

**RESEARCH  
ON  
TEACHING AND LEARNING  
QUANTUM MECHANICS**

**Papers presented at the annual meeting  
National Association for Research in Science Teaching  
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## INTRODUCTION

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*"I believe that any lover of nature should study quantum mechanics -- not its mathematics but its ideas."*

*--Douglas Hofstadter*

Until recently the main purpose for students other than physicists and chemists to study quantum mechanics was for a better appreciation of its influence on modern thought. Now people who will be making decisions about business and technology need an understanding of modern physics. Recent developments in miniaturization of electronics and nanotechnology bring into the business and engineering world devices that can be appreciated only through the principles of quantum mechanics. Likewise, in the past few years experiments have directly analyzed some of the fundamental paradoxes in quantum mechanics. Thus, an understanding of quantum physics beyond the level of a coffee table book is needed for the well-informed citizens and all types of professional in the 21st Century.

As the need for students to understand quantum phenomena increases, so does our need to understand the learning process for these abstract and counterintuitive concepts. In recent years research in student understanding of quantum science has increased greatly. Some researchers have investigated traditional methods of learning, while others have developed and assessed techniques such as hands-on experiments and interactive computer visualizations. (Generally, hands-on experiments would not be considered non-traditional. However, the usual method of teaching quantum science is with little or no experimentation.) Over the past ten years a small number of researchers have been involved in these efforts. Their work is now showing some good results that can help us understand how to teach quantum mechanics and, perhaps, other abstract scientific concepts.

Most of the studies have concentrated on conceptual understanding of quantum science. The primary question is, Can students learn the ideas of quantum mechanics even if they are not familiar with the advanced mathematics that forms the basis of the topic? By studying the learning process researchers have been able to determine some techniques are effect and some that are not. Modifications in learning materials and suggestions for improvements in traditional approaches have been created as a result of these studies. At the 1999 Annual Meeting of the National Association for Research in Science Teaching seven different groups who are addressing the learning of quantum mechanics from different perspectives present their findings. Two of the groups have relied heavily on interactive computer visualization and other minds-on activities. One group has assessed a learning technique that uses a commercial computer problem solving technique has a foundation. The other three have relied primarily on more traditional approaches to learning/teaching although they have moved beyond the lecture and textbook. In all cases research data have been collected about the process. One additional group which was unable to present at NARST is represented by a short paper here.

As can be seen from these paper, the research of each group is closely related to the others. At the same time each group's approach is sufficiently different that their research complements the others. Further, different groups have focused on different groups of students. The students include university-bound students in science classes, physical science students in both high school and college and physics majors at universities. Thus, the NARST session and these papers provide meeting participants and readers with a broad view of the research and development concerning the learning of quantum science.

# CONCEPTUAL UNDERSTANDING OF QUANTUM MECHANICS AFTER USING HANDS-ON AND VISUALIZATION INSTRUCTIONAL MATERIALS\*

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## ABSTRACT

Materials developed by the Visual Quantum Mechanics project teach some basic ideas of quantum mechanics to high school and introductory college students by integrating hands-on activities and computer visualization. During field tests of the materials we obtained data concerning student understanding of some quantum concepts including potential energy diagrams, energy levels and spectra in atoms, energy bands in solids, wave functions and probability, and quantum tunneling. Data were collected from written responses of students structured interviews and a concept map. While a few misconceptions persist, the overall results indicate that students seem to have acquired a good general understanding of some important concepts that are usually not taught at the introductory level.

## INTRODUCTION

The physics curriculum in most high schools and introductory college courses contains, at best, a passing reference to 20<sup>th</sup> Century physics. Hence, students often do not see the topics of interest to contemporary physicists, the contribution of physics to modern thought or the connection between the physics they learn and modern technology. This lack of exposure can result in a lack of interest in physics.

The Visual Quantum Mechanics (VQM) project makes quantum mechanics and related topics accessible to high-school and introductory college students by minimizing the use of mathematics in its presentation. Instead, hands-on activities, computer visualizations, and written worksheets are integrated in an activity-based environment. (Zollman, 1999) We utilize the Learning Cycle instructional model (Karplus, 1974). Students begin by exploring a modern device – Light Emitting Diode (LED). They realize that they cannot explain the device's operation by using any existing metal models and therefore must construct new models to explain their observations. Subsequently, they apply these mental models in a different situation.

## INSTRUCTIONAL MATERIALS

The curricular materials are organized into instructional units that can each be completed in about 6-12 hours of classroom instruction. The units can be integrated into an existing curriculum since the prerequisites are topics covered in a standard physics curriculum. The instructional units are:

*Solids & Light* – Students use LEDs and gas lamps to understand the concepts of energy levels and energy bands, transitions, and spectra.

*Luminescence: It's Cool Light* – Students utilize fluorescent and phosphorescent materials to understand the effects of impurities on energy bands and on the creation of metastable states. Some overlap exists between this unit and the *Solids & Light* unit.

*The Waves of Matter* – Students explore the creation of a model to explain the discrete energy states. Applying aspects of the model to the Star Trek transporter and the electron microscope students learn about the wave nature of particles, wave functions, Schrödinger equation (qualitatively) and wave packets.

*Seeing the Very Small: Quantum Tunneling* – Using a simulation of the Scanning Tunneling Microscope (STM) as the pedagogical vehicle students learn about quantum tunneling and the factors that influence it.

Early in project we realized the need for two units that would address lacunae in a traditional curriculum. *Potential Energy Diagrams* – These diagrams are powerful representation that is utilized in quantum mechanics. We use magnets placed on a Pasco dynamics and along the track or Hot Wheels cars to create and explore potential energy diagrams of different shapes. (Jolly, *et al.* 1998)

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*Making Waves* – This unit treats classical waves and introduces just those concepts that are needed for the study of *The Matter of Waves* unit.

Prior to the present study all VQM units were field-tested at numerous high schools and colleges in several states. Revisions had been completed based on the field tests.

## PROCEDURES FOR THE STUDY

### Students

The students were enrolled in Contemporary Physics at Kansas State University. This course is offered for students who are planning to be secondary science or mathematics teachers, but have an area of concentration different from physics. If this one-semester course is taken after they have completed one year of introductory physics, it meets the requirement for the students to become certified to teach physics. In addition, some students enroll in the course to fulfill a general education requirement in the physical sciences. These students have completed a one-semester physics course for non-science students. Thus, all 17 students in this class during the Spring Semester, 1998, had taken at least one semester of introductory physics prior to enrolling in Contemporary Physics. However, the level of reasoning and mathematical skill in the students' previous physics course varied greatly. Contemporary Physics was taught in manner which integrated lecture, discussion, hands-on experiments and interactive computer activities. The students worked in small groups with the hands-on and computers activities

### Propose of the study

In this study we examined the level of understanding the students gained from their conceptual study of quantum phenomena. We attempted to ascertain what level of understanding the students reached during their semester of study and what areas of quantum physics provided the most conceptual difficult

### Evaluation Instruments

No established instrument for measuring students' conceptual understanding in quantum mechanics or modern physics, similar to those that exist in mechanics was available. Further, since this material is not usually taught in the traditional format, we could not compare our results in student understanding with those from alternative materials or approaches. Thus, results are based on student responses to questions on activity worksheets, examinations, interviews conductor by one of us (NSR), and a concept map which the students drew at the end of the semester.

## RESULTS

Because of the small number of students in the study and the type of data available, we did not perform a statistical analysis on the data. Instead, we analyzed the various data sources to uncover trends in the students' thinking and successes and difficulties in the conceptual understanding.

### Representation of an Atom

We have assiduously avoided the use of the Bohr model of the atom in all our representations. Rather we have focused on the energy diagram representation. This representation is introduced to students in the *Solids & Light* unit and expanded in the *Luminescence* unit, after they have observed the spectra of gases and studied potential energy diagrams of a cart on the track.

We found that most students do not relinquish the previously learned planetary model of the atom. There is also considerable confusion in students' minds about whether the energy level represents the total energy or the potential energy of the electron. This confusion is reflected primarily in students' inability to correctly determine the binding energy of an electron in a particular energy level.

In using the potential energy diagram model of the atom, most students mistake the vertical axis in the diagram as representing the physical distance of the corresponding energy level from the nucleus, which they believe is located at the center of the bottom of the rectangular potential well. In spite of these misconceptions, however, they are correctly able to predict the dependence of the shape (depth and width) of the potential energy diagram on the nuclear charge

### Energy Levels & Spectra

Students construct the energy level model of an atom after observing the spectra of gases in the *Solids & Light* unit. At this time in their studies, the students are observing spectra as an empirical result. While they may draw an atom as a Bohr model, almost none of them remember its connection to the spectrum of hydrogen. Essentially, none of them have learned about wave functions, probabilities or applied standing waves to bound states. Using their knowledge that light is a form of energy and that the atom emits only

specific energies of light, students come to understand that the atom can have only certain values of energy -- discrete energy levels. Students are, thus, able to use empirical data to grasp one of the fundamental concepts of quantum physics.

Part of the study of energy levels requires the students to construct energy level diagrams to explain the transitions in the atom. In the initial stages of our development we observed that students would assign identical energies to a spectral line to an energy level. For example, if a gas had 3 spectral lines of energies 1.8eV, 2.1eV and 3.0eV, students would construct an energy diagram that had the levels at each of these energy values. This model is incorrect, since each spectral line is related to a transition between energy levels and not the energy levels themselves.

We designed the Gas Spectroscopy Lab program to enable students to overcome this difficulty in understanding. (Rebello, *et al.* 1998) In the program students construct a trial spectrum to match a given gas spectrum. The trial spectrum depends upon the energy differences and transitions created by the student. The program confronts directly the issue of whether the energy of the light is related to the energy levels or energy differences. After using this program almost all students are able to overcome their earlier learning difficulty. Many students draw an energy level diagram with all transitions starting at one energy level and changing to different energy levels with the energy differences corresponding to the energies of the spectral lines. For hydrogen, of course, this energy level diagram is inaccurate because the visible lines are created when electrons move from various states to the  $n=2$  state. However, the students do not have that information available unless they remember from a previous course. When asked explicitly whether their energy level diagram is the only possible answer, most students reply that other energy level diagrams are also acceptable, and that it is the difference between the energy levels that is crucial rather than the energy values themselves. We believe that students realize this because they are specifically asked to compare the energy level diagram of their group with those of other groups in class.

In an interview, students were asked to explain whether the fact that a given spectrum could be constructed by a non-unique set of energy levels contradicted the fact that this spectrum was unique to a given gas. Most students do not see a contradiction between these two ideas.

