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Reforming the Physics Laboratory: From Theory to Practice.

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INTRODUCTION

In Australia, science courses in general and physics in particular are experiencing difficulties in attracting high ranking students. This is reflected by the lower entry requirements compared with courses in medicine, law, business studies or humanities. On the whole, the highest ranking high school students enter disciplines associated with high prestige, high salaries and job security or those which are perceived as new, challenging and stimulating. For students who do enrol in science courses the retention rate is often poor. Over the last ten years less than half the students entering Physical Sciences courses at the University of Technology Sydney (UTS) have gone on to graduate.

What are the causes of these problems? Some insights were provided by Tobias (1990) who, prompted by falling enrolments and poor retention rates in science and mathematics in the United States between 1966 and 1988, undertook a series of studies focussing on students' perspectives and learning experiences in physics and chemistry. She found that these courses were perceived as dull, boring, alienating, competitive, and lacking in student involvement. There was too much emphasis on skills and procedures at the expense of knowing 'how ' or 'why'. In support of these findings, Romer (1993) claims that among students at universities there is a widely held perception that Physics is boring, impossibly difficult and consists of a vast collection of formulae. It is believed that no one can understand it without an advanced course in mathematics.

Mindful of the consequences of a steady decline in quality graduates, the Australian Academy of Sciences, through its National Committee for Physics (1992), has prepared a strategy plan for physics in Australia over the next 10 years entitled "A Vision for the Future". An important part of this plan is directed towards physics education and the need to change the perception of physics by both the general community and the student population. Research suggests there is a need to transform physics from being a content based discipline that emphasises the acquisition of rules, theorems, procedures and skills in highly abstracted forms to one that also develops meaningful integration of knowledge with technology and everyday occurrences. There is a need for creative engagement with scientific problems, and encouragement of more students, especially more women, into physics.

The Department of Applied Physics at UTS has begun to address this challenge through the reform of its first year physics laboratories. This paper describes the processes leading to reform; an evaluation of an existing program, the establishment of new aims and goals, and the development of a new approach to laboratories that attempts to humanise physics and at the same time encompass current developments in learning and teaching. Results from a limited evaluation of the program will also be presented. An accompanying paper at this conference by Cheary, Gosper, Hazel & Kirkup will describe how the goals and aims have been transformed into a workable program and the practical aspects of implementation.

PHYSICS AT UTS

Physical Sciences courses at UTS are applied in nature. This is reflected in the requirement that during the students' program of studies they are required to spend one or two semesters in paid employment for which they gain credit towards their degree. All students enrolled in the School of Physical Sciences at UTS, which includes Chemistry, Physics, Geology and Materials Science majors, undertake a course in Physics during their first year of study: Physics 1 in semester 1 and Physics 2 in semester 2. For many of the non-physics majors, this will be their only experience of university physics so it is imperative it is a positive one. The students in Physics 1 and 2 come with a range of background experiences and knowledge in physics. The majority are likely to have done physics in the New South Wales Higher School Certificate which is the pre-university qualifying program for students up to the age of 17/18 years. Approximately 5% of students have not achieved this level and ceased formal studies in physics after year 10 (16 years). These students are not excluded from enrolling, but are advised that they will need to spend considerably more time on the subject than the majority of the class.

Most UTS first year physics courses consist of six hours per week of class time, of which 2.5 hours per week is laboratory work; the remaining time being tutorials and lectures. The laboratory is regarded as a vital component of the subject as it should provide students with the opportunity to experience science in action, and link theory to practice thus emphasising the applied nature of the course. The laboratory in general can be regarded as representing the heart of the scientific endeavour where the process of socialisation into the discipline takes place and where the life of the discipline is experienced (Latour and Woolger 1979, Boud, Dunn and Hegarty-Hazel 1989, Hegarty-Hazel, 1990). It is also the place where students can most easily be lost or alienated. For these reasons it was decided to begin a review of the first year physics teaching by focussing on the laboratory activities carried out by the students.

