CHAPTER 7

IMPLIEDATIONS FOR TEACHING AND LEARNING

7.1 REVISITING THE AIMS

This chapter brings the research study full circle, firstly by identifying the discipline structure in which the 5 identified themes can be further examined and discussed, and then by returning and addressing the aims of the study. Recall that, as stated in Chapter 1, the primary aims of this research were:

- to isolate key concepts,
- to identify learning difficulties,
- to identify teaching difficulties,
- to situate these research results into the broader associated educational literature, and so
- to provide both teachers and curriculum developers with a useful resource to assist them in making informed decisions.

The research project data presented in previous chapters is rich in detail and the reader can examine specific aspects of interest by visiting the appendices. The following sections describe the remaining challenge to develop a framework in which the themes, which contain the encompassing ideas and describe the dataset, can be used to meet these aims. To complete the chapter, the research methodology is reflected upon and three research topics are proposed for future investigation.

7.2 IDENTIFYING THE DISCIPLINE STRUCTURE AND MAPPING THE THEMES ONTO THIS FRAMEWORK

From a practical standpoint the results of this research are most usefully presented in a context and manner which addresses an audience of teachers, curriculum developers and textbook authors; therefore the framework needs to be drawn from the environment in which quantum mechanics is being delivered to students. In order to find an appropriate framework, the first step is to identify the key foundations that make up the discipline of quantum mechanics. From our theoretical perspective described in Chapter 2 this framework is the discipline structure of quantum mechanics.
7.2.1 Discipline Structure

Tertiary level quantum mechanics is taught by experts. Therefore the discussions with lecturers, which were conducted during the grounded phase of the investigation, provide an appropriate starting point. These expert group discussions/interviews identified eight broad overlapping categories (refer to Appendix 2). In the light of the results of this research, this analysis was revisited and the eight categories were found capable of being reorganised and collapsed into three distinct areas associated with the discipline of quantum mechanics. To cross-check and validate this result, a selection of commonly used quantum mechanics textbooks was then analysed.

The three key areas underpinning the discipline of quantum mechanics were identified as the following:

- **Mathematics Area** – the formal mathematical tools,
- **Quantum Concepts Area** – the postulates and associated formal ideas that make up quantum mechanics, and
- **Outside Applications Area** – the applications, experiments and natural phenomena against which quantum mechanics is tested

The relationships between these three areas can be visualised in a simplistic diagram (refer Figure 7-1).

---

Figure 7-1: A diagrammatic representation of the discipline structure and framework showing the relationship between the three identified areas underpinning quantum mechanics
7.2.2 Mapping the Themes

These three areas form a natural and familiar framework on which to superimpose the five themes. Initially I tried to map the five themes individually against the three areas. But the relationship is more complex than a simple one-to-one mapping.

The attitudinal categorisations include all of Theme 5 (Difficulties) and components of Theme 1 (Type of Student — the students’ attitudes to physics) and Theme 4 (Contextualisation — the students’ attitude to analogies). These clearly tell us about the students’ feelings regarding difficulties and personal preferences toward aspects of the teaching and learning process. On the other hand, the remaining theme categorisations can be directly superimposed over the three areas. Taken all together, they provide a model of the sampled students’ operational view of quantum mechanics.

The following diagram provides the reader with a schematic overview of the results within the contextual framework of the discipline structure. The first four themes have been superimposed over the previous diagram, showing where the student sample fits into the discipline’s structure.
By way of explanation, note the following points.

- **Theme 1 - Types of Students** is a component of the Mathematics Area.
- **Theme 2 - Entity**, which identified the starting point for a student within the suite of representations, is a component of Quantum Concepts Area.
- **Theme 3 - Potential Diagrams** primarily links the Mathematics Area and the Quantum Concepts Area for this sample. For example, when students were talking about square wells they were linking mathematics and quantum concepts via the potential diagram.
- **Theme 4 - Contextualisation** provides a mapping of the links between and internal to the areas. This provides an overall picture of how the students link the areas together. It includes the types of tools and anchors within the areas they utilise to make the links.
- **Theme 5 - Difficulties** relate to all areas, and is not associated with any specific part of the diagram.

