improve communications between teacher and

student, and allow learning designs that explicitly supported students in the elements of problem analysis that were problematic.

Method and Results

Students' problem analysis processes were examined via a qualitative analysis of student responses to selected questions in the first year mechanics Mastery Skills quiz that we discussed in Section 3. As a template for analyzing students' answers, we interpreted the development of a free-body diagram into a process of eight steps. Some of these steps, align with levels in van Hiele's Taxonomy, and other steps are relatively straightforward maths or physics operations. The eight steps are as follows:

1. Isolate the body of interest, replacing the contact with other bodies with forces and moments (van Hiele level = analysis)
2. Recognise the relationships $\Sigma F=0$, $\Sigma F=ma$, $\Sigma M=0$ and $\Sigma M=I\alpha$ are useful in this context (van Hiele = informal deduction)
3. Define coordinate system (x,y,z) (basic physics)
4. Separate forces into (x,y,z) (basic physics)
5. Recognise that the relationships identified in 2 can now be used to solve for the 3 directions. (van Hiele = informal deduction)
6. Substitute values into equations. (basic maths)
7. Solve for unknowns from 6. (basic maths)
8. Complete 1 using the values obtained (van Hiele = informal deduction)

These process steps for free-body diagrams were used as a template to determine where it was that students had difficulties in solving the nominated mechanics problem. The answers provided in the Mastery Skills quiz for a sample of students were examined in detail against the process identified. Of the 24 student scripts analysed, the errors made were recorded for two quiz questions against the steps identified for the process. The results of this analysis are presented in Table 4. The question denoted here as question 1 involved a structure in static equilibrium, and question 2 involved a structure that was not in static equilibrium. Question 2 generated numerous errors and the process steps that caused the most difficulty for students were steps 1, 2 and 6.

Table 4: Errors against process steps indicating most difficulty with Step 2

Question	Process step							
	1	2	3	4	5	6	7	8
1		2			1			
2	8	15				9	1	

What appears to have emerged from our analysis of students' approaches to problem solving for free body diagrams are the following:

1. There was little evidence of mathematical errors for the questions analysed. The questions analysed did not require a high level of maths but did require some rigor. Equally, problem elements calling on basic physics caused few problems. The area of most substantial mathematical error was process step 6 in question 2. This step required the students to accurately substitute values into equations. This finding

reinforced our results from the Entry quiz (Table 3) that suggested students were ill equipped when it came to manipulating equations.

2. Eight students erred at process step 1. Most of these students did not consider it necessary to draw a free-body diagram as a matter of course. This process step aligned with van Hiele's level of 'analysis' which is seen as a precursor to successful 'informal deduction'. It would appear that it is a relatively frequent failure for students to leap over the analytical step of the problem analysis process (at least as it is described by van Hiele).

3. The most common downfall was in recognition and use of one particular concept, that of moments on a body, both in static equilibrium but more commonly when the body is not in static equilibrium. This was process step 2, and over half of the scripts examined exhibited errors in this step for question 2. This called on a capacity to recognise the usefulness of things already known (ie. $\Sigma F=ma$, . $\Sigma M=I\alpha$) and their application to deduce relationships aligns with the higher level of van Hiele's Taxonomy of geometric reasoning, 'informal deduction'. It is perhaps understandable that students tended to struggle with this higher order thinking, particularly given the added conceptual challenge of the body not being in static equilibrium.

Our findings from analysing students' approaches to solving free body diagram problems refined our sense of how we might intervene to improve students' learning in basic mechanics. The finding of problems with substituting values into equations reinforced that idea that we could spend time with students identifying specific basic skills that were problematic, and working to improve them. The second finding of failure to draw a free body diagram endorses the idea of Sharp and Zachary (2004) that students need to be coached into the habit of sequential use of van Hiele's levels (ie. undertaking visualisation and analysis, then deduction). The third finding endorses the idea of coaching students in the habit of analysis, but also suggests we need to pitch questions or pace learning so that students develop a (religious) propensity for isolating complex functions and dealing with them one at a time (eg. the concept of not in static equilibrium, and need for application of multiple known equations).

Response to preliminary findings

In 2006, we instituted changes in teaching basic mechanics that responded to some of the results of our study into the effect of students' problem analysis processes. A number of lectures and associated tutorials for the subject ENGG101 Foundations of Engineering were designed according to the van Hiele Taxonomy. Complex problems were presented for which it was known that the basic knowledge existed for most students. Some emphasis was placed on working from an understanding of the elements of the problem through to recognition of those elements in the complex problem. The case of a stream of water emanating from an orifice in the bottom of a water storage tank is an example of a teaching problem we adapted according to van Hiele's Taxonomy. The approach we took is illustrated in Figure 1. Students were guided in taking a sequential approach to

problem analysis, and other simple measures were instituted to test student's problem analysis process. For example, we insisted that students sketch out problems as a first step to analysing them. We also ensured that worked solutions were refined by students to ensure their presentation highlighted the stage of the Taxonomy represented by their approach to problem analysis.
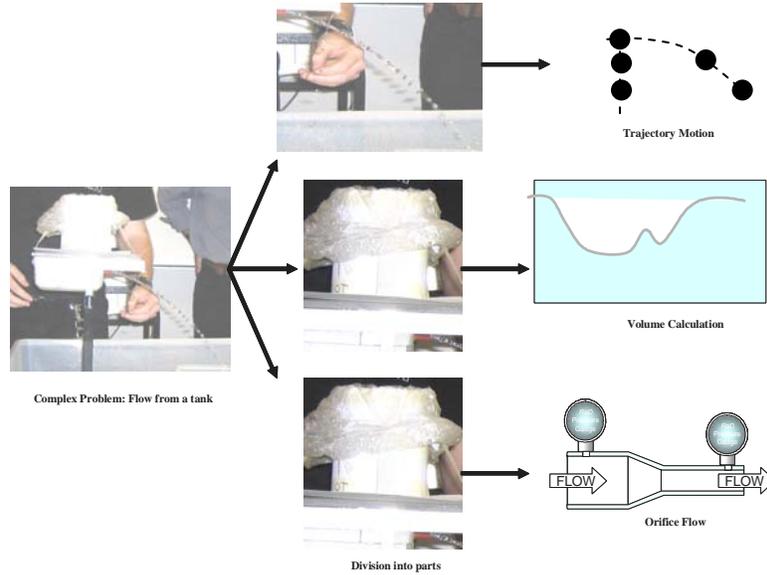

