Improving Engineering Students' Design Skills in a Project-Based Learning Course by Addressing Epistemological Issues

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1. INTRODUCTION

A novice designer is prone to making premature decisions. Rather than explore issues and research information and options, he may quickly jump to posing solutions and view design as a linear, step-by-step process. Instead of testing a variety of ideas, a beginning designer often becomes mesmerized by his initial ideas. An experienced designer, on the other hand, is much more likely conduct research and delay making decisions until the challenge has been fully explored [1]. She uses a variety of techniques to generate ideas, test them, and see how they inter-relate, sees design as an iterative process, has a variety of approaches, integrates feedback and reflects on the design process. She uses rational inquiry to cross-reference and integrate ideas, information, and personal experience. Such behaviour reflects beliefs about knowledge and its creation and such actions are hallmarks of the relativistic thinker [5] who can set goals, reflect on thinking, identify what is needed and understand why it is necessary. Although the individual seeks new experiences and multiple views, she also seeks to achieve well-integrated solutions that are simple (as opposed to simplistic). This person is able to confront discontinuities and paradoxes, ask key questions, resolve key dilemmas, and generate new insights. According to Belenky et al. [7], such a person is inherently reflective, passionate about knowing, and willing to struggle to achieve balance. The novice and expert enact very different personal epistemologies, in particular how they view themselves as sources of knowledge, how they justify decisions and view knowledge as fixed or tentative[1].

In this study, we explore how personal epistemology influences the design process in the context of a project-based learning (PBL) module in which students are asked to design, build and test simple measurement systems to create a weather station. The curriculum is largely traditional in nature but has seen a small but significant increase in the amount of PBL in the last few years. Many, often competing, decisions must be made by the students throughout this module, for example when designing the signal conditioning circuits or choosing the variables, and many can rush through this process, failing to justify their choices and making decisions for arbitrary reasons. Were they to pay more attention to the decision making process the students, with little extra work, could engage more fully with the module, produce better artifacts and achieve higher grades. In this paper we argue prior knowledge and motivation, other key drivers of the learning process along with epistemology [2], are not the reasons why some students lacked independence and failed to justify many of their decisions in this module.

2. LITERATURE REVIEW

The field of epistemological development research was started by Perry and his colleagues in the 1950s and 60s which led to Perry's model of intellectual development [3]. This and the other models that evolved from it (Reflective Judgment Model [4], Women's Ways of Knowing [5], Epistemological Reflection Model [6]) are now regarded as one-dimensional stage models – students progress from stage to stage, sometimes falling into two or three adjacent stages, but moving forward in life on a path to more complex thinking and reasoning [2]. While holding on to the notion that epistemology is belief like in nature, i.e. one has stable beliefs about knowledge and therefore exhibits these in all contexts, subsequent researchers expanded the number of dimensions from one to five [7, 8]. These dimensions were shown, through statistical analysis, to be independent of each other so, for example, views about knowledge and knowing are independent of views about learning and how fixed one's ability to learn is[2]. A person may be advanced in one area and behind in another; although all five dimensions vary from naive to advanced, not all develop synchronously. For example, one may believe that knowledge is tentative but regard ability to learn as innate. A third view is that we all have a framework of epistemological resources available from an early age covering the full spectrum in thinking, from simple to complex [9, 10]. These are not beliefs that are replaced by more complex beliefs or stages that can be arrived at and left behind but are resources that can be called on to different extents in different contexts. Instead of developing more complex thinking, the student exhibits greater epistemological expertise by choosing more appropriate ways of thinking about a topic.

The resources model differs from the other two in its view of the nature of epistemology and how it should be explored –ontological and epistemological differences. Viewing epistemology as stable beliefs across contexts implies that we can probe an engineering student's concepts of justification by presenting him/her with a dilemma on creationism versus evolution[3]. How he/she responds is a predictor for thinking and reasoning in

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[1] S. Chance discusses these topics in greater detail in another paper included in this set of proceedings.

