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An Investigation of Introductory Physics Students' Approaches to Problem Solving

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An investigation of introductory physics students' approaches to problem solving

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Abstract

This paper outlines ongoing research investigating students' approaches to quantitative and qualitative problem solving in physics. This is an empirical study, which was conducted using a phenomenographic approach to analyse and interpret data from individual semi-structured interviews with students from introductory physics courses. The result of the study thus far is a preliminary set of hierarchical categories that describe the students' problem-solving approaches when faced with various physics problems. The findings from the research presented here indicate that many introductory students in higher education do not approach problem solving in a strategic manner and many do not try to link or use their physics knowledge in order to solve problems.

Introduction

In recent years two of the most significant drivers leading to transformations in science education have been education research and changes in student profile. The changes in student profile stem from mass education, dramatic changes in information technology and the decline of student numbers in science education (Institute of Physics 2002). These factors have led science educators in higher education to not only take a critical look at what is being taught but also how this is being taught. Therefore in the last thirty years the importance and need for science education research has led to the development of many research groups and projects undertaken to get a better understanding of how students learn and how educators can help students learn and develop. Education research, where the emphasis is on theory and practice, had already shown the importance of student-centred and lifelong learning, which has led to a paradigm shift in higher education. Science education research, where the emphasis is on how students learn and develop understanding was largely ignored among science educators for many years. In 2001 the School of Physics in the Dublin Institute of Technology set up the Physics Education Research Group to carry out research to inform curriculum development, teaching and assessment practices.

Physics education research of student understanding in physics indicates that certain naïve conceptions about the physical world are common among students entering higher-level education (Clement 1982; McDermott 1991; Hake 1998 Knight 2002; McDermott and Redish 1999). Research also shows there is often little or no change in conceptual understanding before and after formal instruction and that students are unable to apply the concepts that they have studied to the task of solving quantitative problems. It is widely accepted that physics graduates are required to be adept problem-solvers with the ability to conceptualise and transfer their understanding and knowledge, but research has shown that many students are not developing the necessary conceptual understanding (Van Heuvelen 1991). Some research has found that students cannot develop as problem-solvers without first having the conceptual understanding (Hake 1998; Knight 2002). This study set out to gain a better understanding of how students learn physics, and how their knowledge impacts on their ability to solve problems, and specifically to answer the following research questions.

- What are the various different ways in which introductory physics students approach problem solving?
- How does conceptual knowledge affect their approach and ability in solving qualitative and quantitative problems?

This will in turn inform teaching and assessment practices in order to improve students' learning and problem-solving abilities leading to better problem-solvers who can organise their knowledge in a coherent manner and transfer their understanding to solve 'real world' and more complex problems.

Theoretical background

A large body of research in physics education has reiterated research from cognitive psychology, indicating that for students to develop an understanding of the conceptual nature of physics, education must first start with their prior conceptions (Roth 1990: Redish *et al.* 1998; Redish 2003). These prior conceptions, which are internally inconsistent, are remarkably resistant to change and conventional instruction can make almost no difference to a student's conceptual beliefs (Halloun and Hestenes 1985). According to these researchers, the teaching approach must allow for students to restructure their own understanding by first seeing where, when and why their conceptions fail. Only after this can students start to build up a new and correct understanding. Research into student understanding in physics indicates that certain 'misconceptions' about the physical world are common among students entering third-level education (Clement 1982; McDermott 1991; Hake 1998 Knight 2002) and this is particularly true for many mechanics concepts (Trowbridge and McDermott 1981).

