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Inside the quantum mechanics lecture: Changing practices

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Abstract: *Quantum mechanics is one of the most difficult subjects to learn or teach but it has only recently become the focus of educational research. Studies have documented common misconceptions and areas of difficulty by examining student performance, but have not independently explored current teaching practice. In this study, an audit of all quantum mechanics classes was conducted over the spring semester of 2004 in the School of Physics at the University of Sydney. This comprised courses from first, second, and honours years. Although the traditional lecture format is still intact throughout these courses, lecturers are experimenting with computer simulations, visual teaching aids, and innovative demonstrations, attempting to overcome the abstractness of the subject with enabling technologies. There is substantial overlap between material taught in the first and second years, however this content bears little resemblance to the honours level curriculum. Interactivity is limited in all courses; implications for teaching are discussed.*

Keywords: *quantum mechanics, lecture method, educational technology*

Introduction

With the growth of the computer industry, increased research into nanoscale materials and nuclear medicines, it has never been more important to have a strong conceptual understanding of the quantum world. Future developments in science and technology will undoubtedly arise from studies of the very small. Nano-computers, fortified nano-structures, and Bose-Einstein condensates are just a few of the exciting technologies on the frontier of twenty-first century physics. Students endeavouring to work in these fields, however, must first undertake the challenge of learning quantum mechanics.

Quantum mechanics is widely regarded as one of the most difficult subjects to learn or teach due to its counterintuitive nature, dependence on high-level mathematics, and abstract subject matter; it typifies the "complex knowledge domain" characteristic of physics (Sharma, Millar, Smith, & Sefton, 2004). Its students must reject traditional conceptions of nature like the wave or particle and develop entirely new understandings of matter and energy. Even experts in the field debate the interpretations of quantum mechanics, as traditional notions of reality no longer apply. Only a limited range of problems can be attempted as computers and approximate methods are required to solve even the most rudimentary problems. Furthermore, students cannot readily see nor do they have personal experience with quantum effects. Quantum mechanics is an intricate subject, demanding of its students a wide array of skills from advanced mathematics to conceptual abstraction.

Debates have erupted among educational researchers and practitioners over how to approach the teaching of quantum mechanics. Due to long held views of some physics professors, "introductory courses are still taught in much the same manner as they have been for the past seventy years," (Fletcher, 2004, p.1). Some support this practice believing "the mathematics should be covered 'step by step and then tie in the physics,'" (Fletcher, 2004, p.104) while others promote the opposite viewpoint. They suggest that traditional teaching methods may lead to misconceptions and advocate a qualitative conceptual approach without the vestigial historical underpinnings of the subject (Müller & Weisner, 2002). There is no clear answer to this debate, however, as quantum mechanics has only recently been investigated by educational researchers (Domert, Linder, & Ingerman, 2005) and the development of improved teaching methods is in its infancy.

Studies thus far have focused on misconceptions (Styer, 1996), quantum curricula (Wittman, Steinberg, & Redish, 2002), student conceptions and understanding (Fletcher, 2004; Johnston, 1998), experimental teaching practices (Müller & Weisner, 2002; Zollman, 2002; Lawrence, 1996), and specific quantum topics (Wittman, Steinberg & Redish, 2002; Olsen, 2002). Most of the research on teaching practices is performed by practitioners on interventions they have developed. Searches of educational databases yield no literature independently documenting the current practices of quantum mechanics teaching in a tertiary institution.

The goals of this study were to observe the cross-section of quantum mechanics courses at one university, identify prominent aspects of the teaching method, trace the progression of subject matter through the years of study, and compare these observations against the related literature. This is intended to provide researchers with (a) a picture of contemporary quantum teaching highlighting sources of misconceptions and conceptual difficulties, and (b) a starting point for improvement in teaching and learning practice. This paper outlines prominent features of the current quantum mechanics teaching program in the School of Physics at the University of Sydney, emphasizing the comparison with traditional teaching in quantum mechanics.

Method

Over the course of this study, five lecture classes were surveyed: three first year classes, second year quantum mechanics, and the honours level relativistic quantum mechanics (RQM). The fraction of classes attended by the researcher, enrolment, and average attendance are summarized in Figure 1.