[2] In a purely philosophical sense epistemology relates to what constitutes knowledge, where it comes from and how it is justified. Schommer extends it to include beliefs about the speed and control of learning as strongly related epistemic issues[8] M. Schommer-Aikins, "An Evolving Theoretical Framework for an Epistemological Belief System," *Personal epistemology : the psychology of beliefs about knowledge and knowing*, B. K. Hofer and P. R. Pintrich, eds., Mahwah, NJ: Erlbaum, 2002.

[3] One's position on the Reflective Judgment Model is determined using three semi-structured interviews in which the participant is presented with a series of dilemmas such as creationism versus evolution [4] P.

engineering [3, 4]. Those following the multi-dimensional models [e.g. 7, 11, 12], have endeavoured to find a generalisable quantitative method of measuring personal epistemology. With the resources model, however, the aim is not to quantify. Rather, the emphasis is on understanding and interpreting how students think and reason in class room contexts through the lens of personal epistemology. Sample sizes are typically small and data are collected using qualitative methods [e.g. 9, 13, 14]. When questionnaires[4] are used, the purpose is to provide general data on large samples and the results are limited to a "*crude read-out of the epistemological state of a class*" [15, p16]. Since all three model types seek to understand more about how students think and reason during college they have much to offer each other. For example, Knefelkamp [3], operating from Perry's model, provides qualitative descriptions of personal epistemologies that are equivalent to epistemological resources. Likewise, Schommer's [7] dimensions are qualitatively different categories of epistemology that can be used in the resources model.

In this paper we are ontologically and epistemologically aligned with the resources model because we view epistemological development as a *qualitative* change in thinking that is not well served by quantitative analysis or decontextualised interview protocols. Should the context or phrasing of interview questions or questionnaires statements be changed responses can change dramatically. Indeed, those promoting the stage [4] and multi-dimensional models [8] support qualitative methods where individual personal epistemologies are being explored. So, rather than collect data that is generalised across contexts we have opted to study in context and limit our findings to it. We seek to develop a greater understanding of how epistemology influences student performance in a project-based learning module.

3. CONTEXT

This study was carried out in the second year of a three year electrical engineering technology programme in a third level institute in Ireland in the second semester of the 2011/2012 academic year. It was the first experience for the students of an entire engineering module delivered through PBL in which the learning process is facilitated by the tutor, responsibility for direction and management of the project work lies mostly with the student groups and feedback on the process is given to both individuals and groups by the tutor. The class contained a significant number of advanced entry, mature students with an electrical trade background. The students were timetabled for two hours of PBL per week with three to four groups present, each containing three to four members. Groups typically arranged to meet for a further two hours per week outside of class time. The entire class (n=47) had a two hour tutorial each week in which common learning issues from the group-based sessions were addressed. The tutor ensured the groups retained control of the learning process during the PBL sessions but took the lead during the tutorials. The first weather variable was specified (temperature) with the groups choosing the other three from a reasonable range of options with limits on availability of components. Each group was expected to design, build and test a measurement system for each weather variable. A measurement system consists of a transducer, a simple electrical circuit called a Wheatstone bridge (if the transducer is resistive) and an amplifier to increase the voltage so it can be read by an analogue input card of a programmable logic controller (PLC).

An end of semester written examination carried 50% of the module marks with the PBL sessions making up the remaining 50%. This was broken down as approximately 25% (i.e.

M. King, and K. S. Kitchener, *Developing reflective judgement : understanding and promoting intellectual growth and critical thinking in adolescents and adults*, San Francisco: Jossey-Bass Publishers, 1994..

[4] Epistemological Beliefs Assessment for Physical Science (EBAPS, available at http://www2.physics.umd.edu/~elby/EBAPS/home.htm) and the Maryland Physics Expectations Survey (MPEX, available at http://www.physics.umd.edu/perg/expects/mpex.htm)

half the PBL marks) for individual contribution to the learning process (the process mark) and 25% for individual reflective reports and group products such as presentations, reports and demonstrations. The process mark was an assessment by the tutor of the student's contribution to the learning process. It contained many elements such as completing tasks during the self-directed phase between PBL sessions, contributing to the discussion during the PBL session by summarizing group position, offering and defending ideas, questioning others and checking for mistakes, and, most importantly, working towards understanding. The latter requires the students to take a 'PBL Deep' [16] approach to learning in which the student focuses on discussing, explaining and reflecting on his/her and other group members explanations.