### **Energy Bands in Solids**

Most students can “discover” the energy band model for a solid when they are asked to create an acceptable set of energy levels to explain the continuous spectrum of an LED. They are also able to predict the spectrum and turn-on voltage of an LED given its energy band diagram. Some students, however, relate the turn-on voltage to the energy gap rather than the energy difference between the P and N sides of the LED. (Rebello, Ravipati., Zollman & Escalada, 1997)

To see how well the students had understood energy bands and gaps, we asked them to apply these concepts to a device which can detect infrared light. This device is a small solid strip which can be purchased at electronics stores such as Radio Shack. When infrared light is incident on the strip it emits visible light. Thus, the solid is converting relatively low energy light (IR) into higher energy visible light. Before being asked to explain the device in terms of energy bands and gaps, the students completed a series of experiments which would help them build a model. Most students had difficulty creating a model of an infrared detector using energy levels, bands, and transitions. However, we should not be surprised. In workshops involving research physicists we have observed some of the same difficulties.

### **Wave Functions & Wave Packets**

The wave nature of particles is “discovered” by students when they compare an electron diffraction pattern (real and computer simulated) with that of light from Young’s double slit experiment. By slowing down the formation of a computer simulated electron diffraction pattern in a simulation and asking students to predict where an electron (represented by a bright spot) will be visible on the screen, we have them construct the probabilistic model of an electron. The wave function is then presented as a graphical representation of the electron, which when squared gives the probability density function.

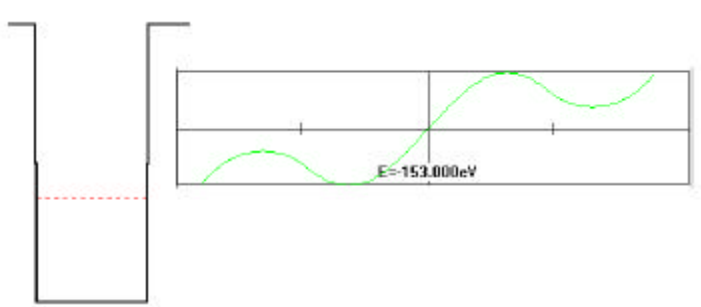
Students can sketch the probability density function from the wave function and vice-versa, but do not completely understand the relationship between probability and probability density.

Although most students are clear that the wave function is not the path of the electron, when asked to sketch the wave function of an electron beam in a tube (experimental set up for the e/m experiment), most of them sketch a static sinusoidal wave. A few students believe that this picture is a snapshot at a given instant of time, and would travel as the electron traveled down the tube.

In *The Waves of Matter* unit, students learn the relationship between the wave function and the potential energy diagram. They are also expected to learn the reason why the wave function model concludes that

only certain energies are allowed in an atom. Without learning the mathematical formalism of the Schrödinger equation, students are introduced to various scenarios that result in sinusoidal and decreasing wave functions. Students are quite successful in applying the criteria for sketching wave functions for different shapes of potential energy diagrams. When students observe the diverging wave functions in the *Bound States* program (Figure 1), they are unable to relate these to the disallowed energy levels in an atom.

Students are introduced to wave packets created by adding waves functions each representing a particle with a different momentum. The Uncertainty Principle is introduced by demonstrating that a larger spread in momentum values results in a more compressed spatial wave packet. Students also use a simulation showing the time evolution of a spatial wave packet. Most students, however, are unable to apply the Uncertainty Principle to relate the increasing spatial spread to an increasing certainty in the momentum of the particle. On the positive side these students do not identify the Heisenberg Principle with a difficulty in measurement or with momentum transfer of from a photon to an electron. This teaching technique seems to help them understand that the Uncertainty Principle arises because of the wave behavior of matter. In this respect they have a better understanding than many physics students.



**FIGURE 1: Bound States Program demonstrates a diverging wave function for a disallowed energy level.**

### Quantum Tunneling

Students learn about quantum tunneling by exploring a computer simulation of a scanning tunneling microscope (STM). (Rebello, Sushenko & Zollman. 1997) The STM uses quantum tunneling to collect information about a surface without physical contact with it. Tunneling is a natural consequence of correctly applying the criteria for sketching wave function for a barrier. Given the tunneling probability of an electron, most students are successfully able to sketch the wave function, including the relative amplitudes of the oscillating wave functions on both sides of the barrier. They are also able to predict correctly how this wave function would change if the width or energy of the potential energy barrier were changed. Using the *STM Simulator* program students learn these relationships in the context of the position and voltage of the probe tip of an STM.

While students successfully apply the concepts of tunneling to an STM, they are unable to extend these concepts to the macroscopic world. When asked to explain why the cart in the *Potential Energy Diagrams* unit could not tunnel through the barrier, most of them incorrectly reason that the cart did not tunnel because the total energy of the cart is less than the potential energy of the barrier. That this in fact, is a necessary condition for tunneling alludes most students. A few students, however, correctly respond that the cart does not tunnel because its de Broglie wavelength is much smaller than thickness of the barrier.

### Overall Concept Map

At the end of the semester, each student was asked to draw a concept map relating various concepts that they had learned in the course. 10 students (Group I) were asked to create a list of concepts by themselves. The remaining 7 students (Group II) were provided with a list of over 50 concepts/words. Both groups were provided with some written instructions and an example of a concept map.

The concepts can be grouped into 12 concept clusters. In general the concept cluster maps from both groups are fragmented with most connections shown only between topics that are in the same instructional unit. Fragmentation was more severe in Group II, although the maps in that group better matched the instructor's expectations. Most maps did not show a central theme. Connections between "Energy Levels" and "Wave Functions", or "Schrödinger Equation" and "Wave Functions" were absent in most maps. There is no correlation between the richness of the concept map drawn by a student and her/his performance on related exam questions.

## CONCLUSIONS

The goal of the Visual Quantum Mechanics project is to enable students who have little science or mathematical background. The emphasis is placed on conceptual learning and visualization in place of mathematical rigor. In the present study we attempted to ascertain which concepts have been made understandable to a group of students with a broad range of previous experiences in science and mathematics. The analysis at present is preliminary, so we have not yet attempted to correlate the students' level of understanding with their previous experience. Instead, we have looked for overall patterns and trends. In doing so, we have identified those concepts which seem to cause the students more difficulty than others have in reaching an acceptable level of understanding.

Overall, we observe that hands-on activities, computer visualization programs and constructivist pedagogy enable our students to build mental models which explain their observations. For example, the empirical approach seems to be quite effective in helping students come to a conclusion about the discrete nature of energy levels in atoms. Likewise, students are able to move readily from the energy levels in gases to the energy bands and gaps in solids – again by taking an empirical approach. They are also able to understand the limitations on their energy models and when more than one model is possible. Many of the basic features of wave functions also became understood by most of the students. In particular, the students were able to grasp the empirical reason for the necessity for matter waves and wave functions after they had explored the interference effects of light and of electrons. They could also relate probability to wave functions and understand the relationship between standing waves and the discrete energy levels in atoms. Thus, many of the basics of quantum physics seem to be able to be understood at a qualitative level by these students.

At the same time the subjects in this study had difficulty with some concepts which the authors think are presented equally well. In particular, expanding the energy band and gap model to a device that displays a rather perplexing behavior (absorbing low energy light and emitting higher energy light) was beyond the reach of many students. Likewise the reason why quantum tunneling should be considered surprising (from the classical physics viewpoint) was not fully appreciated. Others and we have observed difficulties with some of these same issues in students with much stronger physics background. (Johnston, Crawford, & Fletcher, 1998; Petri & Niedderer, 1998; Euler, *et al*, 1999)

This preliminary study provides us with information about the relative difficulty in helping students learn abstract concepts through hands-on activities and computer visualizations. It also can point the way to ways in which we can improve the learning of quantum physics for more advanced students. Presumably the concepts which gave our students the most difficulty at the conceptual level are those that will require the greatest effort in teaching and learning for students who are attempting to understand both the conceptual and mathematical aspects of quantum physics. Thus, we intend to build on this foundation with future studies of student learning of quantum phenomena at all levels.

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# HOW COMPUTER SIMULATIONS AFFECT HIGH SCHOOL STUDENTS' REASONING IN QUANTUM CHEMISTRY

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## INTRODUCTION

The focus of this paper is on alternative conceptions in quantum chemistry held by honors students in high school. The study investigates how an intervention using interactive simulations in quantum chemistry alters student understanding. The researcher compares the effects of traditional methods of instruction, i.e. lecture/lab, against the use of discovery via computer simulation on the alternative conceptions of students in quantum chemistry. The researcher observed chemistry students in four high schools prior to, during, and after their use of the Quantum Science Across Disciplines (QSAD) materials which were developed at Boston University, through a National Science Foundation Grant.

Student concept maps, and interviews were used to find the baseline misconceptions of the student cohort regarding understanding of quantum science in chemistry. The high school students constructed concept maps and were interviewed after the intervention. The student information including concept maps were coded, and compared to the information obtained from students that exit a class using a more traditional approach. As a result of the intervention, high school chemistry students shift to a paradigm that uses the atomic or molecular explanations of quantum chemistry to explain macroscopic phenomena like polarity, and solubility.

Students in the experimental classes were required to investigate quantum phenomena using the simulations and then make presentations. Classmates were encouraged to ask probing questions. Several answers included molecular explanations using quantum chemistry to explain measurable phenomena. A Student began to use quantum science when explaining acid strength.

"The charge density of the molecule shows the degree of polarity in HF. Notice that the charge density shifts in favor of the fluorine side of the molecule. The electron cloud still surrounds both nuclei and therefore indicates that the hydrogen probably does not dissociate as easily as other acids."

As a final example a student trying to explain bond length stated,

"You need to calculate the superposition of the wave functions from the nuclei. If the amplitudes cancel then bonding is not favored, but when constructive interference is observed, then a charge density will result when you square the amplitude."

The teachers of the experimental and control classes used similar methods of assessment, while the teacher of the experimental classes used learning logs (Audet, 1996) during the units. For the learning logs, groups of three students were required by their teacher to achieve consensus and write a response to selected issues within quantum chemistry.

## METHOD

### Participating Students

For this report students were chosen from the Honors Chemistry classes of one of the high schools in suburban Boston. Two classes of twenty students each, and taught by teacher "A", underwent the intervention, while one class of twenty students taught by teacher "B", was used as the control group. The students were drawn from Honors Chemistry courses and were randomly selected to include an even distribution of males and females as well as varying ability levels. The two cooperating teachers used the same textbook (Zumdahl, 1993) and stated that previously they covered the same material in their classes.

### Research

An investigation of the literature on alternative conceptions shows only minimal prior research on quantum chemistry. There is a study on student misconceptions for light and energy at the undergraduate level

(Zollman, 1998) that points to confusion around the concepts of color, energy, intensity, and amplitude. The Bohr Model is often used in high schools as a simple way to explain bonding. Teachers do not explain to their students the shortcomings of the Bohr model with regard to the heavier atoms. Current high school texts include more abstract concepts, which are only useful if students adopt and apply them.

After conferring with the target high school faculty, the most difficult topic areas seem to be centered around the categories of phase, amplitude, molecular bonding, the lack of a localized phenomenon and, in general, connecting the concepts to other phenomenology.