7.2.3 Discussion

The schematic overview provides a model which represents the sampled students’ operational view of quantum mechanics within the contextual framework of the discipline. This provides an opportunity to further explore the relationships between and the nature of the 5 identified themes. The following sections identify and discuss features of interest which relate to the mapping of the first four themes, then discuss the attitudinal components associated with Themes 4 and 5.
Features of Interest

The most prominent visual feature of the diagram is the absence of an identified theme located in the Outside Applications Area. To me, this means even though I specifically asked questions about these things, it was not one of the key things they talked about. This area appears in relation to the four superimposed themes identified in this study, simply as a reservoir of isolated anchor points. Therefore from our theoretical perspective of schema-based cognitive structures the schemata for the outside applications examined in this study are largely independent elements or resources with weak associations. Examples are: the list generated from the question ‘name three things quantum mechanics has given us?’; or the list of key experiments. Now the number of links made by any individual student to any one of these anchor points is very small. Therefore the Outside Applications Area is quite isolated, and only tenuously connected to the other areas by a small number of very context specific links. It is also worth noting, although outside the scope of this dissertation, that cursory examination of the chemistry student interviews conducted during the early phenomenological stage of this investigation indicates that the chemists have a different set of links.

Looking at the linkages between the Mathematics Area and Quantum Concepts Area reveals a greater number of links per individual student, but a similar situation exists in that these links tend to be very context specific and are often one way in nature. The linkings provided by the potential diagrams and those of some analogies are good examples.

Overall therefore, it appears that the schemata or tools utilised by students to link the three areas of the discipline together are small in number, are often one-way in nature and are seldom generalised. In contrast, when the lecturers discussed aspects of the discipline, they could draw together and discuss relationships. They could identify and debate a broad range of issues indicating that they possessed a very rich and well developed linking structure between all three areas.

Attitudinal Components

The attitudinal components of the themes inform us about the feelings regarding difficulties and the personal preferences of the students. Theme 5 - Difficulties clearly indicated that the students were concerned about the ‘big picture’ of quantum mechanics. They were particularly concerned that the courses they had studied did not link concepts appropriately, and that mathematical tools
were being taught in isolation. The results of this investigation support this concern and clearly identify shortcomings in the current teaching strategies in regards to developing a rich network of links between the three areas of the discipline.

Theme 4 – Contextualisation, when it explored the students’ attitude to analogies, revealed that there is a large variation in the role students believe analogies should play. Analogies formed a significant proportion of the links identified and they are by nature very narrow and context dependent. Therefore analogies themselves maybe providing links that are inappropriate to gaining a view of the ‘big picture’. It is interesting to note that lecturers did not see analogies as important tools in the learning of quantum mechanics.

7.3 REVISITING THE LEARNING MODEL AND SITUATING THE RESULTS INTO THE CONTEXT OF THE LITERATURE

In Chapter 2 an extended Presage-Process-Product learning model was outlined in order to provide a framework to interpret and understand our findings. Reflecting upon the model a picture of student learning in quantum mechanics emerges, which resonates with other work in the physics and science education literature.

The results indicate that the characteristics of students, the teaching and learning environment and the cognitive structures built by students all strongly influence learning outcomes. The results also strongly support the belief that the act of applying knowledge and transferring it to unfamiliar situations is a complex and difficult activity. In particular the study identified a deficiency of scaffolding for knowledge transfer. The following sections briefly discuss a selection of factors identified by this research in terms of the extended model.

7.3.1 Characteristics of Students - Pressage

The model predicts that different learning outcomes can arise from the same learning environment. This is attributed to different inputs. One of the primary inputs is the characteristics of the students. This study identified, for physics students studying quantum mechanics, that they possessed similarities, such as the majority’s being interested in physics; and also identified differences such as their mathematics level/ability.
Upon review of the student interview transcripts it was evident that students could be easily categorised and it was apparent that these identified characteristics played a pivotal role in the Process and Product stages. For example students categorised with similar mathematical experiences and skills, could be used as a generalised predictor for their response to questions such as describing a certain specific mathematical result. Yet on the other hand it was clearly evident that students who appeared to possess very similar mathematics ability, interest in physics, prior experience and motivation would explain a shared learning experience in two totally different ways.