While a large amount of physics education research has been carried out on conceptual difficulties experienced by students, fewer studies have focused on students' ability to solve quantitative problems (Heron and Meltzer 2005). This is surprising, as one of the principles goals of a physics course is to produce adept problem solvers who can transfer their knowledge and understanding to real world situations. An issue which has been raised by a number of physics education researchers recently is whether the community is placing too much emphasis on gains in conceptual understanding, while 'sacrificing problem solving skill development' (Hoellwarth *et al.* 2005 p. 459). Many studies have shown that although students can learn to solve quantitative problems by simply plugging values into formulae and obtaining a correct answer, they may not be developing the skills necessary to transfer their understanding and solve more complex problems (Leonard et al. 1996; Mazur 1992; Mazur 1997; Thacker et al. 1994; Tuminaro and Redish 2005; Van Heuvlen 1991). A common view throughout most of this literature is that instruction should encourage students to 'think like a physicist' or result in a shift from 'a novice problem solver' to 'an expert problem solver'. Reif and Heller (1982) pioneered the view of student problem solvers by comparing and contrasting the problem-solving abilities of novices and experts. Their findings show that the principle difference between the two was how they organise and use their knowledge in the context of solving a problem. Experts rapidly re-describe the problem and often use qualitative arguments to plan solutions before elaborating on them in greater mathematical detail. Novices rush into the solution by stringing together miscellaneous mathematical equations and very quickly encounter difficulties. Physicists organise their knowledge in a very structured way and therefore can call on this knowledge when and in the order that it is needed. However novice physics students do not necessarily have this knowledge structure, as 'their understanding consists of random facts and equations that have little conceptual meaning' (Van Heuvelen 1991: 893).

Research approach

Phenomenography was chosen as the strategy of inquiry or methodology with which to answer the research questions involved in this study (Entwistle 1997: Marton 1981, 1986, 1994; Booth 1997; Marton and Booth 1997; Marton and Saljo 1997; Bowden et al. 1992; Prosser and Trigwell 1999; Wihliborg 2004). It has become a popular methodology in education research as it aims to understand the various ways in which different people experience, perceive or understand the same phenomenon. Unlike other methodologies its foundations are in educational research where it evolved out of the desire to understand why some students were better learners than others. Although the relationship between phenomenology (Arons 1982) and phenomenography has been regarded as unclear (Hasselgran and Beach 1997), and phenomenography is sometimes seen as a subset of phenomenology, it did not in fact emerge or derive from phenomenology (Uljens 1996). To take a phenomenological approach is to step back from ordinary assumptions regarding things and to describe the phenomena of experience as they appear rather than attempt to explain why they appear that way. Phenomenography, however, aims to find out the qualitatively different ways of experiencing or thinking about some phenomena (Marton 1994). This approach assumes that there are a limited number of qualitatively different ways in which different people can experience a phenomenon.

Different people will not experience a given phenomenon in the same way. Rather, there will be a variety of ways in which people experience or understand that phenomenon. The researcher seeks to identify the multiple conceptions, or meanings, that a particular group of people has for a particular phenomenon or a number of phenomena. Thus, the objects of study in phenomenographic research are the qualitatively different ways in which people experience or make sense of different phenomena in the world around them. The outcome of phenomenographic research is therefore a list, or description, of the qualitative variation in the ways the sample participants (e.g. students) experience, interpret, understand, perceive or conceptualise an object of study, a phenomenon, a concept or an activity (e.g. the study of physics) (Marton 1986). The ordered and related set of categories or descriptions is called the 'outcome space' of the concept being studied. However, it is more than just identifying these conceptions and outcomes spaces, phenomenography also involves looking at their underlying meanings, the relationship between them and the implications in a given context.

From this theoretical stance, it is irrelevant if these conceptions are considered 'correct' or 'incorrect' by current standards. The aim is simply to elucidate the different possible conceptions that people have for a given phenomenon. The analysis involves identifying the conceptions and looking for their underlying meanings and the relationship between them (Entwistle 1997). Although it is appropriate to answer the research questions of this study using a phenomenographic approach, it is not a 'pure' phenomenographic approach. Marton (1986: 38) suggests that the concepts under study are mostly 'phenomena confronted by subjects in everyday life rather than in course material studied in school'. Pure phenomenography is not appropriate as the aim of the research is to provide information on students' understanding in order to use the outcomes in the context of learning and teaching. Therefore, a variation of phenomenography is used called 'developmental phenomenography' (Bowden 1995). Bowden and his research group have carried out a number of investigations into student learning in physics using a developmental phenomenographic approach (Dall'Alba et al. 1993; Walsh et al. 1993; Ramsden et al. 1993). For instance, Bowden et al. (1992) used this research methodology to investigate students' understanding of displacement, velocity and frames of reference. The research found that student responses to qualitative and quantitative problems could be categorised according to the variation in the responses. Sharma et al. (2005) also adopted a phenomenographic methodology to describe the variations in the way in which students understood the concept of gravity. Therefore, this methodology and the methods used and developed by these researchers were adopted to undertake the research presented here.