#### **Data analysis**

The researcher divided this part of the study into three main areas expressed as questions: First, what preconceptions do students hold with regard to quantum science in chemistry? Second, what causes these preconceptions? Third, what can be done to minimize the impact that students' alternative conceptions have on student learning?

#### *Coding*

The researcher started with an outline which grouped the interview information into possible codes and larger categories. The outline was based on interviews conducted with three chemistry teachers from area high schools. Using the outline as a protocol for five student interviews, a complete list of fifty seven codes were generated. The concept mapping program C-map (Novak, 1989) was used to list the codes obtained from the interviews and then rearranged until they fit comfortably under eight categories: electronic structure, molecular geometry, bonding, periodic trends, polarity, solubility, energy, and color. After the main concepts were chosen, all related concepts were listed. Subsequent interviews and concept maps were focused on the eight main concepts with follow-up questions probing for student understanding of the relationships of the entire set of fifty-seven quantum chemical concepts.

A system of triangulation was used to check the codes that developed. Student concept maps were compared to an expert map derived from the eight categories found earlier in the preliminary interview process. Chemistry class test results from the target school showed the same areas of misconception prevailed. Student subjects and staff were shown the results as it accumulated. They agreed the conclusions were reasonable.

#### *Concept mapping*

An expert concept map was produced by looking for other possible categories and then gradually reducing them into eight major concepts under the heading of atomic structure. Several rearranged listings of the concepts were used in order to decide what topics are the most closely related. One parent map with expert links and cross-links between the eight concepts was completed for comparison. It was important to observe whether students can link their basic molecular understanding to macroscopic events.

The researcher instructed each of the honors chemistry classes in the art of concept mapping prior to their study of the topic of quantum chemistry. Students were presented the categories to see what connections they could make. Four students, two male and two females, were chosen at random for in-depth interviews by the researcher. The interview allows the students an opportunity to present more elaborate explanations regarding their understanding of the material.

#### **Design**

The teacher of the control group was instructed to proceed through the material in a normal manner. The experimental classes worked in groups of three on the computers studying electronic structure as explained by quantum chemistry including polarity as explained by charge density and bonding as explained by molecular orbitals. Teachers were instructed to assess their students in their normal manner. For the traditional class, this meant tests at the end of each chapter. It was interesting to note that the instructor of the control group was asked by the researcher about the laboratory exercises that were planned for the unit. The teacher stated, "There are hardly any lab activities for these units. After we do flame tests and mess around with spectrosopes, the rest of the activities are designed for the students to get extra practice studying the properties of gases. This year the gas labs were replaced by quantum chemistry activities"

The teacher of the experimental group had access to three computers in the classroom. The students were divided in half and were assigned to either work on the computers or write in their learning logs. The

teacher presented them with questions that related to the computer investigation. These groups also worked on advancing their concept maps.

## FINDINGS

### Baseline data

The literature, interviews, and concept maps indicate that there are alternative conceptions present when Honors Chemistry students start the topic in high school. Several misconceptions fall into the definitional level. For example: when asked about polarity, approximately 5-10% of the students in my sample discussed how, "This term refers to how light of a certain type lines up in a certain way." Another 25% believed that the third major energy level could only hold eight electrons and explained that their teacher said, "The periodic table of elements proved this when you counted the third period."

### Learning Logs

Student groups were required to write their thoughts regarding the relationship between quantum concepts and observable phenomena. One example is the group explanation for the color that is emitted by a gas discharge tube and the relationship to discontinuous spectra. Approximately 10% of the sample reported that the electron making a transition to a higher energy level is the cause of the color. Close to 30% of the sample continued to confuse the intensity of bright line with the energy of the color released.

### Conceptual matrix

A matrix was constructed containing the mistakes from a series of tests given by the chemistry teachers in the host high school. The columns are codes developed by the previous methods while information filled in the matrix holds the misconception. The areas that are dense indicate potential problem areas, while the sparse areas are either ones that the students understood or places where the questions might have been of a trivial nature. The following is the start of an outline developed for teachers at the host school. The purpose is to highlight student difficulties for the teacher. Examples of the misconceptions in the matrix follows:

- A. Lewis structure: Student [8317] calculated the formal charge for  $\text{BF}_3$  as 9 for the whole molecule. Trying to put a double bond and indicate resonance where one is required, students sometimes miss that the metal empties its outer shell; therefore, looking to fill the octet does not apply.
- B. VSEPR, valence shell electron pair repulsion: Student [8316] stated  $\text{H}_2\text{S}$  is nonpolar while disregarding the fact that the unshared pairs of electrons bends the molecule and makes it polar.
- C. Formal charge: Student [8312] calculated the formal charge for  $\text{BF}_3$  as 9 for the whole molecule. It is the individual items that we are trying to minimize. The benefit of formal charge is that it is a device for determining the best of a series of potential dot structures, and only one suggests itself with this molecule.
- D. Three dimensional Vs two: Student [8311]  $\text{OF}_2$  drawn in two dimensions can look linear from one direction but is really bent from a perpendicular point of view. This same incorrect interpretation occurs when students diagram water ( $\text{H}_2\text{O}$ ) from the wrong point of view and somehow depth perception is lost.

## CONCLUSIONS

### Causes

The qualitative and quantitative results cannot be generalized because of the small sample size. There is evidence of several areas in which students' misconceptions are produced on entering, during, and after the study of quantum science: courses that repeatedly build to a climax of the atomic model with the Bohr description of the atom, and the inability of students to visualize the scientific model in three dimensional space when all they have seen are two dimensional representations or mathematical models. These deficits were highlighted by the students who had problems with polarity. Their difficulties arose from the students' inability to rotate the three dimensional model in their mind, a lack of depth perception, or limited sense of perspective. The student who is not a visual learner or has problems thinking in three dimensional space is at a disadvantage. Also vague wording of some text material leaves students unable to discern the correct definition for a particular condition. Other misconceptions occur relating to the cognitive level of the student and what degree of abstraction is understood. Some individuals have difficulty relating to models at an atomic scale.

### Shifts in Student Behavior

In this study, students were allowed to make predictions about the macroscopic world based on their understanding of the microscopic. When the content is rich enough, students absorb themselves in study

leading to the development of judgment in the area of scientific prediction. In chemistry, concepts learned in one unit become the foundation for the next. The mindful instructor needs to be alert to typical student errors before these misconceptions get in the way of further learning. Students investigated bonding and anti-bonding in the Diatomic Molecular Explorer prior to reading about them in the textbook. The teacher noted that students successfully used their information on molecular orbitals to predict why the formation of some bonds (e.g. He<sub>2</sub>) are not favored.

### **Lingering Behavior**

The science education literature has many references to the durability of student misconceptions in science. Novak points out that although it can be difficult to positively affect many alternative conceptions not all are intractable (Gabel, 1994). We have evidence that an interesting concept met with considerable resistance. It was noted by the researcher during the preliminary study that students often misinterpreted the signs on ions and also on energy values such as transition energies when a photon is released or when bond energies are evaluated. The symptom is manifested when students use a number line interpretation of the sign when evaluating endo- or exothermic situations. In addition, students were found to continually misinterpret the meaning of (+/-) for ions by adding electrons for plus and subtracting electrons for minus. Even after the instructor emphasized the correct analysis of each of these concepts 5-10% of the students continued to misinterpret the data.

### **Future Study**

The information gathered on student alternative conceptions in quantum chemistry will help to improve both curriculum content and teacher presentation. The findings of this effort are being used to refine the protocol interview for use with a broader set of quantum concepts after students use the computer simulations.

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# USING COMPUTER VISUALIZATION SOFTWARE TO TEACH QUANTUM SCIENCE: THE IMPACT ON PEDAGOGICAL CONTENT KNOWLEDGE

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## INTRODUCTION

We are investigating the relationship between chemistry teachers' pedagogical content knowledge and their teaching strategies for incorporating computer visualization models to teach quantum science. Quantum Science Across Disciplines (QSAD) is a National Science Foundation project (REC-9554198) to develop software and instructional materials, based on the idea that "quantum phenomena are critical to understanding the world around us" and that quantum effects underlie concepts in biology, chemistry, and physics. The QSAD project includes development of computer simulations, which provide visual models for students to investigate the properties of atoms and molecules to "alter the classroom environment so that students have a greater opportunity to explore science and become acquainted with the process of science" (QSAD project summary).

QSAD software applications produce graphical representations of atoms and molecules without requiring students to perform high level computations. Students can create visual models of different atoms and molecules, predict their behavior, and test those predictions. Through in-service training using the software, teachers acquire the content knowledge they need to provide qualitative explanations for the electron behavior that accounts for the visual images. The software enables users to investigate currently accepted models of atoms and molecules in an interactive environment.

Although QSAD software offers a potentially efficient method for teaching and learning quantum science, a number of external variables might influence the effectiveness of these materials. This paper focuses on one part of a larger study that investigates possible relationships between variables in the school setting and decisions about implementing QSAD software and materials. These variables include such factors as teachers' expectations of students, beliefs about learning and teaching, content knowledge, and pedagogical content knowledge. We began with the premise that teachers' content knowledge in quantum science is a critical factor affecting how QSAD materials would be used in classrooms. Therefore, our research was based on teachers who participated in intensive summer workshops at Boston University in which they received instruction on how to use the software and engaged in discussions with the programmer and scientists who designed the software. During the workshop, participants also investigated the capabilities of the software, asked questions about the graphical representations and underlying scientific concepts, and developed lessons that would be appropriate for their students. This paper reports findings related to teachers' content knowledge in quantum science and a close investigation of how one experienced chemistry teacher enhanced his own content knowledge in quantum science and subsequently employed and refined his pedagogical content knowledge during his initial use of QSAD materials.

## METHOD

### **Participating teachers**

Eight Greater Boston public high school teachers participated in workshops at the Science and Mathematics Education Center at Boston University in the summer of 1997 or 1998. Participants included biology, chemistry, and physics teachers. The workshops provided information about the design, interface, and navigation of the software, and participants engaged in discussions with the programmer and scientists who designed the software. During the workshops, teachers investigated the capabilities of the software, asked questions about the graphical representations and underlying scientific concepts, and developed lessons based on the software.

### **Data sources**

Participating teachers answered survey questions to provide background data on their education, teaching experience, and computer experience. They also completed a modified Views on Science Technology and Society (VOSTS) questionnaire (Aikenhead, Ryan, & Fleming, 1989) to assess their

perceptions of the nature of science and the process of scientific learning. Participants created concept maps (Novak & Gowin, 1984) at the beginning and end of the summer workshop. Concept maps were then used as a basis for interviews to evaluate content knowledge and pedagogical content knowledge as it would be applied when teaching atomic and molecular structure and related topics. Preliminary interviews focused on teachers' perceptions of their teaching styles, methods used to assess student comprehension, and abilities of their students. Classroom instruction was observed and recorded on audiotape.