The first stage of the review was to critically analyse the existing program in an attempt to articulate its limitations. Involvement was sought from both staff and students and this has been an ongoing feature of the whole reform process. To begin, in 1991 a content analysis of laboratory manuals was undertaken within the introductory course Physics 1 to characterise the student learning experiences. A working party of 12 staff members from the Department of Applied Physics and the Centre for Learning and Teaching examined students' experiences in 14 laboratory exercises. Each staff member analysed 4 exercises providing 48 data samples for analysis. The tools for this analysis were developed using guidelines from Boud, Dunn and Hegarty-Hazel (1986) and consisted of:
a) a content analysis of the laboratory experiments
b) an assessment of the openness to scientific enquiry
c) an assessment of the importance of the experiment in different contexts.
The questionnaires used for a) and b) appear in Tables 1 & 3 below. Table 2 illustrates the method for assessing openness to scientific enquiry.

The results shown in Table 1 are the percentages of responses over all 14 experiments analysed that clearly indicated the learning activity was present in the experiment. The analysis revealed that:

- the experiments emphasised verification of formulae and abstract concepts, collecting and manipulating data, graphing results, appraising precision and providing answers to predetermined experimental questions.
- the teaching and learning styles were characterised by a reliance on prescriptive instructions from teaching staff, requiring minimal contribution by the student other than following the procedure.
- there was little or no encouragement for independent investigation or scientific enquiry.
- students were rarely required to explore a phenomenon, develop a procedure, design or construct apparatus or formulate tests on scientific models.

Table 2 is a scheme for monitoring the levels of scientific enquiry developed by Herron (1971). The levels are drawn up on the basis of the freedom they give to students to engage in the central process of scientific enquiry. That is, recognition of problems and design of experimental materials and methods. They are arranged from low (0, no enquiry) to high (3, which refers to an open project or research oriented exercises). The analysis revealed that of the 14 experiments analysed, two were rated at level 0 and twelve at level 1. There were no exercises where there was openness for students to find anything other than fairly predetermined answers.

Table 3 is a questionnaire that addresses the presentation of the experiments in terms of their relevance to student experiences and interests, and workplace needs. Although the results do not appear in the table, analysis of this section revealed that less than 10% of replies gave a favourable response! This poor response of the staff clearly reinforced the notion that the experiments needed updating.

Table 1. Analysis of Learning Experiences in First Year Physics Laboratories

n = the number of different laboratory exercises analysed.
The percentage rate is calculated over the 48 data samples collected.

EXPERIENCE	PERCEN n = 14
1. Use experimental skills/instrument	100
2. Use measurement /observation procedures	100
3. Demonstrate application/enhancement of physics knowl	7
4. Engage in scientific enquiry : - (a) Explore	21
(b) Predict	7
(c) Develop procedure	0
(d) Design apparatus	0
5. Use data reduction skills:graphical, numerical, algebraic	100
6. Appraise precision	64
7. Assess validity of results	79
8. Interpretation, deduction	14
9. Draw conclusions	86
10. Integrate	7

Table 2. Level of Openness for Scientific Enquiry in Physics Exercises

LEVEL OF ENQUIRY	DEFINITION OF LEVEL			% EXERCISES AT THAT LEVEL n=14
	AIM	PROCEDURE	ANSWER	
0	Given	Given	Given	14
1	Given	Given	Open	86
2	Given	Open	Open	0
3	Open	Open	Open	0

Table 3. Questionnaire on experimental context

1. Would the experiment be interesting or exciting to a student?

2. Would the experiment help motivate students to continue physics?
3. Does the experiment reflect the importance of Physics to industry or the community?
4. Is the experiment relevant to the world of the student?
5. Does the experiment contain a technique of vocational importance?

Student reaction to the laboratory program was sought through a questionnaire and a series of informal interviews designed to determine how well the existing program matched their abilities, background and future requirements. These revealed that although students followed instructions and performed the necessary measurements, mathematical manipulations, and exercises there was little indication that they understood the key concepts involved in the experiments - their quantitative understanding was not matched by a commensurate qualitative understanding. Their descriptions of experiments were centred on what was done rather than why or how, indicating that they were often preoccupied with technical requirements, leaving little time for analysis or enquiry. Experiments were regarded as isolated experiences with minimal connection to everyday occurrences and contributing little to their understanding of physics. The emphasis on verification of formulae and the investigation of abstract concepts presented problems for those students who had not done physics before or were not familiar with the concepts, ideas and formulae being investigated. Students in this category were forced into acceptance of prescriptive approaches and were limited in any attempts to 'enquire' as they had an inadequate conceptual framework to act as a reference for independent investigation.

