CHAPTER TWO

BACKGROUND

2.1 INTRODUCTION

It is not surprising that even today anyone who starts studying quantum mechanics encounters some sort of psychological barrier. This is not only because of the mathematical complexity. The difficulty arises from the fact that it is hard to break away from the accepted concepts and to reorganise one’s pattern of thinking which is based on everyday experience.

This investigation seeks to expose and isolate some of the difficulties by the application of educational research tools in conjunction with the expertise of physicists currently teaching in the area of quantum mechanics. This chapter reviews the mainstream educational ideas that guided the project, provides a comprehensive review of educational research literature and outlines the courses taught in the School of Physics, University of Sydney, at which the research was carried out.

2.2 EDUCATION MAINSTREAM IDEAS

2.2.1 Educational Environment

The first point to realise is that the medium in which students are trying to learn this material is quite different from what it was when quantum mechanics was first formulated. This cannot help affecting the learning process. The development of quantum mechanics took 30 years, and the scientists who formulated it were guided by a series of unanswered questions based on unexplained experimental findings. It also should be noted that the physicists of the 1920s were highly skilled analytical mathematicians. During these 30 years Physicists debated and refined theories which were based on contentious philosophical and mathematical principles. These debates were also regularly reported in newspaper articles worldwide, therefore any student who studied the material during and soon after this period did so, as with any new theory, in an environment where the context relevant to the issues of the day were explicitly discussed.
As G.P. Thomson remarked during a lecture at a Symposium on the History of Modern Physics in 1961:

“It is difficult for a young physicist ... to realise the state of our science in the early 1920s ... it was not just that the old theories of light and mechanics had failed. On the contrary. You could say that they had succeeded in regions to which they could hardly have expected to apply, but they succeeded erratically. ... And over the whole subject brooded the mysterious figure of h.”

(French and Taylor, 1990)

During the succeeding 60 years, quantum mechanics has become an accepted and successful theory, no different to any other topic in the current undergraduate curriculum. However the social context in which this material is being learned has significantly changed. Even though, in fact, the subject is still not completely understood, it is no longer the grand intellectual challenge it seemed to be in the 1920s. Instead, modern students are expected to learn it in a social context similar to that which is in our secondary schools, where students are required to encode the “approved”, “censored” information which is presented to them in compartmentalised chunks.

2.2.2 Learning and Teaching

There are many theories of learning that seek to describe and explain the processes that occur during learning. This investigation was guided in its inquiry by the ideas of a number of prominent educational researchers. Three views considered concerning the learning process were those of Vygotsky, Rogoff and Brousseau.

The Vygotskian approaches to learning emphasise the non-absolute nature of knowledge and the relationships between knowledge and experience (Vygotsky, 1978) (Wertsch, 1985) (Newman et al., 1985). Vygotsky describes “activity” as a process undertaken in a social context, in which people grapple with new information, to make meaning, to resolve problems and to adapt to the new conditions.

This view of learning will be especially important during the design phase of the instrument and the subsequent analysis of responses. An attempt will be made to develop questions that will bring forward the mental models the students are
using to construct their responses. It is hoped that these mental models can then be examined to reveal their origins.

Rogoff (Rogoff, 1994) describes an educational setting as a community of learners in which different forms of social organisation and intellectual activity result in different forms of knowledge, skills and capabilities. In such a systemic view many kinds of activity are associated with learning. This view is important because it reinforces the fact that students are not isolated entities but instead are members of an interactive social structure. Rogoff provides the investigation with a holistic framework in which the final analysis is to be conducted.

Brousseau (Brousseau, 1992) suggests that a conceptual shift occurs when knowledge is “taught” in courses at educational institutions away from the context of activity where the knowledge first evolved. He states:

“The effort made in order to obtain knowledge independently of situations where it works (decontextualisation) has as a price the loss of meaning and performance at the time of teaching. The restoration of intelligible situations (recontextualisation) has as a price the shift in meaning (didactical transposition).” (Brousseau, 1992)

The conceptual shift described by Brousseau is considered to be of particular significance to this investigation. It is thought by the researcher that the process involving the loss of meaning during the teaching process could be closely linked to the inherent difficulty encountered by students studying the subject.

The ideas of these authors may be taken to define a way of thinking about the process of learning which may be loosely labelled “social constructivist”. Although this term is used by authors with a range of different meanings it is considered that this view of learning is of particular importance in this investigation.