Audiotaped interviews and observations were transcribed, coded, and analyzed. Codes for the data included indications of the teachers' content knowledge, pedagogical content knowledge, beliefs about how scientific knowledge is acquired and how students learn, and terminology used by teachers when referring to atoms and molecules. Comparisons of the teachers' statements about their beliefs and instructional plans were compared to actual classroom practices. Evidence of pedagogical content knowledge included anticipation and recognition of students' alternative conceptions, use of a variety of representations to explain concepts, and ability to modify instruction or explanations based on specific student questions or evidence of students' misconceptions.

## RESULTS

### Teachers' content knowledge and alternative conceptions

All of the participating teachers initially reported having limited knowledge of quantum science concepts. When asked to identify their basis for content knowledge in quantum science, teachers most frequently referred to definitions or explanations in the textbooks they used with their students. However, analysis of the textbooks used by these teachers revealed discrepancies and misleading explanations for concepts such as electron orbitals. This finding is supported by research that shows that the high school textbooks provide only superficial facts about the quantum mechanical model and that they fail to establish convincing arguments for its superiority to other atomic models in predicting and explaining atomic behavior (Shiland, 1997).

Participants in the summer workshops revealed a number of alternative conceptions about atomic structure and electron behavior. Alternative conceptions included the belief that pi orbitals were involved only when multiple bonds were formed between a pair of atoms. None of the teachers understood that the term "orbital" referred to the mathematical wave function. Thus they interchanged the concepts of electron orbital and electron density. Teachers admitted a poor understanding of the relationship between wave properties of electrons and the resulting electron densities of specific orbitals. During their investigations of QSAD software, all of the teachers were surprised to find that the electron density of antibonding orbitals was highest on the outside of the molecule and that a node was displayed in the internuclear region. We also discovered that teachers of different science disciplines used different definitions for the same phenomenon. For example, chemistry teachers explained oxidation and reduction in terms of loss and gain of electrons, while biology teachers' definitions were based on loss and gain of hydrogen ions.

Concept maps and interviews identified changes in quantum science content knowledge for all participating teachers as a result of the summer workshop. The most significant changes in content knowledge were related to wave properties of electrons and factors affecting formation of molecular orbitals. At the conclusion of the summer workshops, all participants expressed a greater confidence in teaching quantum science concepts to their students, indicating that the availability of modeling software made the abstract concepts of quantum science more concrete and understandable.

### Case study findings

#### *Teacher's pedagogical content knowledge*

Six teachers were observed over periods of four to five months to obtain baseline data on teaching methods with topics other than quantum science as well as data on their use of QSAD materials. Data are presented here for one teacher, who has 29 years teaching experience and currently teaches chemistry at a public high school in a Boston suburb. The teacher exhibited well-developed pedagogical content knowledge in his interview answers and his classroom performance. When asked about identifying students' alternative conceptions, he had both general and specific strategies for eliciting, recognizing, and correcting those conceptions. His statement, "Different concepts require different initial strategies," indicated his awareness that student learning is context-specific. The teacher's pedagogical content knowledge was evidenced in his awareness of specific issues that were likely to be barriers to students' comprehension of quantum science. He also demonstrated pedagogical content knowledge by tailoring examples and explanations to students' comments, identifying students' misconceptions, and in designing a

curriculum that guided students in their discovery of atomic structure. His comments reflected an awareness of potential difficulties that students would encounter and variations in students' learning styles and abilities. Prior to teaching this topic, he readily identified analogies, models, and instructional sequence that would facilitate students' understanding of quantum science. In class, he used some of these strategies but added others or modified his explanations in response to students' specific questions and comments. For example, the teacher used the analogy of a staircase when explaining quanta of energy, saying that a person could go up or down in increments of stair steps but could not move up in fractions of a step. When one student's response indicated that he thought that the energy difference between any two principal energy levels was the same, the teacher identified this misconception and explained that analogies are useful for explaining ideas, but that analogies can never give a completely accurate representation. In another case, a student's comments suggested that she was confused by the two-dimensional images generated by the software. The teacher gave the analogy of a loaf of marbled bread and a comparison of one slice of the bread to the entire loaf. He then asked students to visualize slices through different objects such as an orange or a pair of balloons.

The teacher's beliefs included convictions about how scientific knowledge is acquired, how students learn, and the capabilities of his students. Interview comments about the epistemology of science made reference to students' expectations that the teacher should know everything and the inference that students have an empiricist view of scientific knowledge. He stated his own belief that "science is a process by which we continue to build knowledge and that knowledge building process has bumps in the road and dead ends and keeps chugging along." This philosophy was evidenced in the teacher's instructional design. Students proceeded through a series of experiences that led them to question their previous conceptions and rebuild their knowledge.

Observations of instructional and assessment practices reflected the teacher's stated beliefs. For example, his instructional plan for the quantum science unit guided students toward predictable discoveries leading to predictable questions. The historical background of atomic theory was provided through student presentations of the scientists credited with important discoveries, and the teacher augmented these presentations with demonstrations and analogies. After the student presentation on J. J. Thomson, the teacher demonstrated the properties of a cathode ray tube, using an exposed television tube. After the Einstein presentation, the teacher demonstrated the photoelectric effect and its use in a spectrophotometer. Following the historical overview, students investigated some of the ideas proposed by these theories. They used spectrosopes to examine spectral lines emitted by excited electrons of different elements, then built their own spectrosopes, using them to investigate the bright lines spectra produced by sources at home or in the community. Students also used spectrosopes to analyze the "yellow" light produced by a Singerman apparatus, learning that a given color can be perceived in the absence of the corresponding wavelength of light. Students also determined Plank's constant experimentally using a laboratory exercise from Visual Quantum Mechanics (Escalada, Rebello, & Zollman, 1999). These experiences led to student questions about the relationship between atomic structure and spectral lines, why hydrogen has more than one spectral line if it has only one electron, whether the ionizing gas in a neon tube would "get used up" over a period of time, and why light from a television appears blue when seen through a window.

#### *Implementation of QSAD software and materials*

The teacher's pedagogical content knowledge appeared to direct his instructional choices for using the QSAD software. The sequencing of lessons included experiences that were linked to students' prior knowledge of light and the Bohr model of the atom. Through experimental results, students discovered aspects of the Bohr model that were not supported by empirical evidence. Students predicted the wavelengths of the emission spectra of hydrogen and helium through their own calculations and discovered that the predictions were accurate for hydrogen but not for helium. This realization provided dissatisfaction with the prior conception and the opportunity for reception of an alternative model. The teacher reported extensive modifications of his units on atomic structure and periodic properties as a result of his new understanding of quantum science. He consulted with the physics teacher at his school for advice on demonstrations that would model wave properties, and included a new demonstration of constructive and destructive interference in circular standing waves. He also used QSAD software applications to guide students in the discovery of atomic structure and periodic trends in atomic size, ionization energy, and electronegativity.

The researchers did not anticipate the teacher's decisions about how to use the software. He designed activities using a different QSAD application than was emphasized during the summer workshop. During the workshops, teachers focused primarily on the Diatomic Explorer, which produces graphical

representations of atomic and molecular orbitals of designated elements and binary molecules. However, this teacher instructed his students to investigate electronic structure of atoms using the Bond Explorer. In this application, the user selects the energy and sublevel of a single atomic orbital. The program then generates representations of electron orbitals or densities of pseudoatoms. When the teacher was questioned about his instructional choices, he explained that he wanted students to understand the general properties of electron densities independent of the identity of the atom. Students appeared to follow this sequence without difficulty. They asked many questions, but there was little evidence that students were confused or frustrated by the software or in working with the abstract concepts of quantum science.

In response to interview questions, the teacher expressed his position on the necessary foundation for students to be able to understand quantum phenomena. "Students need to be prepared in a background understanding of electron energy [and] wave properties." The teacher commented that in previous years, "as far as the kids were concerned, they were putting numbers with letters and talking about some abstraction called orbitals." He noted that QSAD software changed his own conception of atomic and molecular orbitals and therefore his approach to teaching these topics. He pointed out that by providing manipulable visual images, the software allowed students to construct an understanding of atoms and molecules in terms of electrostatic interactions and wave properties rather than merely committing facts to memory.

The teacher acknowledged that he would not know whether students understood all of the preliminary information they would need until they had actually used the software. Thus, he anticipated growth in his pedagogical content knowledge related to the software as an outcome of his teaching experience. He also stated that his own content knowledge remains incomplete in the area of quantum science, but one of his goals in teaching is to have opportunities to learn. He believes that his content knowledge is greater now that it was before attending the QSAD workshop and gives credit to the increase in his knowledge as the reason for developing a more extensive instructional unit in quantum science.

## CONCLUSION

Data indicate that high school teachers have limited understanding of concepts related to quantum science and the relationship of those concepts to many of the topics included in the high school science curriculum. Use of QSAD software and materials resulted in increased content knowledge for all participating teachers. Case study data from one of these teachers indicate that new content knowledge was integrated into his existing pedagogical content knowledge, enabling this teacher to guide his students to a deeper understanding of the events that orchestrate atomic and molecular behavior. Further research is needed to determine if similar results would be obtained for teachers who participate in less intensive workshops or tutorials provided over the Web.

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# STUDENTS' VIEWS OF MODELS AND CONCEPTS IN MODERN PHYSICS

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Modern physics requires an adequate use of models and a deep conceptual understanding of the underlying abstract ideas. However, there is only limited information available concerning how students have adapted their conceptual frameworks towards incorporating the highly nonclassical issues of modern physics. In the present pilot study we have investigated aspects of this conceptual knowledge and ways of changing the students' views of the strange reality described by Quantum physics. The study was part of a quantum physics seminar. Most of the students had completed a course in quantum physics. Yet, a pretest indicated that their conceptual understanding was not on an adequate level. An experimental design was used to examine the impact of instruction emphasizing concepts. The experimental group was assigned three special lectures on concepts and models. A posttest was designed to investigate how the students' views of models and general conceptual understanding had changed. Statistical analyses were done with  $U$  tests. The experimental group showed a significant improvement in their understanding after treatment and a convergence towards experts' views.

## INTRODUCTION

It is a generally accepted aim of a modern physics course at the upper secondary level to develop a worldview that supersedes the view of classical physics. Obviously such a goal requires an understanding of physical theories which goes beyond manipulating variables and formal understanding. It is more important to have a conceptual understanding of the abstract ideas expressed in the symbolic language of mathematics. Especially, this applies to modern physics concepts such as the theory of relativity, nonlinear physics or quantum theory, which deal with some of the most abstract conceptual issues of modern sciences.

As they have to moderate the learning processes of their students, teachers must have an adequate conceptual understanding of the various theories. This calls for research in science education that focuses on the conditions that enable teachers to reach such a level of understanding. Particularly, it is interesting to know if the university education of teachers sufficiently supports the development of an adequate conceptual understanding and, if not, how the situation could be improved.