Class	**1st Year Environmental**	**1st Year Technological**	**1st Year Advanced**	**2nd Year**	**RQM**
Number attended	10	7	2	13	18
Total classes	14	12	12	19	21
Enrolment	83	115	160	121	NA
Average attendance	47	69	118	94	14

Figure 1. Proportion of quantum classes attended by subject

The advanced first year class is for students with strong backgrounds in high school physics who are interested in developing a deep, mathematical knowledge of the subject. The environmental class places special emphasis on radiation and its interaction with matter, whereas the technological class covers the topics of quantum mechanics more generally. The second year classes were aimed at giving students a strong conceptual foundation in quantum mechanics. RQM is the highest-level undergraduate course on the subject, enabling students to understand and solve problems pertaining to the combined theories of relativity and quantum mechanics.

Observations were collected by the researcher as an observer-participant immersed in lectures as a student. The researcher is a recent graduate of engineering physics from a Canadian university. The "student perspective," as it appears in this paper, is a construct of the researcher based on conversations with students, observations of the class as a whole, and personal experience. Relevant works on the student perspectives of learning in higher education include Prosser & Trigwell (1999) and McInnis et al. (2000).

Lectures were broken down into segments of teaching time, subjectively determined by topic or teaching method changes, ranging in length from one to twenty-five minutes. Fletcher (2004) has identified areas of difficulty for students and teachers by accumulating and thematically coding interviews with students and lecturers. He identified specific topics of interest:

- wave-particle duality
- the uncertainty principle
- tunnelling

and the teaching styles in which topics are presented:

- demos or visuals
- analogies
- real world examples
- mathematics
- discussions
- predictions
- history
- lecturer explanations.

A six point rating scale was initially used to give a rough measure of the significance of the above items in each segment. The criteria evolved over the course of the study and are shown in Figure 2.

Score	Criteria	Student Perspective
0	Item was not associated with the segment explicitly or implicitly over the entire duration	No correlation between the item and segment
1	Item was implicitly associated with part of the segment	Only the keenest of students would recognize the relevance of the item
2	Item was implicitly or explicitly associated with part of the segment but was not presented in a meaningful way	Advanced students may see the relevance of the item in the segment and gain something from it
3	Item was implicitly or more likely explicitly associated with part or all of the segment and was sufficient in its presentation	The majority of the class would see the relevance of the item in the segment and may gain something from it.
4	Item was explicitly associated with most if not all of the segment and was well presented	Almost all of the students would see the relevance of the item in the segment and should learn something from it.
5	Item was explicitly associated with all of the segment and was presented in a way that inspired interest	Even those students not paying attention would be attracted to the segment and therefore see the relevance of the item and engage with the content

Figure 2. Overall teaching segment rating scheme.

A sample data point is given below. The teaching segment rated in Figure 3 explained the Heisenberg uncertainty principle using an analogy to uncertainty in measurement on a macroscopic scale.

Time (min)	Visual	Math	Analogy	Prediction	Discussion
12	4	2	3	0	0
Real World	History	Explanation	Duality	Uncertainty	Tunnelling
0	0	4	3	5	0

Figure 3. Sample teaching segment rating from the first year environmental class

In addition to these ratings for each teaching segment, the subject matter and any other relevant details were noted. These data were compiled in a database and analysed for the most significant trends.

From the data, four key themes emerged in the areas of interactivity, technology, math, and course content. Interactivity is composed of discussions, predictions, and lecturer explanations; technology incorporates demonstrations and visuals; and course content touches on history in quantum teaching but excludes specific quantum topics in this paper. Three observations that arose independently of the numerical data, but which have strong bearing on the results are: lecturer influence, students' attitudes towards learning and the unique attributes of relativistic quantum mechanics.

Results and discussion

Additional factors

Lecturer influence

The tone of the class, the methods of teaching, and the type of learning taking place were, not surprisingly, heavily lecturer dependent. This deserves emphasizing, as the lecturer's preparedness and presence in class were the most influential factor in the data set. While content was very similar in the first year environmental and technological courses, the lectures were very different in emphasis, length, and depth of explanations, visual aids used, and mathematical descriptions. This is the most obvious cause of variation among the courses surveyed. From discussions with the students, lecturers who were perceived to be the most interesting were not always perceived to be the best to learn from, and vice versa.