In traditional teaching settings, in which a transmission model of learning is adopted, a student’s “success” is defined in terms of accurately encoding information and reproducing it on demand for assessment tasks. In a context of this kind, success for teachers lies in facilitating the above processes. Whereas in professional or research settings, where an ability to apply concepts and principles is at a premium, experience in troubleshooting and problem solving results in
knowledge that can be applied in the interpretation, definition and resolution of other related problems.

The social context for learning physics in undergraduate courses at university is similar in many ways to that present in secondary schools. Course designers tend to compartmentalise the learning content, divorcing that part of the subject which the scientific community has agreed upon. It is also noted that tertiary textbooks and lectures, particularly in the earlier years, provide “correct” information.

For assessment purposes students are required to demonstrate that they have encoded the information accurately, can reproduce essential facts and ideas in examinations and can apply physical models to solve problems. Such an educational context favours cognitive processes associated with encoding and reproducing information. It is not conducive to reflection and review, nor to the construction of personal meanings that are necessary to develop new concepts or a new schematic lens through which to interpret the physical world. Assessment tasks usually assume an absolutely correct answer even though the scientific mental models that are the focus of study are constantly under review.

Successful learning is defined in terms of correctly completed assessment tasks that demonstrate a “correct” interpretation of the course “content”. These traditionally involve paper and pencil activities that are completed under pressure of time. Teachers of physics at university level, even those actively researching in the field, come to view well established topics in terms of their experience as providers of information — decision making about the best textbook to use, how best to convey key ideas to groups of students and how to check that they “understood” the material. In such a context, “difficulty” is noticed when students are unable to perform assessment tasks. When many students are unable to complete the tasks according to teacher expectations of “correctness”, the topic or physical concepts are then considered to be difficult.

Quantum mechanics is a good example of a field where students experience this kind of difficulty. Learning about quantum mechanics involves a fundamental reconceptualisation or shift in intellectual activity in many different areas. In thinking about quantum mechanics students must move beyond models based on sensory experience towards models that encapsulate theoretical sets of abstract
properties. It may be expected that if the context of learning does not promote the
kinds of activity that foster conceptual development and personal involvement in
meaning making and remaking, then students will fail to develop adequate mental
models as a basis for reasoning, researching and problem solving in this field.

2.3 CHEMISTRY AND PHYSICS EDUCATION RESEARCH

It has already been noted that there has not been much research devoted to
the teaching of quantum mechanics. The subject is far too specialised to have much
presence in mainstream education literature. What work has been done is reported
mainly in Chemistry and Physics journals, and may be summarised as follows.

2.3.1 Chemistry (papers 1 - 14)

In the period 1970 through to the mid 1990s, there are a small number of
articles in chemical education literature devoted to quantum theory and
introductory quantum mechanics. These include short essays addressing historical
and philosophical issues, descriptions of atomic models, representations of bonding
and energy levels, example problems suitable for presentation and computer
simulations.

Though these papers cover a wide variety of topics, their approach is
surprisingly similar. By and large they focus mainly on providing teaching support
materials. One paper, chosen more or less at random, can be taken to be
representative. It is entitled Presenting the Bohr Atom (Haendlers, 1982) and is typical
of the format of the majority of literature.

The paper first acknowledges that the current available text material lacks
context and treats the topic in a simplistic way, ignoring the events and debates that
lead to the formalisation of theories. The paper then describes the context of the
topic, in this case an historical outline of the development of Bohr’s ideas. It cites
and contextualises the observations, theories and experiments from Faraday’s
experiments with electrolysis through to the Schrödinger theory of quantum
mechanics. The main body of the article then refers back to this preliminary
information. The main topic of this article is entitled ‘Derivation of the Energies of
the Stationary States’ and details the derivation of Bohr’s model. The summary
section entitled ‘The Bohr atom in the Chemistry Curriculum’ then links the ideas
presented in the article back to the undergraduate chemistry curriculum.
The obvious trait portrayed in this paper, as in other similar articles, is that the conclusions state that a more historically accurate and/or detailed treatment of the material should increase the student’s understanding of the development of scientific theories. Also it is proposed that this treatment of the material would also remove some of the frustration students feel at the arbitrary nature of current textbook presentations.

In summary, the majority of chemical educational publications provide useful teaching materials such as historical reviews and presentation analogies. They generally conclude that these materials would enhance a student’s understanding of the quantum concepts, but do not make reference to supporting educational research. There is therefore little emphasis on pedagogy.