7.3.2 Characteristics of the Teaching and Learning Environment - Pressage

The grounded study clearly identified that quantum mechanics is taught by experts who possess a clear grasp of the discipline structure. The delivery is largely a transmission style, with a formal use of language including mathematics. There is little opportunity for students to discover concepts and attribute their own meanings. For the most part students are not encouraged to use their own language or interpret formal language in their own words. Opportunities to address this through analogies were limited or non-existent, segmented into units or topics, and assessment is strongly examination driven. The learning environment in which quantum mechanics is presented is therefore structured and controlled by the lecturers in a very specific manner.

7.3.3 Student Perceptions of the Learning Context - Process

During interview, students often commented on the lack of diversity of teaching approaches. It is unclear whether this teaching and learning approach is prohibitive or unhelpful in developing an appropriate cognitive structure. The third and fourth year students, when discussing the delivery of the material stated that they would like concepts to be linked together, and half the second and post graduate students expressed that they had difficulty in seeing where quantum ideas and concepts fit into the bigger picture.

It is noteworthy that in the wider physics education literature other areas of physics including Newtonian mechanics, optics and thermodynamics are exploring different teaching and learning approaches which encourage more interaction with the discipline. These practitioners assert that these more hands-on and conceptual approaches produce superior learning outcomes. Interestingly, when discussing
this point with the majority of lecturers concerning the different learning outcomes provided by these strategies, they were not considered appropriate for teaching ‘real’ quantum mechanics as they might produce students with a broader conceptual understanding at the expense of mathematical rigour.

7.3.4 Student Approaches - Process

The depth and richness of information contained in the interviews offered the opportunity to investigate the student’s approach to learning utilising a simple taxonomic approach\(^1\) of \textit{surface}, \textit{medium} and \textit{deep} to several aspects of potential diagrams. The results indicated that there was a progression from second year through to postgraduate level, but the \textit{deep} level of understanding only emerged across all aspects in the postgraduate sample. In relation to the model this indicates that factors are affecting the timely acquisition of deep understanding.

7.3.5 Learning Outcomes – Product

Learning outcomes are primarily associated with the student’s ability to respond to a range of problem solving situations. All the students interviewed were successful, yet a recurring comment from lecturers indicated that novel or unfamiliar problems were seldom addressed appropriately. Several questions were devised to investigate how students solve unfamiliar and novel problems, including: unfamiliar potential diagrams, discussing radioactive decay, electromagnetic shielding and the quantaroo analogy in terms of quantum ideas and concepts. The results from each of these questions confirmed that indeed students, despite being prompted, generally struggled to respond and some were unable or unwilling to provide any response.

In terms of the model it suggests that within the Process component the students are not being provided with the appropriate input stimuli to deal with unfamiliar problems adequately.

7.3.6 Cognitive Structures

The Presage-Process-Product model does not provide great detail on the learning process. Instead it focuses on identifiable learning factors. Therefore we

\(^1\) The \textit{Surface}, \textit{Medium} and \textit{Deep} categorisations are an adaptation of the SOLO Taxonomy developed by Biggs and Collis. In this study these 3 categories are defined as follows: \textit{Surface} – Predominately Uni-structural, \textit{Medium} – Multi-structural, and \textit{Deep} – Relational and/or Extended Abstract.
extended and adopted a cognitive structure of schemata which are grouped to form a model of quantum mechanics.

**Broad Features of the Model**

Individual schema contain elements and resources that are strongly related and stable. For example students when presented with a square potential well recognise its features and have a set of tools/concepts such as matching bound conditions, fitting in harmonics, etcetera. We also found that these individual schema often have a strong contextual basis. For example students have existing schema relating to diffraction gratings which they have developed through physical optics study, and develop a new isolated or weakly link schema in the context of quantum mechanics. In some cases students exhibited distinct schema for different examples from quantum mechanics. For example, a particle in a box, the diffraction of an electron and the radioactive decay of a nucleus.

It appears therefore that the context of learning often dominates individual schema. I propose that the cognitive structure of most students studying quantum mechanics is in this sense a weak model consisting of contextualised schema often drawn from areas including mathematics, waves, electromagnetism, optics and mechanics. For example a highly contextualised and weakly linked schema is clearly evident throughout the previous discussion following the mapping process of the 5 themes onto the discipline structure in section 7.2.3.

**Recognition, Association, Assimilation and Perturbation**

From the model a new element triggers a recognition response and the learner associates this with a specific activity or purpose based on an existing schema. If the learner’s expectation is reinforced the new element will be assimilated into the existing schema.