Overall it was concluded by the Departmental Review Committee that the laboratory program was unlikely to enhance students' interest or sense of excitement about physics, unlikely to help motivate students to continue physics studies at a higher level, unlikely to help develop positive attitudes to science or build scientific literacy. Moreover, the laboratories offered an inaccurate picture of physics and its relevance to everyday life. For Chemistry, Geology and Materials Science majors, who will not continue with Physics beyond first year, it is considered important that they have an appreciation of the contribution Physics makes to the community and industry and they are left with a positive image of physics.

THE IMPETUS FOR CHANGE

With the realisation that its laboratory program had shortcomings, staff at UTS embarked on a course of reform to develop a program that would ‘humanise’ physics, make it more interesting, stimulating and personally involving - to reverse the widely held perception of physics as dull or uninspiring (Rigden and Tobias 1991, Tobias 1990). It was also decided to adopt an approach to teaching and learning that recognises that students construct their own knowledge, that they use prior knowledge and experiences to make sense of new information, and that the context in which knowledge is developed plays a major role in retention, recall and understanding (Resnick, 1989). Research suggests a change to an enquiry oriented approach to teaching and learning could accommodate these aims. This approach opens opportunities for obtaining first-hand experience of science and developing the skills to solve problems, to formulate an hypothesis, to design an experiment, and to collect, analyse and interpret data. It can encourage a deeper approach to learning by enabling students to become active participants in the construction of knowledge.

A major argument for teaching and learning by enquiry is that it is true to the nature of the discipline of science and it exposes students to experiences such as curiosity, perseverance, failure and dealing with doubts (Tamir, 1983). To teach and learn by enquiry involves integrating different aspects of knowledge in ways which can be used to understand novel situations and problems. Students bring a range of knowledge and experiences to the laboratory which can be utilised in the enquiry process. Knowledge comes in a variety of forms, both qualitative and quantitative, which include concepts, processes and procedures gained from formal experiences such as lectures and tutorials, and knowledge from informal sources determined by students' individual backgrounds. When these different aspect of knowledge are inter-related within a meaningful context, students can begin to construct links between discrete pieces of information and begin to appreciate the accuracy and credibility of the knowledge. It is this inter-relation of different aspects of knowledge within a meaningful episode that is crucial to understanding (White, 1988).

Central to the notion of scientific enquiry is the ability to combine knowledge and experience in a meaningful way to investigate and propose solutions to problems. Essentially there are two stages involved in the problem solving process. The first stage involves recognition of an appropriate framework for solving the problem. Conceptual understanding and qualitative reasoning play an important role in establishing this framework as they enable the problem solver to recognise the underlying concepts and principles involved.which can then be used as a guide in devising, executing and monitoring a plan of action (Mayer 1992, Sweller 1989). For an enquiry oriented exercise that is not primarily focussed on developing new concepts, but on combining and utilising knowledge in new and meaningful ways, this would suggest that the problem context should be at a sufficiently familiar level that will allow students to recognise the underlying conceptual structure.

The second stage, or problem construction process can be described as the movement towards a solution and is often facilitated by the application of automated procedures (Sweller, 1989). In the case of laboratory experiments this can involve the experimental processes associated with enquiry. That is, building and testing a model, recording measurements, analysing measurements, relating measurements to appropriate physical equations, and finally interpreting the results in relation to the problem context: processes which link the qualitative and quantitative aspects of the problem and assist in making the connection between theory and practice.

THE NEW PROGRAM.