This lack of pedagogical research into the deeper question of learning is most probably due to the fact that quantum mechanics is not currently considered an important area for the chemical educational research community. This would no doubt be related to the sheer number of topics covered in chemistry curricula, and quantum mechanics is only perceived to be a very small part of the undergraduate chemistry curricula.

2.3.2 Physics (papers 15-61)

Physics education research has been growing over the past 20 years. For a comprehensive literature reading list refer to the University of Marylands, Research in Physics Education (RIPE) WEB site (URL http://www.umd.edu/ripe). At the American Association of Physics Teachers (AAPT) held in 1996, the members decided to form a sub-branch for Physics Educational Research and will publish a dedicated research journal with the proposed name of American Journal of Physics Educational Research. It should be noted that a substantial portion of physics educational research has been devoted to studying student conceptual understanding of topics in physics. Also of note is the recent increase in articles pertaining to theories of learning. However most research has focused on the area of mechanics and to a lesser extent electricity, magnetism, heat and optics. The amount that has been devoted to quantum physics is very small indeed.

The educational literature associated with quantum physics published in the period 1970 to present can be categorised into four main types of articles. These could be broadly described as (1) Historical reviews of people and concepts;
Ideas and methods for teaching quantum concepts, including computer simulations; (3) Packaged teaching and assessment modules; and (4) Educational research articles dealing with concept development. The associated reference lists are essentially complete.

(1) Historical reviews of people and concepts (papers 15 - 30)

The physics and physics educational journals contain many historical accounts that cover both the lives of the physicists and the theories they developed. Although these are not directly aimed at addressing educational issues they are an important resource component accessed by both teachers and students.

(2) Ideas and methods for teaching quantum concepts (papers 31 - 52)

The majority of physics educational publications dealing with quantum mechanics over the last 20 years provide only useful teaching materials outlining the authors’ thoughts concerning the manner in which a topic or concept can be successfully presented. These articles, as do those in chemistry, generally conclude that the material would enhance a student’s understanding of the quantum concepts but make very few references to supporting educational research. It is also noted that half the physics articles do not have conclusions or summaries that describe the outcomes one might expect from utilising the ideas presented. A representative example of a paper entitled “Quantum Mechanics made Transparent” (Henry, 1990) is outlined below:

The article is described as a ‘sampler’. It shows “...how quantum mechanics may be presented to students in a way that makes apparent how natural quantum mechanics is as a description of the world... the basic ideas of quantum mechanics are developed from intuitive first principles to the point where one can connect with the more traditional treatments of quantum mechanics.”.

The article then uses a Socratic dialogue between a teacher and his students which centres around a very detailed question and answer session. The conversation begins with a discussion of the postulates and leads into the uncertainty principle. The discussion then moves on to cover the development of the mathematical machinery associated with Hilbert Space and the idea of representing observables by operators. The terms ‘eigenstates’ and ‘probability amplitudes’ are discussed and each of the operators commonly used are presented. The author does not provide a summary or conclusion to the article.
The advent of low cost semiconductors and programmable calculators in the mid 1970s spawned a series of papers describing how these could be used to generate graphical representations of quantum phenomena. Some examples include “The analogue computer as an aid to teaching elementary quantum mechanics” (Summers, 1976), an article which describes how analogue techniques can be use to tackle simple quantum mechanical problems; “Fundamental quantum mechanics - graphical presentation” (Wise & Kelley, 1977), provides a selection of computer generated displays including a computer simulated diffraction experiment, a derivation of the uncertainty relation, and several spatial distributions of momentum amplitudes and “Simulations of quantum-mechanical measurements with programmable pocket calculators” (Summers, 1978), which provides the reader with the mathematics and the code for the implementation of numerical integration and gives the example of a quantum isolator.

(3) Packaged teaching and assessment modules (papers 53 - 57)

There are three large and two smaller computer assisted learning (CAL) packages currently available for teaching tertiary level quantum physics. These are:

- Software Teaching of Modular Physics (SToMP) - a project funded under the teaching and learning technologies program (TLTP). Coordinated by Dr RA Bacon, Physics Department, University of Surrey, Guildford


- Quantum Mechanics on the Personal Computer - developed by S Brandt and H.D. Dahmen (Berlin Springer).

and

- Visual Quantum Mechanics - Explorations of the Quantum world for Non-Science Students, Physics Department, Kansas State University

- Understanding the Unobservable - a reconstruction of First Year Quantum Physics for Engineers and Scientists by Andrew Cheetham and John Rayner, University of Canberra
Although these packages have been reviewed by journals\(^1\) the quantum physics components appear to have been developed without reference to educational research material.

\[\text{(4) Educational research articles dealing with concept development (papers 58 - 61)}\]

In 1990 a research team at the Free University of Berlin, Germany, headed by Helmut Fischler and Michael Lichtfeldt, presented a paper “Learning Quantum Mechanics” at the International Workshop for Research in Physics Learning: Theoretical Issues and Empirical Studies, held at the University of Bremen (March 4-8, 1991). This was the first published paper to investigate into students’ conceptions and their learning processes in relation to quantum mechanics.