In relation to the model the results of this study indicate that there are strong existing schemas from waves, mechanics, optics, electromagnetism but that they are weakly linked. The quantum mechanics concepts are therefore assimilated into often inappropriate schema and appear to often result in inconsistent structures. For example probabilistic concepts are assimilated into largely deterministic structures with no apparent conflict. I believe this inappropriate process is compounded because current problem-solving activities presented to students, which utilise for example the current mathematical or potential well tools, does do
not cause perturbation in conceptual schema. I believe this is directly related to there being poor or no links between the tools and concepts.

I propose that the recognition response of a new element is the critical step in schema association which lecturers must ensure is executed appropriately to build consistent foundation structures.

**Accretion**

Consider an infinite well then a finite well, and you can see how to modify from one to the other. You remember the history of the problem. If you cannot remember the history or trace of the schema development when confronted by a new associated problem, you are likely to experience difficulty solving unfamiliar problems.

We have identified weak linking between schema blocks, thus the accretion trace within the schema is critical to problem solving for these students. Unless students can remember the original input for a given situation the incorrect schema to solve the problem may be activated. For example when presented with an unfamiliar potential diagram a large proportion of the students got stuck. But when hints were provided in order for them to see the problem in terms of their simple well-barrier schema the students generally proceeded to solve the unfamiliar problem.

**Restructuring and Tuning**

During the students’ undergraduate studies there is little evidence that appropriate restructuring is occurring, the most obvious is the bridging schema of wave/particle duality which is long lived and not replaced by a probabilistic model. In this case students appear to ignore or are unaware of the conflict within their current schema. In discussions with lecturers they expected that students would shift to a probabilistic interpretation of quantum mechanics. Several stated at length that they were conscious that a significant proportion of their senior students had not embraced a probabilistic viewpoint.

In terms of the model it appears difficult for students to make totally new schema. Instead they attach to their existing schema without critically analysing inherent conflict and inconsistencies.
7.3.7 Transferring and Application

Unfortunately there is little compelling evidence that knowledge transfer occurs to any great degree during instruction. This study looked for evidence of transfer/application by introducing novel or unfamiliar problems. Any major restructuring of schema or new schema construction to successfully solve unfamiliar problems takes place some time after formal study, as evidenced by the taxonomic analysis discussed above in Section 7.3.5. in relation to learning outcomes.

We expected to see a gradual progression and reworking of cognitive structure during the delivery of quantum mechanics courses. What we actually observed was the successful use of compartmentalised knowledge to solve familiar problems but little evidence of modified structures to cope with unfamiliar problems. This suggests that appropriate scaffolding to encourage knowledge application is not present in these courses. Therefore in relation to the model I believe that one of the challenges for lecturers is to develop inputs to trigger schema modification. I suggest that deliberate linking of examples to multiple contexts is required.

7.4 IMPLICATIONS FOR TEACHING AND LEARNING

In conclusion, to complete the circle and to measure the success and scope of this research project, we revisit and address the four remaining aims set out in Chapter 1.

7.4.1 To Isolate Key Concepts

The grounded and phenomenological stages of the study identified a list of key concepts considered important by the lecturers (which was not an exhaustive description) and a list of key concepts and experiments identified by the students. The concepts discussed by the lecturers and students overlapped but the predominant difference was the apparent emphasis students placed upon the concept of ‘wave particle duality’ whereas the lecturers did not.

The analysis identified that these concepts act as anchor points for links. Most significant is that these concepts were predominately found to be very context specific, with few links and therefore isolated. Even concepts that appeared to be well linked, when discussed slightly out of context revealed that the students had difficulty generalising their knowledge to the new context.
7.4.2 To Identify Learning Difficulties

The grounded and phenomenological stages of the study identified a list of expected difficulties perceived by the lecturers and a list of real difficulties identified by the students. The lists were similar with the exception of specific content items. The students identified only one item — Heisenberg’s Uncertainty Principle — whereas the lecturers identified 10 separate concepts.

The analysis indicated that the remaining difficulties identified and the difficulties students experienced answering the interview questions were all associated with weaknesses in their schemata — or in other words their ‘personal big picture’ of quantum mechanics. These difficulties exist because the linking internally and externally between the three areas within the discipline were often few in number, isolated, context dependent, one way and not readily generalised.