4. RESEARCH DESIGN

In this project, we are ontologically and epistemologically based in the framework of epistemological resources model [10]. Qualitative data were collected through one to one, semi-structured interviews with five participants. Participants volunteered for interviews and those who did represented a cross-section of the class in terms of epistemology and all were mature students. The EBAPS questionnaire was completed by a majority (n=32) of the class. All participants read and signed an ethics statement before participating, were free to withdraw at any time and it was clearly communicated that participation would not affect their grades in any way. Names have been changed in this paper to ensure anonymity.

4.1 One to one interview

Interview questions were influenced by the qualitative descriptions of epistemology from the stage models [3, 4] and dimensions from the multi-dimensional models [7] and by our experience of delivering this and other modules through PBL. We selected (i) self as a source of knowledge, (ii) concepts of justification and (iii) structure of knowledge as key epistemological issues for project-based learning. We developed a set of interview questions based on these categories and wrote them in the context of the weather station project.

Self as source of knowledge was included because the PBL method (as enacted here) requires individuals and groups to be as independent in managing learning as possible to avoid ownership of the process being passed to the tutor. There are three areas where we considered concepts of justification of design decisions to be particularly important – determining the size of resistors in the Wheatstone bridge and gain of the amplifier and choosing which variables to measure. Although a myriad of other decisions were made during the project, these issues were common themes among all groups and key to the development of the weather station. Finally, a student's view of the structure of knowledge – whether it is fixed or tentative – will influence how he/she copes with uncertainty inherent in design where many right answers can exist.

We also included some questions related to prior knowledge and motivation to check the influence of these issues on student engagement with the design process. Finally, we included a think aloud protocol in which we presented each student with a weight measurement problem requiring the use of strain gauges in a Wheatstone bridge (similar to the temperature system) and asked them to talk through how they might design this system.

4.2 EBAPS questionnaire

The EBAPS questionnaire was adapted for electrical engineering students with the permission of one of the authors (A. Elby) by replacing the words 'physics and chemistry' with 'electrical engineering' in all questions where that or similar phrases appeared. The questionnaire was administered using a web-based survey package. Those who were interviewed were asked to identify themselves at the end of the survey to allow a comparison between their EBAPS results and the interview but one participant (Eric) failed to do so.

EBAPS assesses five dimensions of epistemology explained as follows [17]. The 'structure of scientific knowledge' (axis 1) relates to whether one views knowledge (of electrical engineering in this case) as a collection of separate parts, an integrated whole or somewhere between these two extremes. The second axis, 'nature of knowing and learning', relates to whether one subscribes to a transmissionist or constructivist approach to learning. 'Real life applicability', axis 3, explores views on the application of engineering to contexts broader than the learning environment. The extent to which one views scientific knowledge as fixed or tentative is probed in the 'evolving knowledge' scale, axis 4. Lastly, axis 5, 'source of ability to learn', relates to whether one views the ability to learn as innate and fixed at birth or open to change (and improvement hopefully!). The 30 item questionnaire consists of multiple choice questions and scenarios where, for example, two students discuss study tactics. Following the author's recommendations [17], scores from 0 to 4 (least to most sophisticated) for each item were merged into axes and multiplied by 25 to give a score from 0 to 100 for each axis, with overall score being the average of the axes.

5. RESULTS AND DISCUSSION

5.1 Self as source of knowledge.

In the interview, all described the challeng of thinking for themselves and taking the lead in managing learning and the design process. While none resented this aspect a variety of approaches emerged in the interviews. Sean didn't show independence in design. He typically started by entering fairly general search terms into an internet search engine. The impression given in the interview was that he left responsibility for design of the temperature measurement system with a group member whose decisions he didn't question and who he appeared to view as an authority figure, at least in the context of the module. In the think aloud session he repeated the use of the internet as a starting point in the design process. He was the only one of those interviewed who responded that way, yet on further questioning he proceeded to outline a way of designing the Wheatstone bridge with current limit as the main criterion. In the think aloud, he also provided an appropriate method for calculating the gain of the amplifier, a similar mathematical task to calculating components for the Wheatstone bridge. Although he did report a weakness in prior knowledge of electrical systems, his responses in the interview showed otherwise and he had achieved a very high mark in electrical systems the previous semester. While he demonstrated sufficient prior knowledge to initiate the design his starting point was to find someone else to do it for him. It appears that Sean's challenge is an epistemological one and were he to enact a more appropriate epistemology he could demonstrate greater independence in managing the design process.