Figure 1: Illustration of the application of van Hiele Taxonomy on stream trajectory from a water tank. Visualisation at left moves through an analysis stage and then to an informal deduction: trajectory motion, volume calculation and orifice flow.

Subsequent to the limited implementation of the van Hiele taxonomy we surveyed students broadly on their experiences of learning about problem solving and analysis in ENGG101. Students' responses to those survey questions that were of direct relevance to problem analysis are reported in Table 5. While students in ENGG101 had developed a strong sense of how science and maths apply to engineering, our efforts at structuring lectures and tutorials to explicitly support development of geometric reasoning generated less overwhelmingly positive response when it came to confidence in recognising, breaking down and tackling engineering problems. The survey items targeting this area indicated that between 67% and 80% of students rated this objective of ENGG101 as 'agreed' or 'highly agreed'. While this looks like a positive response, these represent low ratings compared with student ratings for the majority of other elements in ENGG101.

Additionally, our student survey generated some qualitative evidence that suggested this method had merit. Answers students offered to the question "What is the most important or interesting thing you have learnt in ENGG101?" suggested that many had developed a greater sense of the importance of taking a sequential approach to problem analysis.

Examples of the comments we received include:

"The idea of separating components, being able to look at a large object and being able to see the different components and estimate forces" (Materials student who had done engineering studies, physics and maths extension)

"Combining different formulae to solve unknowns"
(Mechatronics student who had not done engineering studies, physics or maths extension)

Certainly the results reported in Table 4, and students' comments on their learning are encouraging. Given these early results, this approach is to be further tested along with

TABLE 4: Student experiences of learning engineering mechanics in ENGG101

	Survey Questions	Students responses
Objective queried	ENGG101 participation…	% agreed/ strongly agreed
Provide context for engineering analysis	Q1…caused me to understand how you can use science to solve engineering problems	95.0%
Provide context for engineering analysis	Q2…caused me to see the relevance of science and mathematics to engineering	92.7%
Engineering problem solving	Q5…caused me to feel confident about tackling unfamiliar problems	66.7%
Engineering problem solving	Q11…has helped me to solve real-life engineering problems	80.0%

the further development of scenario-based teaching exercises in relation to free-body diagrams (Mariappan et al, 2004).

Discussion

Our study attempted to shed light on why so many engineering students struggle with learning basic mechanics. We set out to generate evidence that would either refute or confirm two hypotheses on where students' problems learning about engineering mechanics stem from (insufficient grounding in maths, physics and engineering studies; and gaps in the problem analysis process used by students). The first hypothesis was a commonly held anecdotal view amongst teachers of mechanics, and the second rested on a theory of geometric learning developed by van Hiele.

Based on our research there is an indication that academic history is not the overriding factor in the student's ability to learn the concepts and skills required. This calls into question the frequently heard lament that incoming students' inadequate basic training in maths and physics offers an insurmountable barrier to their future learning. Rather, our study suggested that there was some influence but that it was somewhat sporadic and declined to insignificant by second year. This finding suggests that rather than adopting a deficit model of students based on their variable prior training in maths and physics, it might be more productive to target specific gaps in basic skills (ie use and manipulation

of equations), or to support learning in problem areas of the analysis process and to orient the teaching approach for introductory mechanics to those gaps. Our recent attempts at responding to these findings have not been formally evaluated, however, students' observable behaviour in problem analysis and their responses to an exit survey on their experiences of learning offered support for the use of van Hiele's Taxonomy as a template for designing mechanics learning in the early years of undergraduate engineering. Our early experiences of this approach suggest that further research in these areas could be promising.

References

Ambrose, B.S (2004) Investigating Student Understanding on Intermediate Mechanics: Identifying the need for a tutorial approach to instruction *American Journal of Physics* 72(4), 453-459

Donaldson, K and Sheppard, S (2003) E-pals to Enhance Mechanics Learning *International Journal of Engineering Education* 19(6), 836-846

Ellis. G. W., Rudnitsky, A. and Silverstein, B (2004) Using Concept Maps to Enhance Understanding on Engineering Education *International Journal of Engineering Education* 20(6), 1012-1021.

Mariappan, J., Shih, A and Schrader, P. G (2004) Scenario-Based Learning Approach in Teaching Statics, *Proceedings of the 2004 American Society for Engineering Education Annual Conference and Exposition*

Roylance, D., Cohen, K.C., Jenkins, C.H. and Khanna, S.K (2001) Mechanics of Materials: a materials science perspective *Journal of Materials-Design and Applications* 215(L3), 141-145

Sharp, J M and Zachary, L W (2004) Using the van Hiele K-12 Geometry Learning Theory to Modify Engineering Mechanics Instruction, *Journal of STEM Education: Innovations and Research*; Jan-Jun 2004; 5,1/2; Spatial thinking skills.

Steif, P. S and Hansen, M (2006) Feeding back Results from a Statics Concept Inventory to Improve Instruction *Proceedings of the ASEE Annual Conference*, Chicago, 2006.