Individual interviews

Although many possible sources of information can reveal a person's understanding or conception of a particular phenomenon, the method of discovery is usually an individual interview. For this study semi-structured interviews were used in which specific questions were prepared but any unexpected lines of reasoning were also followed. One aim of the interviews was to investigate each student's conceptual understanding of a small number of concepts. However the most important aim of the individual interviews was to examine the various ways in which the students approach quantitative physics problems. The interviews provided data to answer the following research questions:

- What are the students' perceptions of certain mechanics conceptions, such as motion and force?
- How do students in introductory physics courses approach various levels of quantitative problems?
- Can students who do not have a full understanding of certain basic physical concepts correctly solve quantitative problems?

The interviews consisted of six physics problems, with the first two being typical end-of-chapter linear motion problems. The remaining problems were adapted from context-rich questions developed by the physics education research group at the University of Minnesota (UMPERD 2006). The interviews lasted approximately 45 minutes each and were all videotaped. The interviewer read each question aloud to the student and then asked him/her to state their first thoughts on what they thought the problem involved. The student was then asked to describe, qualitatively, how they were going to go about solving the problem, and after this the student was encouraged to 'talk aloud' as they solved the problem on paper. Once the student had solved, or attempted to solve, the problem, the student was asked how confident they were in their answer and asked to explain this level of confidence. In this way each interviewee was encouraged to qualitatively analyse their solution.

Interview participants

Twenty-two participants were selected from four programmes in a Higher Education institution in Ireland; two were four-year Honours Degree (Level 8, National Qualifications Authority of Ireland 2006) physics programmes delivered through problem-based learning (Bowe 2005; Bowe and Cowan 2004), one was a Level 8 medical science programme and one was a three-year Ordinary Degree (Level 7, NQAI 2006) general science programme. Both of the latter were delivered in a predominantly traditional manner, although each was delivered by a different lecturer. The participants were all in their first year of study and the sample comprised of 12 male and 10 female students, ranging in age from 18 to 24. The participants in the study had completed the Irish Leaving Certificate (Department of Education and Science 2006), which typically consists of six subjects taken at either higher (honours) or ordinary (pass) level. Ten of the participants had studied physics as a subject for the Leaving Certificate, either at higher (honours) or ordinary (pass) level. This two-year course of study is a broad introduction to physics and covers the general areas of mechanics, optics, heat and temperature, sound, electricity and modern physics. The participants for the interviews were chosen based on the results of a diagnostic tool, the Force and Motion Conceptual Evaluation (Thornton and Sokoloff 1998), in order to obtain a cohort with a cross-section of abilities. The FMCE is a 47-item research-based, multiple-choice assessment that was designed to 'probe conceptual understanding of Newtonian mechanics' (Thornton and Sokoloff 1998: 338). The interviews were carried out over a two-week period following six weeks of formal instruction in mechanics.

Method of analysis

The interviews were transcribed verbatim from the videotapes and, in analysing the data, qualitatively distinct categories were identified that described the students' approaches to problem solving. Transcripts of the students' interviews were examined independently by three members of the research group, looking for both similarities and differences among them, selecting significant statements and comparing these statements in order to find cases of variation or agreement and thus grouping them accordingly. Through this process initial categories were developed that described students' approaches to problem solving, with the initial categories developed using only a sample of the interview transcripts. Once this initial categorisation was complete, the researchers met to discuss their categories and their interpretation of the answers. The categories were then revised until the researchers reached a consensus about the final set of categories.

