Developing a prototype conceptual survey in fundamental quantum physics

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Abstract: *In this paper, we describe research results of the performance of students in Thailand on a series of open-ended questions concerning some fundamental concepts in quantum physics. The questions were taken from the University of Maryland Tutorial (Redish, Steinber and Wieman 2006) and asked students to concentrate on the pattern appearing on the screen after electrons and light pass through a double slit. Some common conceptual difficulties were identified and analyzed. The findings from this study are being used to develop a conceptual survey in quantum physics. In this paper, we describe the development of this survey. It will be used in the first instance to compare Thai and Australian second year students.*

Introduction

Quantum physics has long been a topic of interest, not only to physicists who puzzle over quantum interpretations of physical phenomena, but also to physics teachers who are concerned when students do not grasp fundamental quantum ideas covered in class (McDermott and Redish 1999). Understanding concepts is not easy for students as the concepts are usually described in terms of complex mathematical models. Therefore, one way to assess students' learning of the subject is to develop a *conceptual survey* (Hake 1998).

A number of conceptual surveys covering various physics domains have been developed in recent years — such as the Force Concept Inventory (Hestenes, Wells and Swackhammer 1992), the Force and Motion Concept Evaluation (Thornton and Sokoloff 1998), the Heat and Temperature Concept Evaluation (Laws 2006), the Electricity and Magnetism Concept Survey (Maloney, O'Kuma Hieggelke, and Heuvelen 2001), and the Quantum Mechanics Visualization Instrument (Cataloglu and Robinett 2002). These surveys have increasingly been used by a wide range of physics teachers in three significant ways":

- they have offered teachers a way to quickly detect any particular alternative conceptions their students' hold;
- they have allowed teachers to determine whether instruction has had much effect on students' conceptual understanding at the end of a course; and
- they have been used as a means for evaluating gains in students' conceptual understanding across a variety of teaching methodologies and course structures (Davis 1997).

McDermott and Redish (1999) have shown that less than one percent of physics education research is on issues of students' understanding of quantum physics. Thus, the objective of our project is to develop a conceptual survey, called Quantum Physics Conceptual Survey (QPCS). It will tentatively be used in the first instance to compare Thai and Australian physics students' understanding of fundamental quantum concepts at the start of their first serious course on quantum physics.

The objective of this paper is to describe some of the processes involved in developing the QPCS so that it is a valid instrument. Reliability checks will be carried out in the next phase of the project.

Methodology

In order to uncover which topics are most important in quantum physics, we began by analysing the syllabi from eight universities in Thailand: Chiang Mai University, Chulalongkorn University, Khon Kaen University, Mahasarakam University, Mahidol University, Prince of Songkla University, Rajamongala University of Technology, and Ubon Rajathanee University. The analysis was in these steps:

- we identified the topics taught across the universities in introductory quantum physics courses;
- we counted the frequency of appearance of these topics in the syllabi;
- we found we could categorize the concepts into four main areas — the end of classical physics, quantization, uncertainty and the wave function; and
- we consulted experts from the Department of Physics at Mahidol University to consider the significance of these areas to the teaching and learning of quantum physics. They indicated that quantization and uncertainty were the central ideas of introductory quantum physics.

Upon perusal of all the data, we decided to focus on one fundamental construct which underpins both quantization and uncertainty, namely *wave particle duality*. In 2005, students were asked to answer a series of open-ended questions concerning wave particle duality, and that survey is the focus of this paper. The open-ended questions were taken from the *University of Maryland Tutorial: Wave Particle Duality* (Redish et al. 2006). (This tutorial explicitly concentrates on the pattern appearing on the screen after electrons and light pass through a double slit.) Eight physics education students who graduated in the bachelor degree in physics at Mahidol University completed our survey and wrote extensive answers.

The method of data analysis used in this study was adapted from *thematic analysis* (Fereday and Muir-Cochrane 2006) — a technique that involves the identification of themes from students' responses. The data collected was analysed specifically in the following way:

- responses were carefully read in order to identify common quantum physics concepts for each question;
- students' incorrect responses from all the questions were paraphrased, coded and grouped; and
- finally through an iterative process, the groups were clarified and refined, and themes identified.

The way the themes were extracted is demonstrated in the next section.