Students in the first and, to a lesser extent, second year classes tended to view the lecture in a very social way. Noise levels in the technological and advanced first year streams were consistently high. Students were often late to class with many arriving up to twenty minutes into the lecture. This did not appear to bother the lecturers. It was evident that for the vast majority of students, intrinsic interest in the presented material was limited. This is in line with the study conducted by McInnis, et al. which established the trend that

> considerably fewer students found that lectures were a valuable source of learning for them, a finding that is statistically significant…. The findings may indicate that lectures are becoming a less important source of information for students who now have more access to other forms of information, especially via the internet (McInnis, et al. 2000, p.20).

Most students seemed concerned with marks, however, and asked more questions after class around assignment deadlines. Students in RQM were almost always on task in the lecture, presumably due to the small class size, advanced nature of the material, and the fact that only the keenest students were enrolled in this fourth year course.

Relativistic quantum mechanics (RQM)

Of the five courses surveyed, RQM was the notable exception. All lectures in this course used the traditional "chalk and talk" style. The vast majority of information covered was mathematical in nature, limiting the number of diagrams and pictures. The class was also the smallest surveyed and the attrition rate was the highest at 45%. For these reasons, RQM could not be analysed in the same manner as the other four courses and is therefore omitted from the following figures and discussions unless otherwise noted.

Key themes

Figure 4 summarizes the results from all lectures. It is important to note that this data is biased, as proportionally more time was spent in the first year environmental and second year classes. The features of this chart dictate the analysis that follows. The most common use of teaching time was the lecturer explanation, whereas the least was discussions or predictions. This leads to an examination of lecture interactivity.

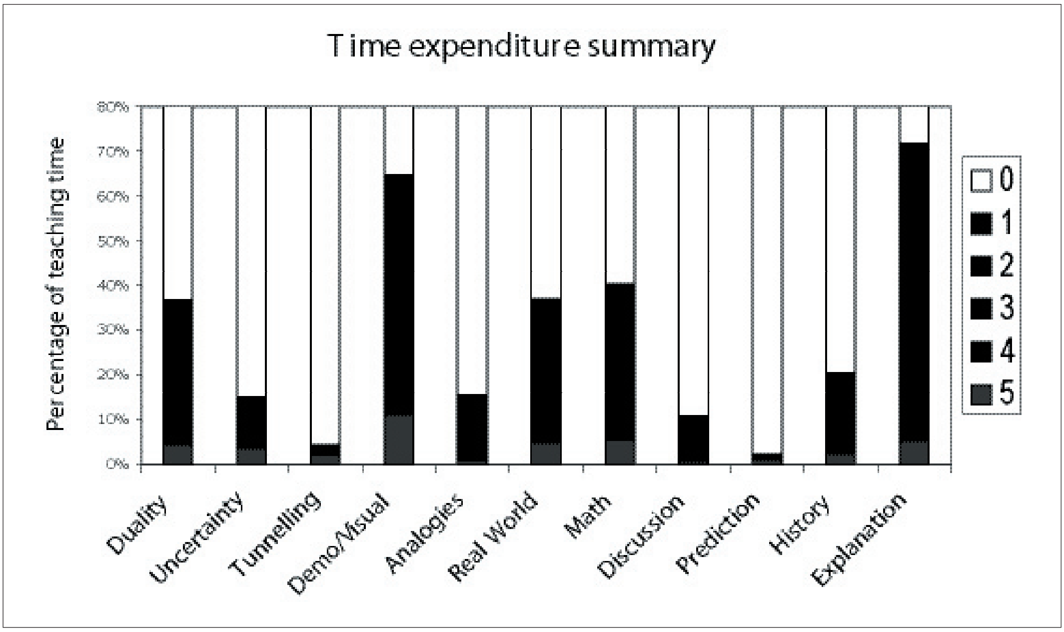

Figure 4. Data summary of rated teaching segments

The next most common teaching method was use of visuals or demonstrations; this is addressed through an overview of the classroom technology that enables its use. Mathematics was the third most significant aspect of teaching and was approached in very different ways by different lecturers. Although specific quantum topics are not examined in this paper, the general content and historical curricula of the courses are compared.

Interactivity

In terms of the lecturer speaking for the vast majority of class time, almost all lectures adhered to the traditional format. The few exceptions were from second year classes where two lectures were explicitly question and answer format. However, the questions posed by students lacked preparation, were often only tangentially related to class material, and were commonly of interest to only a few in the class. This raises the question of how to better structure or plan these sessions to make the best use of class time. In the advanced first year classes, the lecturer often posed questions but only a handful of students responded. In general, questions were rarely asked by the lecturers or by the students.