An outcome space was developed that included the minimum of categories, which explained all the variations in the data. With these categories in mind the interview transcripts were re-examined, to determine if the categories were sufficiently descriptive and indicative of the data. This iterative data analysis procedure is consistent with the phenomenographic approach (Sharma et al. 2005), as Marton (1986: 43) states 'definition for categories are tested against the data, adjusted, retested, and adjusted again'.

Research findings

Approaches to problem solving

The analysis of the interview transcripts revealed the hierarchical set of categories that describe the interview participants' approaches to solving quantitative physics problems (see Table 1). Most students could be described by only one category. There were some cases, however, when a student would change their approach on different problems; this will be discussed later in the paper. Table 1 outlines the categories, the key characteristics of each category, and the number of students in each category.

<INSERT TABLE 1 HERE>

Scientific approach

Students who follow the scientific approach initially approach a problem in a qualitative manner as they first describe the situation qualitatively, based on their knowledge of the physical world. These students identify the concept/s that would be involved in solving the problem and discuss, in a coherent manner, the way in which those concepts relate to the problem.

> Based on the principle of gravity, like gravity is a constant force acting always downwards, knowing this we have a constant acceleration in a single direction, making it a form of linear motion.
>
> (Student 3)

These students outline a plan for solving the problem and then correctly identify the variables that will be used to find an answer. Within this small group, the students are familiar with the equations that they require to solve the problem (they do not need to refer to the equation sheet). The students use the information they have to solve the problem but they may not always get the correct answer due to either a mathematical mistake or a conceptual problem. These students do, however, evaluate their solutions either qualitatively or by defending/dismissing the numerical value they have obtained based on what they believe the solution should be.

Plug-and-chug

<u>*Structured manner*</u>

This group consists of students who do – at some stage – identify the concepts that are involved, but who instead of qualitatively evaluating the problem begin by identifying the variables given in the problem and immediately seek an appropriate formula. Thus they identify the variables that are not given, but are needed for a solution to be found. Students in this category are often able to coherently link their physics knowledge to approach and solve the problem. One such student made the following statement as he prepared to solve Problem 2, in which the student was required to find out how long it would take an object to reach the ground after being thrown upwards at a certain velocity.

> Well you're given a distance and initial velocity so if you work that out, using *em*, you're asked to find its time, you know its acceleration is going to be … its going to have to fight against negative acceleration, in the form of gravity pushing against it, so if you use the formula and let 9.8 equal a minus value, you should be able to find *t*.
>
> (Student 2)

These students often come across obstacles, because even though they are using a problem-solving strategy, it is based primarily on the variables they are using rather than on a solid analysis of the physical situation

Unstructured manner

Students in this group tend to concentrate solely on the variables that are given in the problem. When asked their first thoughts on the problem they often replied by stating the variables that were known or that linear motion equations were involved. These students often identify the variables and equations correctly but may not notice that the manner in which they are solving the problem is incorrect or does not in fact answer the question. These students have difficulty when it is necessary to manipulate a formula or to combine a number of concepts to solve a problem. Another obvious trait amongst these students is that their use of physics knowledge is sometimes rather incoherent. In the following statement the student has been asked his first thoughts on Problem 1, which entails dropping a watermelon from a certain height and finding its velocity as it reaches the ground. The mass of the watermelon is given in the question but it is not needed in order to find the final velocity.

> You drop the watermelon and it's accelerating at -9.8, speed of gravity. And you want to know how fast it is going before it hits the ground, so its final velocity. And we have three things, well we have its weight and we have acceleration due to gravity, its initial velocity and distance. So we can get the final velocity.
>
> (Student 14)

Students in this category often choose an appropriate formula, that could in theory produce a correct answer, but many do not actually find a correct answer. This is mainly due to the incoherency in the structure of their solution.

Memory-based approach

This category consists of students who try to remember how to solve a particular problem. The students try to recall similar problems that they have done or experienced previously. They do this either by trying to recall the type of equation that they should use or by relating the problem to a similar one done perhaps in class. The student in the following example is trying to solve Problem 3, in which two cyclists are travelling at different velocities. The slower cyclist is trying to catch up with the faster one by accelerating and the student must find out how long this takes.