This clearly manifested itself during the interviews when students were asked to discuss unfamiliar problems, to name three things quantum mechanics has given us and to discuss familiar concepts presented slightly out of the usual context.

7.4.3 To Identify Teaching Difficulties

The grounded stage of the study identified a list of difficulties faced by teachers. The lecturers identified that the time constraints, the prior experiences of students, the current teaching approaches, the abstract nature of quantum mechanics and the inability of students to solve problems are all difficulties for the teaching process (please refer Appendix 2 – Table A2-7 for details).

There are some interesting issues that I would like to bring to the reader’s attention as points to consider and debate.

- The students perceive that the course material in quantum mechanics is currently being delivered in compartmentalised chunks. I suggest as a consequence, students see no reason to integrate this material with other knowledge.

- The research indicates students are not seeing a coherent ‘big picture’ for the discipline of quantum mechanics. A large proportion of students expressed that they are confused, one student expressed upon reflection “I was wandering, slightly confused, in the dark, for much of my undergraduate studies”.
As a consequence of current teaching practice the links and tools we are providing students are context specific and isolated. As a result students are often unable to generalise their knowledge to the wider subject.

Lecturers expressed that they were hoping for the students to possess a deeper appreciation of the subject and an ability to solve novel unfamiliar problems. Yet the students during their course of study seldom have been required to perform or practice this type of problem solving activity.

It was universally recognised by students and lecturers that good mathematical skills will get you a good mark in quantum mechanics assessment activities. Therefore there is little incentive for students who possess good mathematics skills to make complex changes to their schemata in order to gain a deeper conceptual appreciation.

This study indicated that half the students cannot visualise the mathematics, it simply serves as a tool or a black box process. I suggest that these students may find immense difficulty in linking the Mathematics Area of the discipline to the Quantum Concepts or Applications Areas.

A common assumption held by the lecturers is that, as the students progress they move to a probabilistic viewpoint. Whereas this research indicated that the majority of intermediate and senior students are still focused on the semi-classical wave particle dichotomy.

And finally, as teachers, we often become so familiar with the concepts and tools that we forget how complex they actually are. For example, the potential well is a complex summary of many ideas, yet we simply present the diagram and solve a few simple idealised problems. Then assume that the students have recognised the power and subtleties associated with the diagram and underlying mathematics that has taken us, as teachers, many years to appreciate.

I discussed and debated the threads that address this aim with several colleagues and it was clearly recognised that they are extremely complex, interdependent and interlinked. There is no obvious simple fix to the issues raised or observed. I suggest that the challenge faced by teachers and text book writers is to provide a contextualised environment in which to deliver the material that encourages the generation and review of appropriate linkages.

7.4.4 To Provide both Teachers and Curriculum Developers with a Useful Resource to Assist Them in Making Informed Decisions

I believe this research project has provided the physics education community with three valuable resources.
• **A Detailed Data Resource** - The Final Tabulated Dataset (Appendices 6 and 7) provides a readily accessible resource which details the internal aspects of the five identified themes.

• **A Framework** - The schematic representation comprising the three areas of Mathematics, Quantum Concepts and Outside Applications, provides the teacher and/or researcher with a framework to examine how the structural and thematic components are related.

• **A Research Methodology** – The research methodology developed during this study, which drew upon grounded and phenomenological approaches, provides an easily adaptable and robust research tool for investigating similar physics education research questions within a tertiary setting.

### 7.5 METHODOLOGY REVIEW

At this point I feel it is necessary to reflect upon the methodology and associated processes adopted in this research and raise points for consideration by fellow physics education researchers.

This thesis focused on the pedagogy of the discipline of quantum mechanics and is exploratory in nature. Initially I unconsciously took a research approach directed at quantum mechanics and how it related to teaching and learning, rather than on teaching and learning and how it relates to quantum mechanics. Either approach is arguably valid but in hindsight I would recommend physics education researchers to consciously approach their research from both perspectives. Once I became aware of, and recognised the importance of viewing the project from both perspectives, they provided a more robust and informed foundation on which to plan and conduct this research.

During the development of the research plan in 1999-2000 it became apparent that the physics education community drew upon a set of commonly used research tools including surveys, concept maps, interviews and tests; but surprisingly they had not presented an overarching methodological framework in which to conduct exploratory qualitative physics education research projects.