Throughout this study we have compared and contrasted new data with the substantial data collected in the previous phases, and also consulted with physics education researchers and the literature. The objective of this iterative process is to develop a set of survey questions which are potentially useful in a broad cross section of introductory quantum physics courses.

Analysis of students' responses concerning wave particle duality

We divide this section into three main parts: (a) identifying common quantum physics concepts and how they emerge in student responses; (b) coding and grouping students' responses; and (c) extracting themes.

(a) Identifying common quantum physics concepts and how they emerge in student responses
In this step, we focused on what the students wrote (or drew) with no reference to the correctness or appropriateness of their response. This is an adaptation of the technique of *open coding* (Strauss and Corbin 1998). Table 1 shows two of the six questions and the percentages of the eight students who gave particular responses to these two questions.

Table 1. A sample of questions from the Tutorial: Wave Particle Duality, and common concepts identified in students' responses to these questions

Question: Suppose the slit is covered so that light can only pass through the right slit. Describe how, if at all, the appearance of the screen would change. Explain you reasoning. **Responses:** • 17% say that no pattern will be seen on the screen because the slit's width is less than the wavelength of light. • 33% say that a single fringe pattern will be seen on the screen because light passes through only one slit. With one slit light cannot interfere with itself. • 50% say that a multiple fringe pattern will appear on the screen, because light behaves like a wave.
Question: Suppose one of the slits is covered so that electrons can only pass through the uncovered slit**.** Describe how, if at all, the appearance of the screen would change. Explain your reasoning. **Responses:** • 17% say that you will see one bright band on the screen behind the slit. • 33% say that you cannot see any pattern, but you will see spots of electrons spread all over the screen. • 50% say that you will still see a multiple fringe pattern but the biggest fringe will move from the center to behind the uncovered slit.

Table 2. Categories and representative examples of students' incorrect responses collected by looking across all questions

Category 1: waves and particles • When a linear water wave passes through a slit, a multiple fringe pattern appears on the other side of the slit. In the same way, because of the wave particle duality property of electrons, when electrons pass through a slit, a multiple fringe pattern appears. **Category 2:** de Broglie wavelength • If the de Broglie wavelength of light is less than the width of the slit, then the same pattern will appear for a single slit as for a double slit. **Category 3:** single and double slit experiment • No matter whether an electron passes through a single or double slit, you will see the same multiple fringe pattern because in the quantum world electrons behave like light. **Category 4 :** uncertainty principle • The position of a photon of light on the photographic film can be predicted by the uncertainty principle. • You cannot tell the position of a photon on the photographic film because it obeys the uncertainty principle. **Category 5 :** wave particle paradox • A wave can act like a particle, and a particle can act like a wave. It means you cannot tell the exact status of the electron or light at that time. • Electrons or light act like waves and particles at the same time. You cannot distinguish these properties.

(b) Coding and grouping students' responses

Since all questions were based on wave particle duality, it was possible to look at all questions (the complete version of Table 1) and group students' responses into categories. This is an adaptation of *axial coding* (Strauss and Corbin 1998). As the purpose of our project is to develop a conceptual survey, we only considered students' incorrect responses when coding for misconceptions and grouping into categories. The grouping and subsequent titling of categories was informed by the manner in which quantum physics is presented in text books, our collective teaching experience, physics education research literature and topics that appeared in course syllabi across the eight Thai universities sampled in the initial stages of this project. Table 2 summarises the categories thus extracted. We note that categories are not mutually exclusive as there is substantial overlap between the concepts.

(c) Extracting themes

In this step, the categories presented in Table 2 are collapsed into *themes*. The issues with this methodology of extracting themes are as follows. How do we know that the themes emerge? How do we know that the themes are authentic and valid? We have attempted to address these issues as follows:

- as individual themes were extracted, all data were reviewed to confirm that the themes genuinely reflected the contents of the students' responses;
- the themes were compared and contrasted during discussions with the Thai researchers (because the student's responses were in the Thai language);
- we cross checked with experts who have experience with teaching quantum physics and who have first hand experience of students' difficulties in learning quantum physics; and
- we cross checked with the literature on students' understandings of quantum physics.

The themes, and how the categories shown in Table 2 were collapsed, are presented in Table 3.