Predictions

Although lecture demonstrations and computer simulations were common in lectures, students were rarely required to make predictions about the outcomes of events. One of the exceptions was in the second year lectures using the CUPS (Consortium for Upper-level Physics Software) simulations (see Hiller, Johnston and Styer, 1995; Johnston, 1996). Students were asked to predict what would happen to a wave packet at a boundary or what affect decreasing the depth of a potential well would have on the bound energy states. According to a study by Crouch et al., (2004) students who witness demonstrations without being asked to make a prediction perform as well on tests as those who don't see the demonstration at all. Therefore, to make the most efficient use of these presentations, students must be asked to predict. Sometimes this is inapplicable due to the nature of the activity, but often with a bit of ingenuity a prediction could be included.

Enabling technologies

Innovative use of technology in the classroom was one of the most significant findings of this study as it most clearly exemplifies the departure from traditional lecture methods.

Lecture slides

PowerPoint presentations were the basis for all lectures attended and students were given slide handouts in lieu of taking notes. Lecturers commonly expressed the belief that students should not be required to take notes to promote lecture learning. Support for this notion exists in literature; "I have to concentrate on what he [the lecturer] says. I don't have time to take notes," (Badger, 2001, p.6). The most common reason students cite for note taking is to be able to recall the lecture (Badger, 2001), but if the slide handouts fulfil this function, note taking may be superfluous. This philosophy was beneficial for students who paid more attention to the lecture but it often allowed disinterested students to "tune out," and rely on the handouts to contain the salient information. Literature also exists supporting the practice of note taking (Ryan, 2001). The main advantage of PowerPoint was that it allowed lecturers to integrate complicated graphics into the lecture and display important information in large, legible writing.

Lecture demonstrations

Despite the traditional difficulty of demonstrating quantum mechanics concepts in class, several experiments were conducted in each of the introductory courses, often with the use of real time technology. In the technological lectures, use of a spectrometer and real-time software allowed for the illustration of the emission spectra of a blackbody with comparisons to a hydrogen lamp and fluorescent lights. In the environmental class, Planck's constant was determined in an Excel spreadsheet using data collected in lecture from a desktop photoelectric experiment. Simple but effective demonstrations were also performed, notably Bragg electron scattering, and superconducting levitation. The latter inspired extensive interest from the students both during and after class.

Simulations

Where desktop demonstrations weren't available to illustrate quantum behaviour, visualization software was used. In the second year lectures, the CUPS program depicted the behaviour of wave functions at barriers and in potential wells. This program was frequently used to explain the counterintuitive concepts of interference and tunnelling, and decreased the dependence on math to describe quantum systems. With the use of simulations, parameters could be changed and their impact on the outcome determined.

Interest agents

Not all of the technologies used in class were of a technical nature; in fact, some of the most interesting, from a student point of view, had little physics content. In the second year class, a clip from an old James Bond film was shown to demonstrate lasers. The actual characteristics and physical structure of a laser were compared against the Hollywood depiction. Students were certainly captivated by this teaching segment. In the environmental lectures, Nobel laureate Richard Feynman's song "Orange Juice," was played to give students an idea of the scientist's eccentric nature.

Visual aids

Overall, the use of technology in the first and second year classes helped create learning environments employing visual aids for over half the total teaching time, as shown in Figure 5. It was reported by Fletcher (2004) that both students and teachers believe the lack of visualization in quantum mechanics to be at the heart of its educational challenge. The second year class showed the highest frequency of effective visuals, followed by the environmental, technological and advanced first year classes. This is likely because of the CUPS simulation program in the second year classes.