> S: I think I did this a couple of weeks ago, I just can't remember.
> I: Really? And what do you associate it with?
> S: What do you mean?
> I: You say, 'I think we did this a couple of weeks ago'. What is this?
> S: Ah, really questions to do with cars and buses going up to traffic lights and going as fast as the other, exactly like this but I never liked it.
>
> (Student 17)

Again students in this category are sometimes successful in answering the problem, this time by remembering a process or similar problem that they have encountered.

No clear approach

Students who are positioned in this category do not try to approach the problem with any sort of strategy and they do not try to structure their physics knowledge in a coherent way. This group of students tends to try and manipulate the given variables in a rather random way to give an answer. The students may realise that some equation will facilitate solving the problem, but they don't attempt to link any coherent physics knowledge when choosing such an equation. Student 15 illustrates such an approach when asked what she believes Problem 1 involves.

> S: Involves an equation of knowing the weight of the watermelon, which we do, and how high it's going to fall. And then the velocity as it falls and what is the increase in velocity, as it hits the ground.
> I: Ok, so what about any acceleration?
> S: Well, I suppose the only acceleration there would be is acceleration due to gravity.
> I: So knowing that then how would you solve it?
> S: I suppose just sub in the values of the weight, the height, the acceleration, the velocity and the initial speed. You sub it all in and find the final velocity.
> I: Ok, sub it into what?
> S: Newton's equation … law … which is …
>
> (Student 15)

These students are generally not faithful to any particular line of reasoning; if the interviewer questions them on a matter they are likely to change their strategy very easily.

Discussion

The findings from the study reveal that the majority of students do not approach physics problems qualitatively. Van Heuvlen (1991) suggests that physicists approach a problem by qualitatively analysing the situation and then constructing a diagrammatical or graphical representation of it. Meltzer (2005) agrees that qualitative representation of a situation is an important factor in problem solving and that introductory students often find it difficult to do this. Only a small number of students actually attempted to make a diagrammatical analysis of the problems. In an effort to compare students' approaches to that taken by an expert, an instructor from the same institution was asked to carry out an individual interview. The most obvious point of departure in this interview was the instructor's tendency to immediately draw a diagram of the physical situation. The instructor was asked to talk aloud as he solved the problem, as were the students who had participated. Another clear difference in the instructor's approach was that he initially approached the problems using the concepts involved rather than stating the equations that would be employed. For example in Problem 1 his 'first thought' was conservation of energy rather than linear motion equations. It is also interesting to note here that none of the interview participants approached Problem 1 using conservation of energy. The instructor explicitly stated any assumptions he was making in solving the problem; for instance, again in Problem 1:

> I'm assuming it's being dropped from rest so you have its potential energy, mgh. I'm assuming that is equal to its kinetic energy just before it hits the ground.
>
> (Instructor)

Again none of the interview participants did this. Furthermore, many of the students did not pay sufficient attention to the wording in the problems. They approached the problems impulsively, often skimming over them and deciding on an approach before changing their minds about the process repeatedly.

Problem 1 required little problem-solving ability in order to be solved, and as long as the student understood that the watermelon would fall with acceleration due to gravity and identified the variables of displacement and velocity, they simply needed to choose an appropriate kinematics equation (which is a very simple form of problem solving). It is worrying to note that a number of students had to be prompted about the acceleration involved. However, this issue will not be discussed in this paper as it forms part of another study involving students' use of their conceptual knowledge, which will be presented in a future paper. Many students from the 'plug-and-chug' and 'memory-based' categories used a trial-and-error approach with the equations; however in most cases the students obtained the correct answer.