Phenomenography was mentioned and utilised as a tool by a number of researchers. Upon investigating this approach it became apparent that it was not an appropriate or suitable overarching methodological stance for a broad exploratory research project. In order to explore this issue I sort advice from science education, mathematics education, medical and psychology researchers and after considerable deliberation a two stage approach was developed for this study. This utilised a
grounded theory approach to develop a set of interview questions and a phenomenological approach in which the student interviews were conducted.

From a theoretical standpoint within the context of education research I believe the combination of these two methodologies was sound and provided a robust, flexible and defendable framework. However, reflecting on the data analysis processes showed that considerable time was spent on the analysis of raw data and associated datasets. My weakness lay in my ‘fear’ of missing something important. I would continually deconstruct the data and often produce too many categories. I acknowledge that early in the study this was appropriate but I continued to over-analyse data throughout the study. I believe this problem manifested itself because I did not strike a balance between the number of categories developed and the process of constant comparison between data sets. In hindsight, the efficiency of my analysis would have been improved by rigorously monitoring an increased repetition rate of the open and axial coding processing during the grounded phase of the research. This increased rate would have assisted in providing me with more practice and confidence in reducing the number of categories being generated in both the grounded and phenomenological stages. This reduction of categories would have provided more manageable datasets and thus allowed more time to explore the dimensions of categories and a more thorough comparison of categories between different datasets.

7.6 FUTURE RESEARCH

Three research topics are proposed for future investigation, an extension of the mapping of themes onto the three areas for other faculties and within other institutions; an investigation into the nature and types of links present and/or available to enhance the process of teaching and learning, and; an examination of the role analogies play in conceptual development.

Map Related
Extend the exercise of mapping themes generated by different groups over the three areas of the discipline, to identify variation in thematic types and positioning.

- Investigate how themes generated by chemistry students differ from their physics counterparts. As noted previously, chemists appear to have different linking structures.

- Investigate institutions that have adopted a matrix algebra approach to teaching quantum physics versus those that focus on the differential approach.

Link Related

An investigation to examine the nature and types of links currently being utilised by the students, and identify new linking that may assist in conceptual development, in order to provide teachers with resources to make informed strategy decisions.

- Identify and investigate links that assist, block or hinder conceptual development.

- Develop a tool to fully reveal and examine the links possessed by experts.

Analogy Related

A project to investigate the role analogies play in conceptual development and if found detrimental “What other choices do teachers have?”.

- Investigate if certain types of analogies enhance, hinder or block conceptual development.

- Investigate if there are delivery mechanisms or contexts that favour the utilisation of analogies.
CHAPTER 7

IMPLICATIONS FOR TEACHING AND LEARNING

7.1 REVISITING THE AIMS

7.2 IDENTIFYING THE DISCIPLINE STRUCTURE AND MAPPING THE THEMES ONTO THIS FRAMEWORK

7.2.1 Discipline Structure

7.2.2 Mapping the Themes

7.2.3 Discussion

Features of Interest

Attitudinal Components

7.3 REVISITING THE LEARNING MODEL AND SITUATING THE RESULTS INTO THE CONTEXT OF THE LITERATURE

7.3.1 Characteristics of Students - Pressage

7.3.2 Characteristics of the Teaching and Learning Environment - Pressage

7.3.3 Student Perceptions of the Learning Context - Process

7.3.4 Student Approaches - Process

7.3.5 Learning Outcomes – Product

7.3.6 Cognitive Structures

7.3.7 Transferring and Application

7.4 IMPLICATIONS FOR TEACHING AND LEARNING

7.4.1 To Isolate Key Concepts

7.4.2 To Identify Learning Difficulties

7.4.3 To Identify Teaching Difficulties

7.4.4 To Provide both Teachers and Curriculum Developers with a Useful Resource to Assist Them in Making Informed Decisions

7.5 METHODOLOGY REVIEW

7.6 FUTURE RESEARCH

Map Related

Link Related

Analogy Related

Figure 7-1: A diagrammatic representation of the discipline structure and framework showing the relationship between the three identified areas underpinning quantum mechanics

Figure 7-2: Schematic overview of the first four themes mapped over the three areas of the disciplines framework