A number of enquiry based experiments, incorporating the themes discussed above, were trialed on a group of 16 students during the second semester of 1992. At the end of 1992 a set of aims was formulated using information gained from the laboratory trials, from interviews with staff and students, and from research on teaching and learning pertinent to laboratories. After extensive discussion amongst staff the following aims for the new laboratory were adopted:

- to promote the role of physics in industry, technology and the community at large
- to present a humanised view of physics which is both gender and culturally inclusive
- to develop links between theory and practice
- to investigate problems within a context which students can identify with

- to develop both qualitative and quantitative understanding of important physical concepts
- to explicitly recognise the student's prior knowledge that is required for experiments
- to promote the development of oral and written communication skills
- to actively promote, throughout laboratory sessions, communication among students and demonstrators

The process of transforming the aims into a workable program is described in an accompanying paper at this conference by Cheary, Gosper, Hazel & Kirkup. To accommodate these aims the overall material content covered in the new laboratory program has been reduced. There are fewer experiments as some extend over two or three weeks to allow students time to engage in the process of enquiry. Experiments are integrated into units of work, each reflecting a focus theme in parallel with the lecture program. Each unit has:

- clearly defined aims and learning experiences
- problems which reflect a practical or everyday context
- conceptual themes which do not precede the lecture sequence
- general guidelines rather than prescriptive instructions
- pre-work designed to familiarise students with background concepts and theory associated with the experiment
- students working in groups, planning and designing their experiments
- designated discussion time for students to present their work for group comment and debate
- a variety of assessments tasks
- a choice of the experiments, where possible, to cater for individual differences
- an emphasis on qualitative as well as quantitative understanding.

SCIENTIFIC ENQUIRY IN THE NEW PROGRAM

The new program was evaluated for openness for scientific enquiry using a scheme adapted by Hegarty-Hazel (1990) and illustrated below in Table 4. This is essentially the same as that presented earlier in Table 2 but with an additional level of discrimination in ‘procedure’ and in ‘level 2’. These extra levels were felt to be necessary to adequately categorise the changes that have been made in implementing an enquiry oriented approach. Analysis revealed that five of the six experiments in the new program are level 2A and one is at level 1, a significant improvement on the 1991 levels. Level 2A has proven to be an appropriate level for first year students; they have the opportunity to experience enquiry without placing unreasonable demands on the Department's resources.

Table 4: Levels of Openness for scientific enquiry

Level	Aim	Materials	Method	Answer
0	Given	Given	Given	Given
1	Given	Given	Given	Open
2A	Given	Given whole or part	Open or part given	Open
2B	Given	Open	Open	Open
3	Open	Open	Open	Open

A content analysis similar to that used in 1991 was attempted, but it did not accurately reflect the changes introduced. The old program was designed to allow students to undertake an experiment with minimal interaction with the demonstrator and other students. Consequently the experiments were written with detailed instructions, explanations and background information and could be easily classified using a content analysis. The new experiments are significantly different: there are very few instructions and there is an emphasis on exchange of ideas among students and the demonstrator. Consequently a contents analysis based on the guidelines provided to students is inappropriate. A description follows of some of the special features of the program that have been influential in altering students perceptions of physics and increasing their active participation in the learning process.

The program features many of the characteristics of an enquiry oriented program. These have been identified by Friedler & Tamir (1990) as: the teachers are less direct, more planning takes place, the processes of science receive more emphasis, there is more post-lab discussion, the teacher gives fewer instructions in front of the whole class and moves around more, checking, probing and supporting, and students are usually more active and initiate ideas more readily.

To incorporate these characteristics into the new approach, fewer instructions are provided requiring students to participate in the planning of their experimental procedure. To facilitate this process group planning discussions are held at the beginning of each session after which individual students are invited to present their plans to the class. This serves to alert students to the range of options available, and give them the opportunity to refine their own procedures.

The following comments offered by students provided encouraging support for this new approach:

Following a method given word for word isn't really thinking for yourself and you are never going to develop experimental skills for yourself.

and *I find that (fewer instructions) better than someone giving us the instructions and saying, do this and do that. If you have a problem you actually work hard at working it out and you feel you have accomplished something at the end. Its better than someone saying calculate this, calculate that.*

Although fewer instructions were generally favoured by the students interviewed, there were those who felt more guidance was necessary in some experiments. It is one of the challenges of the new program to maintain a balance between too many instructions and insufficient guidance.