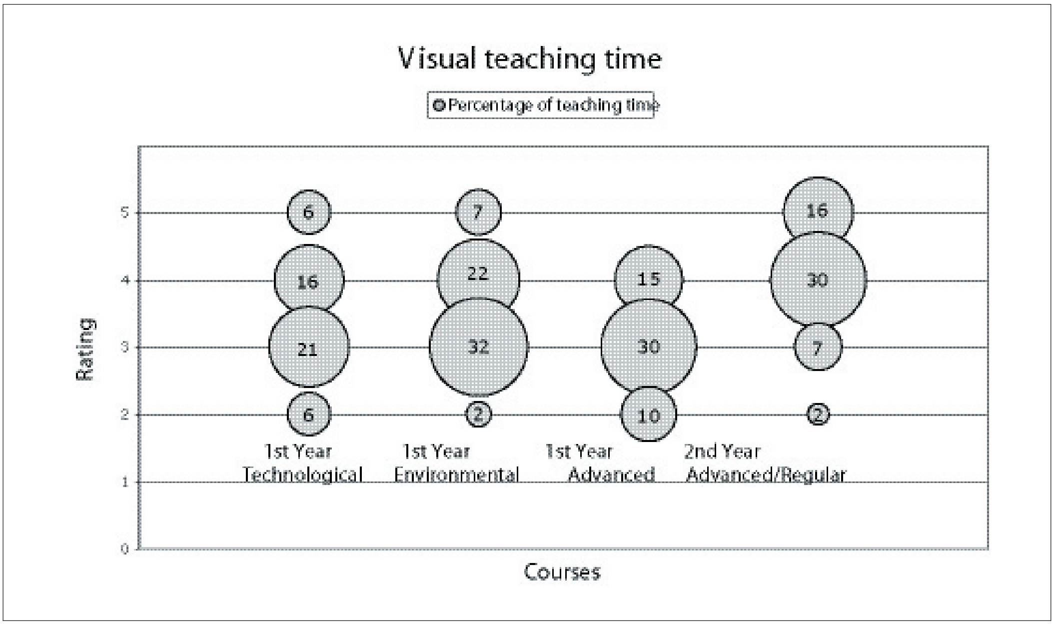

Figure 5. Use of visual aids; numbers in bubbles indicate the percentage of total teaching time

Mathematics

All lecturers handled the intrinsically mathematical nature of quantum mechanics in unique ways. In the environmental first year class, assignment-type questions were solved in their entirety on a PowerPoint slide. In the technological class, some extensive math problems were solved in detail by the lecturer on the chalkboard but were not included in the lecture handouts. Students of the advanced class were asked to solve problems on their own during class time. The lecturer would give suggestions, but leave the students to perform mathematical operations individually. He would then ask students to reveal how they proceeded from one step to the next. Mathematics was limited in second year lectures as there was a much stronger emphasis on concepts than problem solving. Computational methods were explained in class and therefore the numerical solver was used in many lecture problems. Mathematics was explicitly the language of relativistic quantum mechanics and derivations constituted the vast majority of lecture time.

Course material - history

All classes approached quantum mechanics in the same way: with a historical narrative detailing the failings of classical mechanics and outlining the ways in which quantum mechanics solves its problems. This history was covered, to greater or lesser degrees, in all first year streams, and again briefly in second year. This is useful in that it introduces all students to the problems of quantum mechanics in a fairly intriguing way and primes the prior knowledge of students in these areas. Building on activated prior knowledge is a key component to many learning theories, however new knowledge must also be presented to promote interest (Merrill, 2002). Across the first year streams and even into the second year classes the curriculum is fairly similar. In second year, a wider range of topics are investigated and in greater depth with the use of computational methods.

Future investigation

This study provides an important starting point for an array of possible future investigations. In order to further develop the teaching of physics at this university, interviews with students and lecturers should be undertaken to better understand their opinions of lectures. Hopefully this can begin the dialogue that was absent in the observed classes. In addition, a system of evaluation that effectively determines learning gains needs to be developed in order to discriminate between teaching methods. Exams, and to a greater extent, the quantum concept inventory (Falk, 2004) will play a role in this evaluation.

This study will be continued in the autumn 2005 semester to obtain a complete snapshot of quantum mechanics teaching in the School of Physics at the University of Sydney.

Conclusions

Although all classes audited followed the form of the traditional lecture, the assertion that content and teaching method have remained unchanged for seventy years is patently false. With the exception of RQM, all courses employ visual aids for the majority of class time, ranging in complexity from pictures and diagrams to dynamic simulations and excerpts from commercial films. These integrated technologies are not being exploited to their full potential, however, as interactivity remains low in all classes. Predictions and more discussions must be solicited from students to increase the learning impact of technological interventions and to engage students with the physics content. Lecturers should continue to integrate enabling technologies into their lessons, keeping in mind the vital role of implementation strategies in promoting learning. In addition, an appreciation for how other lecturers approach the mathematics related to the subject could lead to more diverse teaching strategies appealing to a wider range of students. Further qualitative studies are necessary to address these issues and develop the means to quantitatively evaluate teaching and learning progress.

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