The article reports on findings from a study that compares a teaching unit that avoids the use of mechanical models commonly presented in texts with a control group. The premise that clinging to a historically orientated development of the subject means the teaching will also cling to the conceptions of classical physics. The researchers propose that these mechanical models will set up additional obstacles to understanding quantum physics.

The teaching unit was trialed at several high schools in eleven physics courses (150 students). The study consisted of an evaluation questionnaire; video recordings of 32 lessons across six courses, in order to discover correlations between student conceptions and their answers given in lessons; pre-interviews for two courses, to find out what conceptions the student had at the beginning of the teaching unit; a post questionnaire five to six weeks after course; and post-interviews of three courses. In addition the same pre- and post- questionnaire was administered to a control group of students in a further 14 courses (120 students).

The range of topics covered by the questionnaires and interviews was — light, atom-electron, particle-body and students’ ideas on the philosophy of science. The questions took the form of open-ended free answer (eg. What is light really?) and word pair associations. The verbal answers were transcribed from videotapes.

\(^1\) For articles referring to these and other CAL & video packages see end of chapter references “(3) Packaged teaching and assessment modules”. For additional information refer to the software clearinghouse UniServe Science WEB site at URL http://www.usyd.edu.au/su/SCH.
The study yielded results covering an overview of the students’ conceptions before and after the teaching unit and a comparison between the test and control groups; and case studies for individual students providing conceptual maps that summarised the students’ network of ideas.

The article’s summary section provides an illustration of the results based upon the examples provided in the results section. Referring to the test group, "A teaching concept, for example like the one here, which in the first stage of planning already considers in detail possible conceptions of students, and consciously provides room for these conceptions to develop in the physics course, will achieve an increased cognitive conflict situation which will then lead the students to grapple with the subject matter in an intensified manner. In this way the students became conscious of their own conceptions and began to question them". Whereas the results from the control group tended to incorporate the “new” phenomena into the “old” mechanistic ideas. “Here, the different ideas in quantum physics were merely acquired verbally in the science language level and forgotten again afterwards.”

Fischler and Lichtfeldt published a second paper entitled “Modern Physics and Students’ Conceptions” (Fischler and Lichtfeldt, 1992) the article extends upon the previous analyses and quantifies the “Change of students’ conceptions of an atom’s stability” and provides “Comparisons of conceptual change between the test and control groups”.

In a recent article, “Common misconceptions regarding quantum mechanics” (Styer, 1996), Daniel Styer presents fifteen preconceptions that students can have concerning quantum mechanics. The article’s content has been drawn from his own experiences and covers misconceptions relating to the idea of quantal state, measurement and identical particles. Styer points out that misconceptions are operational as well as conceptual and recommends a variety of ways to utilise the presented material. These include guided discussions, essay questions and diagnostic examinations.

The quantum mechanics educational literature review is essentially complete and shows that very little formalised research has been undertaken by either the Chemistry or Physics educational research communities. The area of focus of the current investigation, mainly the isolation of difficult concepts and the mental models
used by students in learning quantum mechanics has essentially no specific research literature.

2.4 OUTLINE OF COURSE STRUCTURE AT SYDNEY UNIVERSITY

The School of Physics’ general philosophy of teaching is based on the desire to equip students with skills used by professional physicists. These skills include: problem solving, development of theories through experimentation and observation, research methods and design, communication of scientific material, reasoning and deduction about physical systems and proficiency with computer technology. The academic staff use a variety of individual styles and media including lectures, experimental laboratories and conceptual tutorials to achieve these goals. The aims of the School’s teaching program follows.

“*The teaching and learning programs of the School aim to develop an understanding of the major concepts that underlie current views of the natural world, to provide insights into the experimental and theoretical methods that lead to these concepts, and to reveal the intimate and abundant connections between these concepts and the material and cultural welfare of modern society.*” (The University of Sydney, School of Physics - Strategic Plan 1996-1998)

The School of Physics at the University of Sydney offers a variety of undergraduate programs ranging from service courses for Dentistry students to Honours courses for physics majors. Courses are offered at four levels: Junior (1st year), Intermediate (2nd year), Senior (3rd year) and Honours (4th year) level.