Henry also searched the internet for solutions and advice but was happy to move on and develop his own solutions when he didn't find anything satisfactory. He resorted to using a software package, LTSpice, to guide his design and demonstrated independence in this way. Billy didn't like the Socratic approach and yearned for direct answers from the tutor to his questions instead: "*...we were getting frustrated in the class, I know you're doing your job, but* [when we asked] *'how are we going to do this?',* [the tutor replied] *'Well think about how you would do it'*". However, he feels "*it was good in the end because we figured out things*". Oliver looked to himself for direction. He was challenged to specify the criteria for the design but worked through this and proceeded with the design process quite comfortably.

5.2 Concepts of justification

All used the current limit criterion to justify their design of the Wheatstone bridge which is a defendable approach. Two questioned the actual value of this limit thereby demonstrating greater critical thinking. Oliver was the only one to include other criteria - sensitivity and linearity - in justifying the design which is very appropriate in this case. These and other criteria were repeatedly discussed in the PBL sessions and tutorials. By including them Oliver is prepared to justify another system where current limitation is not an issue.

All except Oliver used a trial and error method to select resistors in which a value was picked, the current calculated, if too high, bigger resistor values were used and the calculation repeated. Oliver rearranged Ohm's law to calculate the resistor value, a slightly more justified approach and mathematically straight forward, hence well within limits of prior knowledge. Both Henry and Oliver calculated a gain for the amplifier to use the full input range of the PLC, again a justifiable and mathematically simple approach. However, Billy and Sean selected a round, even number in the right ball park value for the gain of the amplifier and failed to use the full input voltage range. In the interview Billy revealed that it was only when the tutor questioned this approach in a PBL session that he realized there was an alternative "*engineering*" approach.

For some, justifying the choice of weather variables was based on the perceived ease or difficulty of designing and building them, an idiosyncratic approach. Billy ruled out wind speed because "*it seems to be one of the more difficult ones*", the reason given being the perceived need to design and make a rotating set of cups which are then attached to a generator. He considered atmospheric pressure to be "*straightforward*" because the output from the sensor is a voltage, hence suitable as an input to the PLC, and information on the sensor was readily available on the internet. Sean did the opposite: he perceived wind speed to be a very easy system to build but thought pressure would be very difficult. Henry viewed them all equally. As Henry explained, "[I] *didn't think any of them were going to be too easy anyway*". Likewise for Oliver: "*When you sit down and weigh up for each one there's not any that are more difficult to do than the others*".

5.3 Structure of knowledge

Questions here related to certainty in life, placed in context here as a need to find the 'correct' design of the temperature measurement system. None of those interviewed appeared to have a strong desire to find a right answer from some authority figure. Oliver expressed the most independence in this regard: "*There wasn't really a right answer to find. We set ourselves a target, we want our design to do this, to do exactly that. There's no answer, it's really your own design.*" Henry felt there "*probably is* [a right answer] *but I just got impatient and just went ahead with it*". A lack of certainty "*slowed me down*" but didn't stop him. Billy also stated that he wasn't looking for a right answer. Likewise, Sean did not appear to have required certainty here but his use of online calculators to determine amplifier gain and Wheatstone bridge output voltage, tasks he could have easily done himself, could be interpreted as a demand for certainty. Eric was also comfortable with uncertainty in design and the range of different solutions provided by the groups.