The present pilot study investigates some aspects of these questions focusing on students' views of quantum physics. It was set up to answer the following two questions:

1. What level of conceptual understanding of quantum physics do future physics teachers have?
2. Is it possible to improve students' understanding by emphasizing concepts in quantum physics courses?

The source of data in this study was 13 physics students – 2 females and 11 males – at the University of Kiel. The average age was 25. Nine of them had completed a course in quantum physics while the others were just beginning it. In the summer term 1998 this group of future physics teachers took part in a seminar on advanced aspects of quantum physics. The seminar's title was "Quantum Physics between technological application and philosophical significance". These students will not spend much time studying or using quantum physics after completing their courses on the topic. When they start teaching, they use concepts developed and acquired in these courses. Thus, they provided us with information about typical understandings of quantum physics of beginning physics teachers. On the other hand voluntarily taking part in the seminar means that our thirteen students had a special interest in quantum physics. Hence we expected them to be more susceptible to a concept-orientated course.


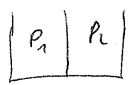
## THE PRETEST

The pretest consisted of questions which mostly had been used in previous tests designed for upper secondary students (Lichtfeldt 1992, Mashhadi 1998, Wiesner 1996). This upper secondary level is comparable to the college level. The approach gave us the possibility to compare the conceptual understanding of prospective physics teachers with the results known for secondary students. Due to the explorative character of the present pilot study we decided us for open questions in order to gain a maximum of information on students' thoughts. Below are some examples of questions. (The numbering scheme applies to the pretest):

1. Please describe in as much detail as possible your concept of a hydrogen atom. You can do this in written form or by using an illustration.
2. Why doesn't the electron collapse into the nucleus in a hydrogen atom?
3. An electron is locked in a box. At a certain point in time the box is divided into two boxes B1 and B2. B2 is brought to a location far away. Suppose the electron is found in B2. Was the electron in B2 shortly before the check?
7. Please explain the meaning of the Heisenberg uncertainty principle (no equations).
11. Do you have a rough idea of what could be meant with the following terms?

Measurement problem of quantum theory	<input type="checkbox"/> Y	<input type="checkbox"/> N
Schrödinger's cat	<input type="checkbox"/> Y	<input type="checkbox"/> N
Bell's inequality	<input type="checkbox"/> Y	<input type="checkbox"/> N
Complementary	<input type="checkbox"/> Y	<input type="checkbox"/> N
Dualism	<input type="checkbox"/> Y	<input type="checkbox"/> N
Nonlocality of quantum physics	<input type="checkbox"/> Y	<input type="checkbox"/> N
Einstein-Podolsky-Rosen-Paradox	<input type="checkbox"/> Y	<input type="checkbox"/> N

The pretest indicated that the group was very homogenous with respect to the level of their conceptual knowledge of quantum physics. The answers revealed that most of the students applied ideas from classical physics to quantum phenomena. Also, these students' conceptual understanding was very similar to those of secondary students. To illustrate the level of understanding found in the pretest here are some excerpts of answers given for the first three questions.

Question 1	{	<p>...electron, which moves around the nucleus on a fixed orbit...(Student E4)</p> <p>...I imagine the electron the same as the proton, only substantially smaller. It buzzes around the proton at a huge distance. (Student C5)</p>	
Question 2	{	<p>The electron does not radiate. (Student C1)</p> <p>Because escape velocity is too huge..(Student E7)</p>	
Question 3	{	<p>With the probability P1 the electron is in B1 and with the probability P2 it is in B2. The question can't be answered with Yes or No. (Student E2)</p> <p>Probability is 50%, if Vol(B1) = Vol(B2). (Student E1)</p>	

We classified every student in one of three categories. The first category was labeled 'C' for classical physics. Ten students belonged to this category because the majority of their answers indicated the use of classical or Bohr-like models and ideas. The second category was labeled 'Q' for quantum physics. This category was meant for students basing their answers upon the concepts of quantum physics. Only one student was classified 'Q' using in the majority ideas from quantum physics. The third category was

**TABLE 1. Subgroups of seminar.**

Experimental Group					Comparison Group				
	Quantum Physics course			Pretest classification*		Quantum Physics course			Pretest classification*
	Age	Sex	completed		Age	Sex	completed		
E1	22	f	N	C	C1	25	m	Y	C
E2	26	m	Y	C	C2	24	m	Y	H
E3	26	m	Y	Q	C3	23	m	N	C
E4	24	f	Y	C	C4	25	m	N	C
E5	24	m	Y	H	C5	29	m	Y	C
E6	26	m	Y	C	C6	24	m	Y	C
E7	23	m	N	C					
Mean	24.4				Mean	25			

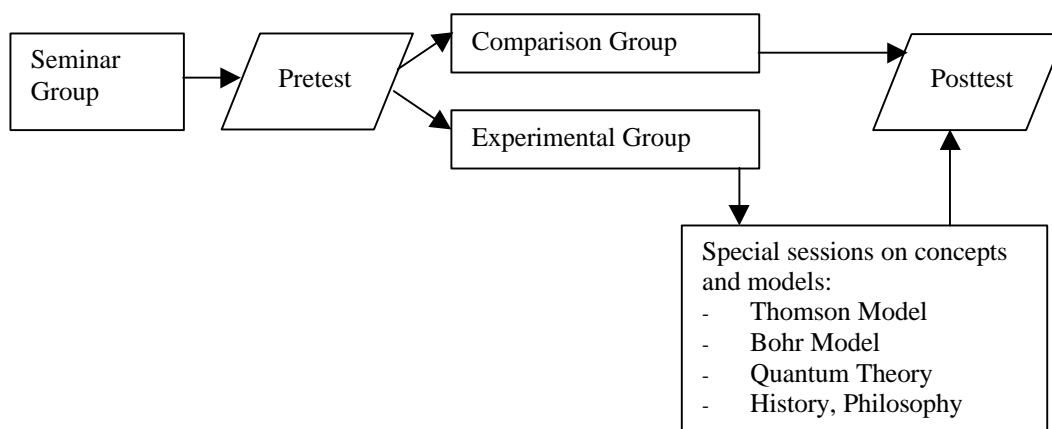
\*C: Classical Physics; Q: Quantum Physics; H: Hybrid

labeled 'H' for hybrid. Two students were classified 'H' because they used concepts from classical physics and quantum physics equally, depending on the content of the question.

### EXPERIMENTAL DESIGN AND POSTTEST

To investigate the impact of emphasizing concepts on conceptual understanding the seminar group was split in an experimental group and a comparison group. Distribution was at random. Table 1 shows the resulting subgroups of the seminar.

The students of the experimental group took part in three special sessions dedicated to models and concepts in quantum physics. These sessions included different models of the atom, the principal concepts of quantum physics, historical and philosophical questions, and a broad discussion of the importance of the several models and concepts in the evolution of quantum physics. The flowchart illustrates the design of the study.



**FIGURE 1. Design of study.**

The posttest questionnaire consisted of 25 questions. In view of the qualitative information available from the pretest we opted for closed questions suitable for a quantitative analyse. We chose questions that gave us the possibility to check improvement of conceptual understanding with respect to the deficits found in the pretest.

Examples:

The Heisenberg uncertainty principle can be explained by a disturbance of the measuring process.

1 2 3 4 5

Probability data of quantum physics reflect a pure lack of information just like the probability data of classical physics (e.g. by diffusion), that means the statement: "In principle, position and momentum have determined values, we are just not able to measure them", is

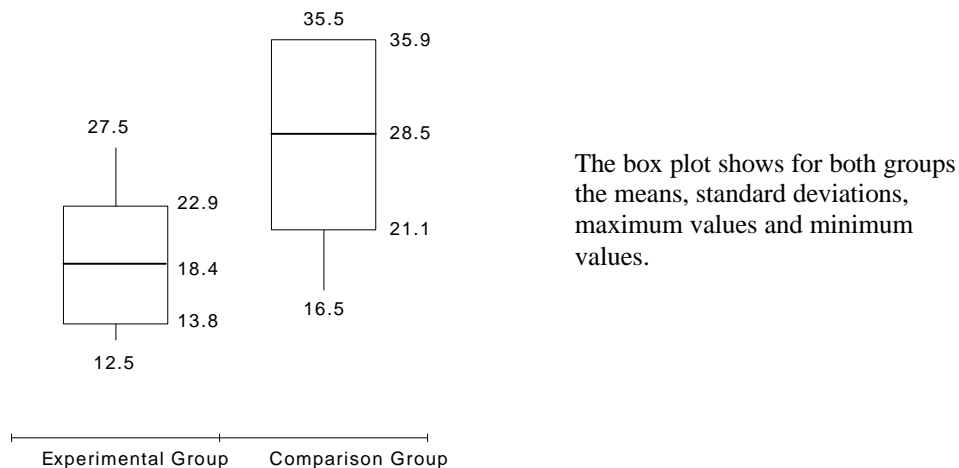
1 2 3 4 5

Statements were assessed using a scale from 1 to 5 with the following classification:

1 = correct, 2 = mostly correct, 3 = contains to an equal degree elements which are correct and incorrect, 4 = contains a grain of truth, 5 = incorrect. The value of the 'correct' answer was established by evaluating the independent choices made by the four authors. Only those questions were finally accepted in which at least three of us agreed on the value of the correct answer and at the same time the remaining author differed in his answer not more than  $\pm 1$ .

## RESULTS

The results of the posttest indicated a significant conceptual change of the experimental group. Performance was measured first by the number of correct answers and second by the added deviations of given answers from the correct ones. This indicator of performance used the 1-to-5 response scale. We calculated for every student the sum of the 25 absolute differences between the values of the marked answers and the values of the corresponding correct answers. For example suppose the correct answer is 5 and the student's answer 1. This would result in a deviation of 4. 'Deviation' reflects better the overall performance of a student than the number of correct answers. E.g., student C4 has only 3 correct answers, but the resulting added deviation of his answers is comparable to the deviation of student C3 with 10 questions answered correctly. This means his performance much better than indicated by the number of 3 correct answers. The following box plot illustrates the differences for 'deviation' between experimental group and comparison group.



**FIGURE 2: Box plot for added deviations of answer-values.**

**TABLE 2. Results of posttest.**

Experimental Group			Comparison Group		
	Correct Answers	Deviation		Correct Answers	Deviation
E1	15	18.50	C1	16	16.50
E2	15	18.50	C2	11	25.50
E3	18	12.50	C3	10	35.50
E4	12	27.50	C4	3	34.50
E5	16	17.50	C5	11	33.50
E6	14	16.50	C6	12	25.50
E7	14	17.50			
Mean	14.9	18.36		10.5	28.50
Standard deviation	1.9	4.53		4.2	7.38
Variance	3.5	20.48		17.9	54.40
Median	15			11	
U-test	Correct Answers p=0.017			Deviation p=0.037	
Effect size*	d=1.3			d=1.6	

\* Effect size was calculated using t-test on the means.