2.4.1 Description of Junior Physics Courses

Students studying physics at this level come from a range of Faculties including Arts, Dentistry, Education, Engineering, Science and Veterinary Science. The School of Physics provides service courses in physics for Dentistry, Veterinary Science and Engineering students. The remaining mainstream students have the choice of taking junior physics at one of two different levels, *advanced* or *normal*.

The advanced level of junior physics is intended for students with a strong background in physics and calculus-based mathematics. The course covers more material than the normal level and in greater mathematical detail. Students are invited to participate in this level if they have satisfied certain entrance requirements based on the New South Wales Tertiary Entrance Rank (TER).
At the normal level of junior physics, there is a further division of the course into the *regular* and *fundamental* options in first semester to accommodate different student backgrounds. The regular option is suited to those students who have studied physics at secondary school level. The fundamental option is primarily for those who have not studied physics before. Both the regular and fundamental options of the normal level are based on the same syllabus, and there is a common examination. In second semester students choose between *Technological* and *Environmental* options depending on interest and professional relevance.

The junior Technological Quantum course comprises fifteen one-hour formal lectures. Non-compulsory tutorials designed to promote student conceptual understanding are available and student attendance is encouraged. The course is based on relevant chapters in the textbook, *Fundamentals of Physics* (1993) by Halliday, Resnick and Walker, of which students are expected to have a copy. References given during the course and assignment problems for class assessment are contained in the textbook.

Assessment of the junior physics courses is by assignments, laboratory quizzes and formal examinations at the end of each semester. These three assessment components have different weighting for each course option, however in all cases the formal examinations are the most significant component.

The preliminary studies of multiple choice questions drew upon formative questionnaires administered to the normal and advanced junior streams during 1994.

The sample of students participating in the primary investigation reported in this investigation were from the *Technological* (normal and advanced) streams in second semester of 1995.

2.4.2 Description of Intermediate and Senior Physics Courses

Intermediate and Senior physics is offered at advanced and normal levels. Students are allocated to these streams based on their previous performance in university physics. Teaching and learning environments provided are lectures,
experimental laboratories and computational laboratories. To meet the course requirements, students must complete modules whose content includes: quantum physics, astronomy, electromagnetism, optics, instrumentation, thermal and energy. The students use general reference material such as the junior course textbook, *Fundamentals of Physics* (1993) by Halliday, Resnick and Walker, as well as notes provided by lecturers. The modules are usually based on a more specific text. The recommended text for quantum mechanics modules are *An Introduction to Quantum Physics* (1990) by French and Taylor and *Introduction to Quantum Mechanics* (1989) Bransden and Joachain. Assessment is dominated by a formal examination at the end of each semester.

The preliminary studies of the open-ended questions drew upon formative questionnaires administered to the senior streams during 1994.

2.4.3 Additional Links and Relationships Considered Important

The first of these is the mismatch between the progression of the Mathematics Courses and the levels of mathematics required to do second and third year Quantum mechanics courses. A substantial portion of the introductory lectures in quantum physics deal with mathematical techniques that are required to solve problems in quantum mechanics. For example, calculus of many variables and the concept of an operator. Although these mathematical tools are taught in the standard second and third year options in the School of Mathematics they are considered advanced and are therefore presented later in the courses.

The second is that the arguments and discussions concerning quantum mechanics presented in popular science books and articles are missing from the curricula and texts seldom dwell upon such discussions. The links between philosophy and quantum mechanics are few and only briefly discussed in the senior years of undergraduate studies and are presented as asides during lectures.
BIBLIOGRAPHY


Chemistry (papers 1-14)

Chemistry - Historical


Chemistry - Teaching


Chemistry - Computer Simulations


Physics (papers 15 - 61)

(1) Historical reviews of people and concepts (papers 15 - 30)

Physics - Popular & Historical Accounts

Physics - History of Concepts


Physics - Historical People


(2) Ideas and methods for teaching quantum concepts (papers 31 - 52)

Physics - Ideas for Teaching


41. Martin J.L., "Quantum mechanics from the cradle?", *Physics Education*, Vol 9, pp448-451

Physics - Computers/Simulations


(3) Packaged teaching and assessment modules (papers 53 - 57)

Physics - Video


Physics - CAL


(4) Educational research articles dealing with concept development (papers 58 - 61)


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