Table 3. Themes

Themes	Category
Theme 1: Waves and particles	1, 5
Theme 2: de Broglie wavelength	2
Theme 3: Analysis of a double slit experiment	3
Theme 4: Uncertainty principle	4

During our checks for authenticity and validity we found that the themes in Table 3 reflect content areas taught in all introductory quantum physics courses. We also found that the student difficulties shown in Table 2 appear in questions in the syllabi of the eight Thai universities and in text books. Consequently, even though only eight students completed our survey, the surrounding data confirms the authenticity of the themes which emerges from an introductory physics context.

Identifying an additional theme – the photoelectric effect

The next task was to develop a prototype conceptual survey. However, prior to commencing the survey we decided to reflect on whether the themes were adequate. In discussions with physics education experts and in view of the data collected so far, we decided to include a theme 0 on the photoelectric effect. The new theme and why it is theme 0 are justified by the following:

- in the essentially all introductory quantum physics courses, the photoelectric effect is taught first;
- historically, the photoelectric effect introduced the concept of light as a photon; and
- the photoelectric effect is easily demonstrated experimentally.

As it turned out, during 2004, a 30 question Photoelectric Effect Conceptual Evaluation (PECE) test had been developed and administered to 32 students at Mahidol University (Wuttiprom, Chitaree, and Soankwan 2005). As a result, using data from examination scripts, interviews and responses to this survey, a set of seven themes relating specifically to the photoelectric effect were identified. Since the aim of the current project is to develop an inventory covering five themes, a reduced version of the PECE is necessary for the QPCS.

Developing a prototype conceptual inventory

The aim of this project is to use the themes to develop a prototype conceptual survey, a set of multiple-choice questions probing the concepts underlying the themes. We now describe how the questions were generated.

We did a literature search on the themes and found two conceptual inventories on quantum physics—Quantum Mechanics Visualization Instrument (QMVI) (Robinett 2005) and Quantum Mechanics Conceptual Survey (QMCS) (McKagan and Wieman 2006). The QMVI questions have not been used because it contains questions which are at an advanced rather than introductory level. However, the nature of these questions has informed the way in which we have framed our questions. From the QMCS we have adapted two questions for theme 4 (the uncertainty principle). The nature of other inventories such as the FCI and FMCE has also influenced our questions which were generated as follows:

- The questions were developed based on students' responses to the *Tutorial: Wave Particle Duality*, text books (such as Hewitt 2005; Halliday, Robert and Walker 1997; Knight 2003a, 2003b), literature (such as Fletcher and Johnston 1999), web sites (such as McKagan and Wieman 2006) and data collected to date.
- The questions begin with a question stem, followed by alternatives based on students' responses.
- All of the questions were reviewed and commented on by experts who have experience with teaching quantum physics and are involved in the physics education community. Postgraduate and undergraduate students also provided feedback on the questions. In particular, we considered the appropriateness of the questions, relevance to introductory quantum physics, ambiguity in question wording and redundancies or other structural difficulties.
- Further modifications were made based on their recommendations as we went through several iterations of the survey.

The first draft of our conceptual survey, QPCS comprises 20 questions covering the five themes as shown in table 4. The complete (draft) survey can be viewed at:
http://www.physics.usyd.edu.au/super/QuantumSurvey/

Table 4. Number of questions for each theme of the QPCS

Final themes of the QPCS	Questions on the QPCS
Theme 0: Photoelectric effect	1, 2, 3, 4
Theme 1: Waves and particles	5, 6, 7, 8
Theme 2: de Broglie wavelength	9, 10, 11
Theme 3: Analysis of a double slit experiment	12, 13, 14, 15, 16
Theme 4: Uncertainty principle	17, 18, 19, 20

The QPCS is now being trailed with Senior and Honours students. Further trials with second year students are envisaged prior to full implementation with the intended audiences of introductory physics students.

Discussion

We have used extensive data and iterative feedback loops to establish the overall validity of the QPCS. The major limitation of eight student responses has been counteracted through consistent referral to other data sources of which we have a substantial amount. In the end we have a QPCS which is a solid start to a survey that is valid and ready for reliability checks.

Acknowledgement

This project could not have been carried out without support from SUPER (Sydney University Physics Education Research), PENThai (Physics Education Network of Thailand) and Institute for Innovation and Development of Learning Process, Thailand. The authors gratefully acknowledge funding provided by the Faculty of Science, Ubon Rajathanee University, Thailand.

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