Another feature of the program is the weight attached to improving written and oral communication skills in both formal and informal settings. Class and group discussions are encouraged in the planning stages of the experiment. In addition, further discussions are introduced at various stages during an experiment and at the end of each session to enable students to present their results to the class for positive comment and criticism, to pose questions, and consolidate ideas. A study by Heller, Keith & Anderson

(1992) investigating the effects of co-operative group learning on the problem solving performance of college students in a large introductory physics course found that better problem solutions emerged through collaboration than were achieved by individuals. A comment from one student at UTS bears witness to this;

The discussion helps to answer the questions that never get asked or answer the questions you wanted to ask and felt too stupid to ask. Everyone benefits.

Formal communication is addressed in a more structured manner than was the case in the old program. Teaching time is allocated for introducing students to formal report writing which has resulted in students' first attempts at writing reports being at a higher standard than in previous years. Students are also required to present their investigations as a poster presentation: a method of communication encountered both in the academic and business world. The poster requires students to focus on particular problem or situation by reflecting on their learning and distilling their investigations down to the basic concepts. To do this effectively requires a thorough understanding of the principles involved. Another benefit is the opportunity for students to reveal a creative side to their intellectual development that is often overlooked in physics classes.

Student assessment in the new program has received special attention. It is recognised that the style of assessment is a significant factor in determining how students respond. It also influences whether or not they adopt a shallow or a deeper approach to learning (Ramsden, 1992). It is important for all the aims of the program to be reflected in the assessment methods. To incorporate the aims, four assessment tasks of equal weighting are given to students, a skills test, a formal written report, a poster presentation and a practical test designed to examine the experimental enquiry skills practised throughout the semester. In keeping with the aims of the program, the practical test is rated at level 2A on the openness for scientific enquiry scale. The variety in methods of assessment serves to provide a more comprehensive profile of student abilities and reduces the likelihood of inadvertent cultural or gender bias.

The new program attempts to humanise physics and change it from being abstract, inaccessible and likely to produce anxiety. Roychoudhury and Gabel (1991) claim that anxiety is widespread among science majors. A positive learning experience in physics therefore, can help to reduce anxiety. A comment from a student attempting physics for the second time offers encouraging support for the program in this area. On comparing the old with the new program she states

It's giving a much better perspective about what physics is all about. When I started term this year I wasn't sure whether I was interested - but now that the course has turned out the way it has, I'm really enjoying it and its actually one of my favourite subjects at the moment as opposed to the one I hated. It makes physics seem much less intimidating as a subject.

THE FUTURE

Over the next six months an extension of the new laboratory program will be introduced to 150 Physical Sciences students enrolled in the second semester subject Physics 2. The new program for Physics 1 will be repeated for the first time and this will present special challenges. As with any innovation success depends on the enthusiasm and commitment of those directly involved in the implementation. Their role is no longer that of a teacher imparting knowledge, but of a facilitator guiding and encouraging students to seek out and construct their own knowledge. To ensure continuity of the new approach to laboratory teaching a staff development program has been introduced.

At this stage no in-depth evaluation of the extent to which the new program has been successful in addressing conceptual change has been undertaken. One reason for this is that the focus of the first stage of development, has been on improving students' enquiry skills through the introduction of more personally involving forms of learning and teaching. To enhance the new program there are two important aspects of knowledge construction and student learning that need to be addressed in greater depth. The first is the role of misconceptions. Much has been written on misconceptions and methods of dealing with them in a learning situation

(Scott, Asoko & Driver, 1992; Arons, 1990). We need to look towards incorporating appropriate strategies for dealing with misconceptions in the new program. The second is the promotion and fostering of student autonomy. The use of concept and vee maps are some instruments that have been used to encourage students to actively and independently reflect on, and take control of their own learning (Novak, 1990) Once again we need to investigate the possibility of incorporating these, or other strategies, into the program to further enhance learning opportunities.

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