The number of correct answers for the experimental group was more than 40% higher than for the comparison group. Simultaneously the deviation from the correct answers' values was 55% higher for the comparison group. To test the significance of the obtained results a Wilcoxon-Mann-Whitney U-test was performed (Bortz 1989). Having only a small sample and without the possibility to be sure that the “correct answers” and “deviations” fulfill the condition of being normal distributions the U-test is the adequate test because it uses only the ordinal information of the data. For “correct answers” the result was significant,  $p(n_1 = 6, n_2 = 7, U=6) = 0.017 < 0.05$  (95% confidence level). For “deviation” the result was also significant,  $p(n_1 = 6, n_2 = 7, U=8) = 0.037 < 0.05$ . Effect size was large in both cases  $d = 1.3$  and  $d = 1.6$  (Cohen 1988). But these values must be interpreted with caution because we did the calculation using t-test on the means.

We conclude from the results that emphasizing quantum physics concepts in teaching considerably helps students to improve their conceptual knowledge which seems to be inadequate after completing ordinary quantum physics courses. A conceptual reflection and reorganization of these courses is necessary. Because this work is a pilot study, the results can be considered only as hints. Therefore we continue to investigate the conceptual understanding of modern physics in the broader context of German physics teachers.

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# STUDENTS' CONCEPTIONS OF QUANTUM PHYSICS.

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## 1. INTRODUCTION

How do future physics teachers envisage atoms? Do they regard electrons as being permanently localized? What does the Heisenberg uncertainty relation mean for them? To answer such questions, we carried out an empirical study on students' conceptions of quantum physics in the years 1996 –1998. The study has been carried out to support the development of a new course on quantum physics for the German "Oberstufe" (12<sup>th</sup> to 13<sup>th</sup> year). In the center of this course we put the novel type of interpretative problems that quantum mechanics entails. Such a course makes high demands on the students as well as on the teachers. It is of particular importance for the teachers to have gained an understanding of the interpretation of quantum mechanics during their university education.

Up to now, there exists only a relatively small number of studies on this topic. Most of the existing studies deal with students' conceptions [1-9]. They show marked misconceptions. Since we are interested in teachers we have carried out our study with future teachers (3<sup>rd</sup> to 5<sup>th</sup> year). As a side effect we gained some insight on the effectiveness of the German university education in this field.

## 2. INTERVIEW SCHEME

We invited the students to an oral interview (duration ½ to 1 hour) that was recorded on tape and later transcribed for the evaluation. Of the 37 students that participated, 52% had heard about quantum physics already in school. 79% had attended a quantum mechanics lecture (on the level of, e. g., Baym). They were asked the following questions:

### **Atoms:**

- Which ideas do you link up with the state of electrons in an atom?
- Does an electron in an atom have a definite position at each moment of time?
- How are charge and mass distributed at a certain time?
- How does an electron change from one state to another?
- How would you assess Bohr's atomic model in school?

### **Heisenberg's uncertainty relation:**

- What is the meaning of the uncertainty relation?
- What do  $\Delta x$  and  $\Delta p$  mean?
- Does the uncertainty relation refer to a single quantum object?

### **Wave function, probability interpretation:**

- What is  $|\psi|^2$ ?
- You find an electron at the position  $x$  in a measurement. Does that mean that it has been there already before the measurement?
- Meaning of an eigenvalue equation (e.g. for momentum)

### **Interpretation of Quantum Mechanics:**

- Double slit experiment: How can the electron "know" whether the slit through which it not went was open or not?
- How do you envisage the spin of an electron?
- Have you ever heard something about Schrödinger's cat?
- Have you ever heard about quantum mechanical non-locality / EPR paradox/ Bells's inequality?
- How do you envisage a photon?
- Which textbooks / popular books have you read?

### 3. RESULTS

In the following, the answers of the students are arranged in categories. To each category, typical student utterances are given. Since they consist of spoken language with all its grammatical inaccuracies a proper translation was not easy. We have tried to match the meaning of the sentences as close as possible.

#### A. Conception of atoms

Question: Which ideas do you link up with the state of electrons in an atom?

- a) *Bohr's atomic model (17%)*  
S31: There are circles ... around the nucleus... just orbits. They are circles. And the electrons are on different orbits. They move on them and they can jump from one orbit to another ... if they get more energy, they can jump to a higher orbit.
- b) *Bohr's model with graft-on probability interpretation (24%)*  
S18: The orbits... I still have that picture when I think of an atom. One is told that it's not correct, but one is so used to it and, after all, it is employed again and again.
- c) *Concrete ideas of "clouds" / smeared charge (14%)*
- d) *"Orbitals" with probability distribution (38%)*  
S29: It's the wave function that represents the particles, there is the theory of orbitals, the orbitals can be represented in space. Then you know where the electrons are approximately and the whole thing works with the probability interpretation.

The two dominant conceptions are the two variants of Bohr's model (together 41% ) and the picture of orbitals (38%). It is remarkable that Bohr's model is almost always used as the starting point of the discussion. Quantum mechanical modifications are "graft upon" the Bohr model more or less strongly. The "planetary model" of the atom seems to be a very robust conception.

These findings lead to a further question: Do the students confuse the different models (i.e. planetary model, Bohr's model, quantum mechanical model), or are they able to keep their features apart? 55% of the students were able to distinguish clearly between models (and/or to reflect the model character of physical description); 17% applied different models indiscriminately. 28% mentioned only one model.

#### B. Permanent localization:

Question: Does an electron in an atom have a definite position at each moment of time?

- a) *Electron has a definite but unknown position (21%)*  
S1: Yes, it has to be somewhere, but it isn't accessible through a measurement.  
S2: I would say in principle it has a definite position, we just don't know it. That's how I imagine.
- b) *Electron has a position but no trajectory (due to insufficient knowledge of initial conditions) (7%)*
- c) *Localization in a region with some probability (25%)*  
S8: It's like that, they have no definite position, to my mind, they are just located arbitrarily somewhere in a certain region.  
S32: You cannot localize it that precisely, you can only give a probability of finding...
- d) *No definite position because of the uncertainty relation (18%)*  
S28: You cannot assign a definite position to an electron because of the uncertainty relation.
- e) *Other (11%) / indifferent (18%)*

#### C. Heisenberg's uncertainty relation

Question: What is the meaning of  $\Delta x$  and  $\Delta p$ ? (multiple responses allowed)

- a) *Measurement uncertainties (15%)*  
S15: Suppose you know the error  $\Delta x$ . Then you can determine the minimum error you have done in the momentum measurement
- b) *disturbance during measurement: position measurement influences the particle's momentum (21%)*  
S13: When I measure the position very precisely, I alter the momentum.
- c) *"Regions of localisation" (18%)*  
e. g. spatial region where the particle is confined; width of the wave function  
S34: The deltas are the bandwidth, within which you can determine the position and the momentum. If I try to measure position very precisely, the momentum bandwidth becomes very large. I will only get a result within this bandwidth. If I confine an electron very narrowly within a potential, then the momentum fluctuations are here within; the electron can take any momentum within this bandwidth. And of course vice versa, if I fix momentum very precisely, I cannot predict where it is, but I can give at least a scope where it is with a high probability.
- d) *Interval within which the exact value lies with some probability (18%)*  
S18: It is, so to speak, the probabilities of the momenta at this place. This is the most precise statement about the momentum. I can only say the momentum lies in the interval between  $p \pm \Delta p$ .
- e) *Standard deviation of a statistical distribution (13%)*  
S21: If I repeat an experiment several times and measure position and momentum, I don't get always the same, i. e. if I have identical initial conditions, I don't get always the same  $x$  and the same  $p$ , but it varies. If I graph it I get a standard deviation.
- f) *Never heard about the uncertainty relation (3%)*

**D. Have you ever heard about Schrödinger's cat?**

- a) *Yes, but I don't know what it is (62%)*
- b) *Yes (and the idea could be explained) (31%)*
- c) *No, never (8%)*

**E. Have you ever heard about quantum-mechanical nonlocality / EPR paradox / Bell's inequality?**

- a) *Yes, but I don't know what it is (13%)*
- b) *Yes (and the idea could be explained) (13%)*
- c) *No, never (75%)*

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# EVALUATION OF A NEW APPROACH IN QUANTUM ATOMIC PHYSICS IN HIGH SCHOOL

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## TEACHING APPROACH

The teaching approach under consideration has been under development for about ten years. *Basic ideas* are:

(1) From Bohr to Schrödinger

A modern representation of atomic physics using the Schrödinger equation as a theoretical basis. The main focus here is on qualitative understanding and interpretation of the  $\psi$ -function, not on mathematical capabilities.

(2) Reducing the mathematical demands

We use the analogy of the standing wave in order to introduce the basic concept of a state ( $n, W_n, \psi_n$ ). In addition, the computer is used for modeling the Schrödinger equation for many special cases like hydrogen atom, higher order atoms (He, Li) and molecules.

(3) Relating measurement to theory in a variety of phenomena.

Our approach is directed to the development of applications of our quantum model to a wide range of phenomena in atomic physics, chemistry and solid-state physics.

(4) Student Orientation

The process of conceptualization and learning of students is to be specifically promoted by student-oriented phases at the beginning of each new chapter.

The investigation reported here had the aim to use this new concept in normal school teaching with three voluntary teachers, who had to be trained with this approach before. A special manuscript with about 120 pages was prepared for students and teachers (Niedderer&Deylitz 1997; a shorter draft version of 40 pages is available in English.). The chapters of this script are: Light and electron as quanta; classical standing waves; the hydrogen atom; higher order atoms. Instruction took place in three classes (H, V, W) in three different high schools in great 13 in advanced physics courses in Bremen.

## THE EVALUATION CONCEPT

### Research questions of the evaluation study

1. How far are students achieving the objectives related to this new approach? Do they develop a deeper understanding of atomic physics as it is defined by this teaching approach?
2. How are conceptions and understanding of students changed during instruction?

### Design

Data were gathered from questionnaires before and after teaching, from interviews after teaching, and from observations during teaching. There were altogether 26 students in three classes.

### Knowledge domains

Coming from our basic ideas as stated above, we defined the basic knowledge domains from the main contents of our manuscript. As the basis for the evaluation, we defined six *knowledge domains* of the approach:

#### *Atom*

This objective means that students should develop a description of atoms using an orbital model. Some special aspects of this tested by specific questions of the questionnaire are: Use of a consistent description in different situations; use of physics concepts (such as charge cloud, probability density, state, etc.) to describe an atom; an understanding of the model character of these descriptions; to be able to distinguish different models of the atom.

#### *$\psi$ -function*

This objective is related to an understanding of the  $\psi$ -function and its interpretation. Special objectives are: To draw  $\psi$ -functions in different states; interpretation of the  $\psi$ -function with the notion of charge distribution or probability density distribution; to connect the  $\psi$ -function of an atom with the notion of a state.

*Notion of state*

This objective is related to an understanding of the concept of state. Special objectives are: To connect the concept of state with special physical variables which are characterized by the state (energy distribution); use of the concept of state to describe the model of an atom; to explain processes like emission and absorption using the concept of state.