On the other hand Problem 3 required little conceptual understanding in order to solve it. In this case the students had to realise that both cyclists would travel the same distance in the same time and that simultaneous equations were required. Therefore this problem may not have been a typical problem that the students would encounter in class. However, when confronted with this problem most of the students did not approach it in a structured manner; many simply calculated how long it would take to increase velocity until they had reached the velocity of the faster cyclist while not taking into account that the faster cyclist is moving forward all the time. Of the few students who did recognise that the displacement of both cyclists would be the same, only one attempted to use simultaneous equations to solve the problem. This problem required a more sophisticated problem-solving strategy, as it required students to see the 'big picture'. This problem must be approached as a whole rather than attempting to solve it in parts, but most students approached it by breaking it up into the two cyclists' independent journeys. This problem posed no difficulty for the instructor; he immediately made a diagrammatic representation of the problem before he qualitatively analysed it and stated the assumptions that he was making. He continued by determining his goal, constructing his plan and finally executing his plan. When he had obtained a quantitative answer, he looked back over his work and the problem itself before concluding that he believed his answer was correct.

Another interesting finding that emerged from analysis of the interview data was that a person categorised as taking a scientific approach to problem solving could simply adopt a plug-and-chug approach for certain problems when appropriate. This means that if a problem only required a student to recognise the need to use a certain formula, then students who could use a strategic approach may not employ that approach but simply plug the variables into the formula and obtain a correct answer. However, these students are confident, not only in their approach, but in their choice and use of the appropriate formulae. But students who depended predominantly on the plug-and-chug approach cannot adopt the scientific approach when the plug-and-chug approach is not adequate. The type of problems typical of end-of-chapter problems (Young et al. 1999) and some examination questions could be solved by students within the plug-and-chug structured category as these students tend to use a somewhat strategic approach when solving the problems. However as the problems become more complex the strategy simply of identifying the correct variables is no longer adequate. Those students categorised as unstructured could attempt these problems and may obtain an answer but may not know or recognise that the approach or answer was incorrect and this is also true for those students categorised as memory based. However those students who are described as having no clear approach would find it quite difficult to solve typical end-of-chapter problems, as they do not seem to use any coherent knowledge structure with which to solve the problems.

Conclusions and implications for further research

This paper has outlined phenomenographic research describing students' various approaches to solving physics problems, through the preliminary analysis and interpretation of interview data with 22 introductory students. The hierarchical approaches are represented by an outcome space which consists of four main categories: scientific approach, plug-and-chug approach, memory-based approach and no clear approach. The plug-and-chug category was clearly split into two sub-categories: structured and unstructured. The result of this study shows that the majority of students who begin higher-level education do not approach problem solving in a strategic or scientific manner. Most of the students in the study used a plug-and-chug approach by identifying variables and trying to find some formula, whether appropriate or not. This implies that traditional education may not be encouraging students to develop as adept problem solvers.

Ongoing research in this area involves further rigorous phenomenographic analysis in order to fully develop the categories of description. It also involves investigating how the students' conceptual knowledge affects their ability and approach to problem solving. Another aspect of the study will involve examining students' approaches to problem solving as they progress through their undergraduate careers. Perhaps as their conceptual framework becomes more coherent their approach will become more scientific.

Also during the course of the present study the pedagogical delivery of the physics material was not taken into consideration, and further research will examine the development of both conceptual knowledge and problem-solving skills within the different learning environments in which students learn physics. In addition, these studies will inherently inform the pedagogical processes that will support the development of problem-solving skills and encourage students to more towards the highest category of scientist.

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Table 1. Outcome space of students' approaches to problem solving

Category		Key characteristics	No. of students
1 Scientific approach		• Student aims to qualitatively analyse the problem • Views problems as a whole that can be solved using knowledge of physical world • Tries to piece together the information in a structured manner	2
2 Plug and chug	a) Structured manner	• Some problem-solving strategy (although not clearly defined) • Linking physics knowledge with the understanding that an equation will produce the correct answer	3
	b) Unstructured manner	• No problem-solving strategy, no 'big picture' • Some linking of physics knowledge with an attempt to find the formula that will produce the correct answer	9
3 Memory-based approach		• Student tries to 'recall' a method of answering the problem • No linking of physics knowledge	2
4 No clear approach		• Student does not see problem as governed by any particular law • Must 'make up' some way of solving the problem • No linking of any coherent physics knowledge or concepts	6