5.4 Prior knowledge and motivation

All were asked in the interview if they felt they had sufficient prior knowledge and motivation to engage with the module. Sean was the only one who reported feeling that he had a "*bit of an issue*" with electrical principles although he had achieved a very high grade in this subject in the previous semester. All of the others felt comfortable with prior knowledge and all, including Sean, did not report any other obstacles to engagement in the module.

5.5 EBAPS Questionnaire

A noticeable qualitative difference in thinking emerged during the interviews between Sean and Oliver, with Oliver enacting a more advanced epistemology. The overall scores from the EBAPS questionnaire (Table 1 below) support this finding with Oliver scoring 75.8 to Sean's 58.8. However, this may not be definitive as only some of the dimensions in EBAPS were explored in the interview. The axes from EBAPS of most relevance to the interview appear to be 'nature of knowing and learning' and 'evolving knowledge'. Likewise, the process mark given by the tutor relate strongly to these dimensions. Oliver scores the highest in both of these and in the process mark. Scoring higher than Sean suggests support for the interpretations from the interview data but Sean is not the lowest which appears to either contradict the findings from the interviews or suggest further work is required to reconcile the two data collection methods. All four students scored poorly on 'evolving knowledge' yet demand for certainty in knowledge did not emerge strongly from the interview. EBAPS is not intended to pinpoint an individual student's epistemology; much interpretation occurs when students fill it out. It is mostly used to describe or check for overall changes in a sample of students. The scores for 'nature of knowing and learning' might indicate that, apart from Oliver, these students expectations are not strongly disposed to knowledge construction, an important dimension of epistemology in a PBL environment.

Table 1. EBAPS Results and Process Marks†

	Overall	Structure of Knowledge	Nature of Learning	Real-life Applicability	Evolving Knowledge	Source of Ability to Learn	Process mark
Class	60.9	55.9	60.8	52.7	56.5	73.0	51%
Billy	67.1	53.8	64.1	71.9	33.3	100.0	65%
Sean	58.8	56.3	62.5	18.8	50.0	90.0	40%
Oliver	75.8	66.3	87.5	53.1	58.3	85.0	80%
Henry	60.0	62.5	59.4	37.5	33.3	70.0	58%
Eric††							60%

† The process mark is the tutor's assessment of a student's contribution to the learning process and is not part of the EBAPS questionnaire.

†† Eric failed to declare himself on the EBAPS questionnaire so we don't know what his scores are.

6. SUMMARY AND CONCLUSIONS

In PBL and similar student-centred learning environments the epistemology enacted by a student is one of many key issues influencing the student's performance. We explored the impact of some epistemological issues – structure of knowledge, view of self as source of knowledge and justification of decisions – on the design process in a PBL module. Qualitative differences in the enactment of these epistemological issues were observed among a sample of students who were interviewed. For one student, Oliver, certainty in knowledge was not expected in the context of the system he designed; compared to his peers he demonstrated a relatively independent approach to design and justified his product based on a well considered and comprehensive set of criteria. Oliver achieved a high score in the tutor's assessment of his contribution to the learning process. His enactment of personal epistemology seems very appropriate for PBL. The process mark assigned by the tutor supports conclusions drawn from the interviews in terms of the differences between Sean and Oliver. Oliver's enactment of personal epistemology achieved a higher process mark.

Sean chose not to look to himself for direction in design, instead searching the internet for solutions to adapt and taking direction from his peers. This may explain why he was happy not to have been directed by the tutor. He justified his design based on a limited set of criteria. However, he appeared to have sufficient understanding and motivation to be independent but did not enact such independence in this module and achieved a low mark on his contribution to the learning process. We make no comments on whether students like Oliver learn more or less than students like Sean in such modules. However, were Sean to enact a more advanced epistemology he could engage more with the module, develop better designs, produce better artifacts, improve his grade and become a better engineer. Through continued exposure to PBL with feedback on the learning process Sean could be encouraged to enact more appropriate epistemologies more often. The reflective reports prepared by the students could be more targeted to encourage change. In Sean's case, he could be asked to reflect on ways he justifies decisions by recalling good examples from any context in his life and exploring how he could transfer these to the context of engineering. Such an approach has been shown to be effective in creating change in conceptual understanding [15].

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