*Schrödinger equation (SEq)*

This objective is related to a theoretical understanding of the use of the Schrödinger equation to describe atoms. Special objectives are: List and explain the variables in the Schrödinger equation; describe processes to solve the Schrödinger equation in a special case; to be able to explain properties of solutions; to explain the form (curvature) of a  $\psi$ -function by using the Schrödinger equation and especially the variables of energy and potential in it.

*Relating measurement to theory*

This objective is related to the understanding of relations between theoretical results from the Schrödinger equation and corresponding results of measurements. Special objectives are: To connect differences in energy level diagrams and frequencies of light spectra; to connect the form of a  $\psi$ -function (and a theoretical definition of the radius of an atom) with measurement of size of an atom.

*Higher order atoms*

This objective is related to students' ability to understand, how higher order atoms with more than one electron can be described and modeled with the Schrödinger equation. Special objectives are: To understand the shielding effect of electrons on the potential; to understand the combination of states in higher order atoms; to understand the use of the Schrödinger equation for each single electron and their interrelation; to distinguish the state of an electron and the state of an atom.

**Questionnaire**

From this content structure, we developed our questionnaire with mainly open ended questions and a final interview with all 27 students.

Selected questions of the questionnaire

- 1a Draw a picture of an atom and label it!
- 1b Describe your model with a few sentences.
- 1e Can you determine the size of an atom in your model of an atom?
- 3b Given are three drawings. Describe commonalties and differences between these three atomic models and use the notions "electron orbit", "probability density", and "charge cloud".

**Performance levels**

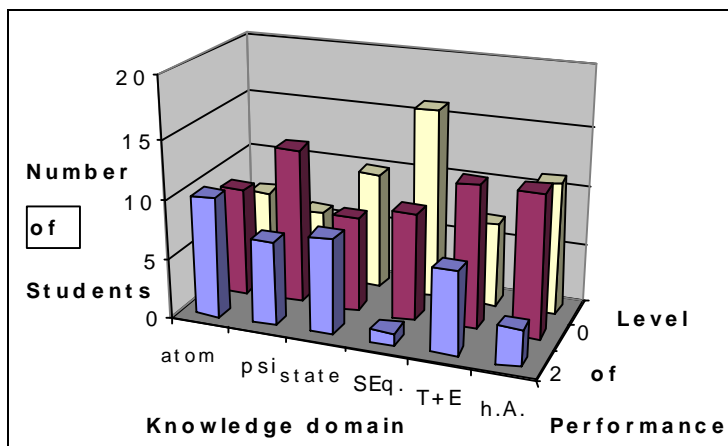
In order to define performance levels for all six knowledge domains, we had to find out combinations of different answers to different questions related to these knowledge domains. Because of the open-ended nature of questions a student could answer with his knowledge to one question or another, and we had to take into account the different answers to different questions related to the same knowledge domain. So, item combinations were defined to determine performance levels. These item combinations were determined by logical analysis of the answers in relation to our knowledge domains and justified by correlation between different item combinations. By this method we got the following three performance levels for all six knowledge domains

Level	Description
2	The combinations of students' answers were along the expectations from our teaching approach.
1	The combinations of students' answers showed some major deficiencies.
0	Students' answers were weak in relation to the expectations from our teaching approach.

## RESULTS

### Results about performance levels

The results for the three performance levels in all six knowledge domains (research question 1) are displayed in figure 1. Good results in the domain "atom" tell us, that most students have gained a good or moderate understanding of the orbital model. In the domain " $\psi$ -function" a qualitative understanding of the Schrödinger equation (details see above) was gained to some extent. Some students did very well, but most of the students had some deficiencies. The knowledge in the domain "notion of state" turned out to be the second best, so many students got a good or rather good understanding of the notion of state and its importance for explaining phenomena of size and light spectra. In spite of some efforts of our approach to foster a qualitative understanding of the Schrödinger equation (domain "Schrödinger equation (SEq.)"), and work with it in graphical computer models, the understanding here of most students was on a rather low level.



**Figure 1: Number of students in three performance levels 0, 1 and 2 of six knowledge domains (atom,  $\psi$ -function, notion of state, Schrödinger equation (SEq.), relating measurement to theory (T+E), higher order atoms (h.A.))**

#### *Knowledge domain "relating measurement to theory"(T+E)*

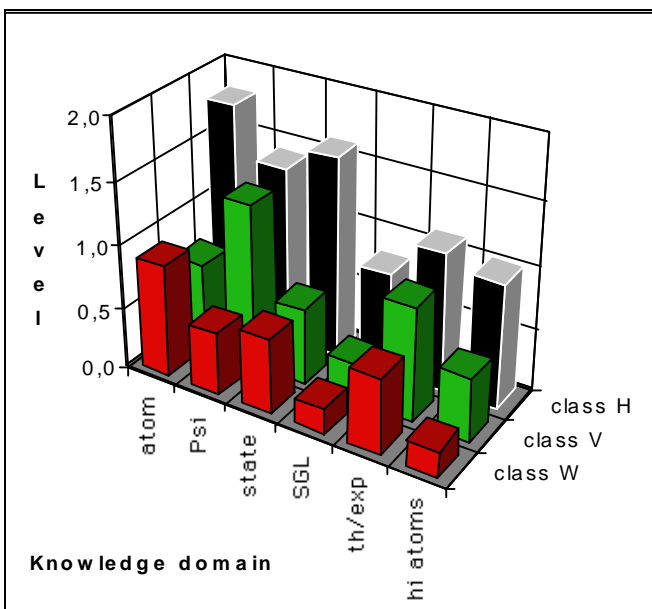
In this content domain we analyze students' ability to relate theoretical models and experimental observations and measurements. From students' responses to various items of the questionnaire we analyze whether experimental observations can be explained with the intended atomic model. The items are divided in two groups: Measurement of spectra related to the changing energy of atoms and items where students tell something about the size and radius of atoms. The results in figure 1 show, that students did rather well in this - from the view point of our approach - important knowledge domain.

#### *Higher order atoms*

This also was an important part of our approach. But most teachers had not enough time for this chapter, so the low results were not so surprising.

### Results about different classes

In addition we show differences between the three classes in figure 2.



**Figure 2: Performance levels 0, 1 and 2 of six knowledge domains (atom,  $\psi$ -function, notion of state, Schrödinger equation (SEq), relating measurement to theory (T+E), higher order atoms (h.A.) in three different classes**

Students in class H have achieved better results than in the two other classes. From our observations of the classes there are several preconditions that have influenced the outcome. The teachers differed in their acceptance of our approach and in their physics background. Half of the students in class W were not native German speakers. In average the students in class H spent more time for preparations and reading the text book than students in classes W and V. Despite these preconditions the results in each class for its own are quite similar;

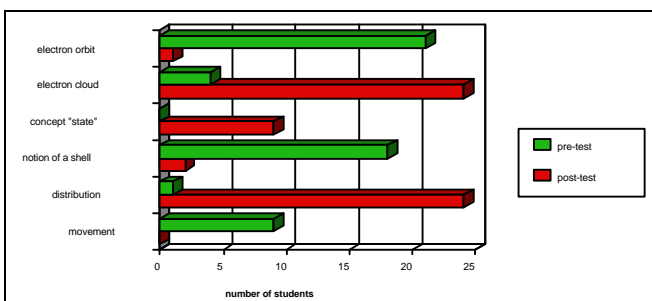
students have achieved a better understanding of the objectives atom, Psi and state compared to the objective SEq.

The levels on the vertical axis might be translated as 2.0 is excellent; 1.5 is very good; 1.0 is sufficient; 0.5 means students have achieved a preliminary understanding, and 0.0 means that they have got nothing out from the course. The values on the vertical axis are mean values of all students in one course. With respect to the objective "atomic model" students in class H have achieved very good results, whereas students in the two other classes have achieved only average or less results. With respect to the objective " $\psi$ -function", students in the classes H and V have achieved average results, whereas in course W they have only reached a sufficient level on average. With respect to the concept of state, students in course H have achieved very good results, whereas in the classes V and W they have only achieved sufficient level.

The knowledge achieved about the mathematical understanding of the Schrödinger equation gets the lowest scores in all three classes. The average even in class H is less than 1.0, so this means that a mathematical understanding was not developed to a high level. One of the most important objectives for our approach was to enable students to see a connection between results of theoretical modeling and results from measurements, such as size of the atoms or frequency of spectral lights. The results show that this aim was achieved to a good average level in course H and course V, whereas the average level of students in course W was only sufficient.

The aim to understand the modeling of higher order atoms with more than one electron was achieved to a good average level in class H, the other classes got lower results, but we know from observing the teaching that the teachers in these classes gave only little time to this part of the instruction.

### Results about students changes in conceptions from pre to post questionnaire



**Figure 3: Changes in conceptions from pre to post questionnaire**

Some results about students' conceptions (research question 2) related to electron orbits, electron cloud, concept of state, concept of shell, distribution and movement and their change from the pre test to the post test are displayed in figure 3. More than 20 students change from an electron orbit view of electrons in an atom to a charge view.

Nearly all students develop a good notion of an electron distribution. Nearly 50 % of the students develop some good notion of a state and abandon a description of electrons which includes the notion of motion.

## CONCLUSION

A new approach to teach quantum atomic physics in upper high school has been transmitted to three teachers of ordinary high school with partial success. In one of the three classes all but one objective have been reached by many students. Only the mathematical understanding of the Schrödinger equation got less average level than 1.0. In two other classes some of the objectives also have been reached with good success, for instance achieving a new atomic model or understanding some relations between theoretical model and results of measurement. Other objectives failed to reach a sufficient level. We conclude from these results that although it was not possible for most of the students to develop a deeper understanding of the theoretical description they achieved an average to good understanding of the basic quantum mechanical concepts.

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# QUANTUM MECHANICS : EXPLORING CONCEPTUAL CHANGE

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The purpose of this study was to develop a survey instrument to explore the conceptions that students hold after completing their first year of tertiary studies in quantum mechanics. The survey comprised four questions covering fundamental concepts: the photoelectric effect, the meaning of uncertainty, the nature of waves and the nature of energy levels. The instrument was administered to 231 physics students at the University of Sydney in 1995. A phenomenographic analysis was adopted and supported by content, context and correctness analyses. The results suggested that new concepts presented in class are considered superficially; reintegration of inappropriately associated pre-existing concepts does not frequently occur; development of mental models with time is minimal, the majority of students retain their original secondary school conceptions; and students have great difficulty in using models to interpret data.

## INTRODUCTION

Despite the fact that quantum mechanics is an area of widespread importance, it has not until recently attracted much pedagogical research and introductory courses are still taught in much the same manner as they have been for the past sixty-five years. There have been impressive advances in understanding how students conceptualize other areas of physics, but these have not impacted or addressed the problems associated with quantum mechanics. It was the purpose of this investigation to design a survey instrument to explore the conceptual development of students by examining four key concepts.

## METHODOLOGY

### **Instrument Construction**

The final instrument comprised four questions printed double sided on a single sheet of paper and a multi-page answer booklet. Whilst it was desirable that questions should encourage students to construct carefully thought-out answers and provide rich responses, purely open-ended formats tend to generate diverse responses, raising issues with coding and validity in the final analyses. To strike a balance it was decided that a tick-a-box-and-explain format would be used where good distracters were known, and open-ended with sufficient prompting to constrain the diversity of responses were used when distracters were not available.

### **Analysis**

The analysis took several forms. For the tick-a-box responses a simple correctness analysis was performed by comparing the responses with approved answers. This analysis provided fast feedback for students and timely statistical information for the lecturers. For the open-ended components of the responses a selection of appropriate qualitative analyses were performed.

### *Phenomenographic*

The primary method of analysis was to categorize the responses into qualitatively different groupings based solely on what the students drew or wrote; with no reference to the correctness or appropriateness of their response. This approach draws on the work of Marton<sup>1</sup> and for convenience has been described as phenomenographic.

### *Contextual*

During preliminary analysis it was noted that that students would offer their responses in a variety of contexts. For example some would chose to mention the properties of a wave (*what it has*); some offered a metaphor or pictorial image (*what it is like*); and some brought forward experimental evidence (*what it does*). It is believed that this form of analysis should provide information about the structure of the mental models that the students have constructed.

### *Content*

In light of the importance of terminology and the primacy of standard textbooks in determining the subject matter, it was felt that terminology used by students is an important component of their responses. Therefore all terms and ideas presented were recorded and categorized to be “appropriate” or “inappropriate”.

### *Correctness*

Analysis of the correctness of the written responses was not considered particularly important in such a project directed towards investigating the learning process. However, from a physicist’s point of view, the original motivation for the project suggested that some attention be directed to the appropriateness of the responses. Thus it was only carried out superficially in this study.

## **RESULTS / DISCUSSION**

A series of survey-based questions were used to explore the conceptual development of introductory level students. It is useful to identify four different phases in the process by which students develop mental models of the subject material they are studying: assimilation, accommodation, accumulation and application. This research addressed one question to each of these four phases in order to probe where potential problems might lie. The results suggest that the processes used by students in each phase are failing to provide them with sufficiently robust frameworks to successfully solve problems. The main difficulties encountered by the students at each phase follows:

### **Assimilation Phase**

The student was asked to imagine they are in a quantum mechanical world and had to consider a measurement involving catching a bus. Their timetable said the bus would arrive at 9:00am. The student then had to explain what was meant by the bus having an associated Heisenbergian uncertainty. A set of known good distracters was presented in the multiple-choice component.

The analysis sought to explore the students’ understanding of the term uncertainty in the context of quantum mechanics. It was revealed that a third of the students picked the correct tick-a-box response but only 9% ticked the correct response and provided correct supporting reasoning. The phenomenographic analysis indicated that 90% of the students are not seeing uncertainty as a new concept and are just utilizing other meanings associated with the word uncertainty in other contexts. Quite interestingly it was noticed that nearly one third of the written responses did not mention the bus within their descriptions although explicitly directed to do so.

The main problem seems to be that students file information in the wrong place. It appears that the material is being learnt out of context, as far as their everyday experiences are concerned. Therefore the only things they can relate to are other ill understood pieces of physics and mathematics they have encountered that seem to relate in some way. The students are not recognizing uncertainty as a new concept but instead they take their prior conceptions and simply apply them to the world of quantum mechanics.

### **Accommodation Phase**

In this question the student would pretend they were listening to a conversation between fellow class members discussing concepts raised in previous lectures. The conversation treated spectral lines as evidence for energy levels. It described how Bohr’s model combined several earlier ideas and included de Broglie’s proposal that electrons are also waves. The conversation then turned to the student, who was then asked whether they know “What is meant by energy levels?” and “What is meant by wavelength fitting into an atom?”. The question was purely open-ended.

This question was basically a ‘fishing expedition’ to find out what conceptions students associated with some fundamental ideas concerning Bohr’s atomic model. The phenomenographic analysis was considered the primary research tool followed by context analysis. The analysis revealed that the students have adopted either a concrete or an abstract model of the atom. It also appears from the responses being limited to only explanations related to physics that the students did not or could not associate these concepts with any everyday experiences.

The phenomenographic analysis of the question concerning the nature of energy levels revealed six categories of description with two predominant being *orbit/shell* 46% and *discrete energy* 44% and all other categories making-up approximately 10%. It was noted that categories were not referred to in the stem of the question; they were new concepts that students offered from their own background knowledge. The two predominant categories were not exclusive but identify a very strong separation, this separation was noticed to reflect a dichotomy between concrete and abstract. The context analysis revealed several important aspects concerning how students relate to the topic. The first point was that essentially no responses provided analogies (only one response used the analogy of a vibrating guitar string to describe a localized wave). It was noted that all responses were purely limited to presenting equations and evidence that related purely to physics. These observations indicated that students have not made any substantial associations with non-physics phenomena.

Analysis of the question concerning the nature of the wavelength fitting in revealed six non-exclusive categories, three were predominant: *fitting in* 60%, *integer multiple of wavelengths* 48% and *energy* 25%. An interesting distracter included in the 2nd category was that the electron moved along a wave-like path around the orbit, upon investigation 8% of the total responses articulated this belief. Further analysis revealed that students predominately hold one of three different conceptualizations concerning what is meant by a wavelength fitting into an atom; (1) Integer number of wavelengths fill in the orbit and join head to tail 48%; (2) the energy of the electron match the energy of the orbit 25%; (3) the electron moves in or traces out a 'wavy' orbit 8%. Supporting the results in the prior analysis it is worth noting that (1) and (3) are concrete ideas that can be visualized, whereas (2) is an abstract conceptualization.

Our analysis suggested that students do not reorganize concepts sufficiently nor seek cross-linkages outside the confines of the topic. Despite having dealt with these concepts for at least two years, the students had not thought about the overall integration of the associations they held. Their knowledge has simply been filed by tacking it onto the first notions associated with these ideas. There was no evidence that they had constructed new links to other disciplines or developed alternative ways of describing the concepts during more recent studies.

### **Accumulation Phase**

The student was provided with information about what constitutes a particle and then given several examples of waves. They were then asked to tick the box that most clearly describes what is meant by "something is a wave". The tick boxes did not include the usually accepted response superposition/diffraction/interference, therefore the final "None of the above" option would be the 'correct' response. They were then asked to support and explain their answer.

The analysis sought to investigate the similarities and differences between mental models possessed by first and third year students. The question was based upon a survey previously carried out on third year physics students<sup>2</sup>. The final analysis showed that students appear to cling to the secondary school ideas associated with a wave and do not significantly modify their mental models during their studies of physics.

We point out that there exists a standard textbook answer to this question and when first year students were previously quizzed 70% chose the option containing interference/diffraction whenever that response was explicitly one of the options offered. Whereas in this study only 30% ticked the response which had the textbook answer hidden within it. But more surprisingly only 12% of these (ie 4% of the whole) provided explanations justifying their selection by referring to the textbook answer. The most popular distracter was everything is a wave scoring 33%, the major reason for this was probably due to the profile or emphasis that was placed upon the 'wave nature of matter' during the course. A correctness analysis was applied which checked each written response, this revealed that only 12% of the total responses could be considered correct in the sense that they had provided the textbook answer and fewer than half of these, although they provided the textbook answer, were tempted by the distracters.

The wider and more important question concerning the actual ideas and mental models that students possess and the comparison between the first and third year responses was investigated using phenomenographic analysis. The analysis of the third year responses revealed two categories and the first year responses revealed four distinct non-overlapping categories of description. These categories can be considered as representations of what students 'think' when considering the nature of a wave. Each category comprises a structured path and interestingly the two third year categories mapped exactly in



internal structure to the two dominant first year categories. This result clearly indicates that there is not a great deal of significant development of these mental models during the students' studies in physics.

This question was designed to find out if the mental models of first year differed from those of third year students. The comparison strongly indicated that there was very little development in content, context, structure or complexity. The majority of students still retained a secondary school view of waves. The third year responses were more focused, yet the distributions between and internal to the phenomenographic categories were very similar. This is even more surprising when one considers that the first year sample comprises a mixture of students from a variety of backgrounds with varying interests. The third years on the other hand have chosen physics as their major line of study and have completed a minimum of two years in secondary school and two and a half years of undergraduate level physics.

### **Application Phase**

The nature of the photoelectric effect lent itself nicely to the construction of a survey question that utilized an analogy and visual model. The question focused upon the two key experimental observations and their relationship to the wave and particle nature of light. The students were provided with the "bird on a wire" analogy and a standard text book description of the experimental observations. They were asked to explain the observations in terms of the analogy.

Analysis of responses revealed that the students are indeed having great difficulty in several areas. The students were clearly guessing which answer was correct, only guided by a thought that the photoelectric effect had something to do with the particle model of light. Students were unwilling or unable to use the models presented in the question to explain the observations. These problems appeared to stem from their inability to recognize, interpret and apply features of the model.

The analysis of the multiple-choice component showed that approximately 45% of the students selected the correct option in each observation and 18% of the students ticked both correct options. However upon examination of the written responses only 7% got the part dealing with intensity correct, only 1% got the part dealing with the frequency correct. In toto, only 1 student out of a sample of 205 got both parts correct.

It is abundantly clear that students have difficulty in applying their mental models in new situations. The final consequence of the problems identified in the previous phases is reflected in the analysis of this question. When the student is presented with a different model which contained familiar concepts in an unfamiliar context, they were unable to perform the necessary re-interpretation. They did not have the capacity to make the links between their own mental model and the new model. For example, this study found clear evidence that the majority of students did not understand the terms frequency and intensity in relation to the "bird on a wire" analogy.

## **FUTURE DIRECTIONS**

This study has identified a number of interesting points. It is also recognized that there are a number of shortcomings mainly concerning the reliance on written responses captured in a survey. What is needed now is to undertake an extensive program of student interviews to confirm that our interpretations of what they are thinking is correct and to expand the scope of concepts examined.

The development of a more streamlined survey instrument that could be used earlier in a course as a diagnostic instrument and provide fast formative feedback would prove invaluable. This study has provided the basic foundation to assist in further exploring the questions surrounding this topic.

<sup>1</sup> Marton, F., "Phenomenography – A Research Approach to Investigating Different Understandings of Reality", *J.Thought*, **21**(3), 28-49 (1986)

<sup>2</sup> Johnston, I.D., Crawford, K., and Fletcher, P.R. "Student Difficulties in Learning Quantum Mechanics", *International Journal of Science Education*, **20**, 427-446 (1998)

# INTRODUCTION TO QUANTUM PHYSICS -DEVELOPMENT AND EVALUATION OF A NEW COURSE

Helmut Fischler

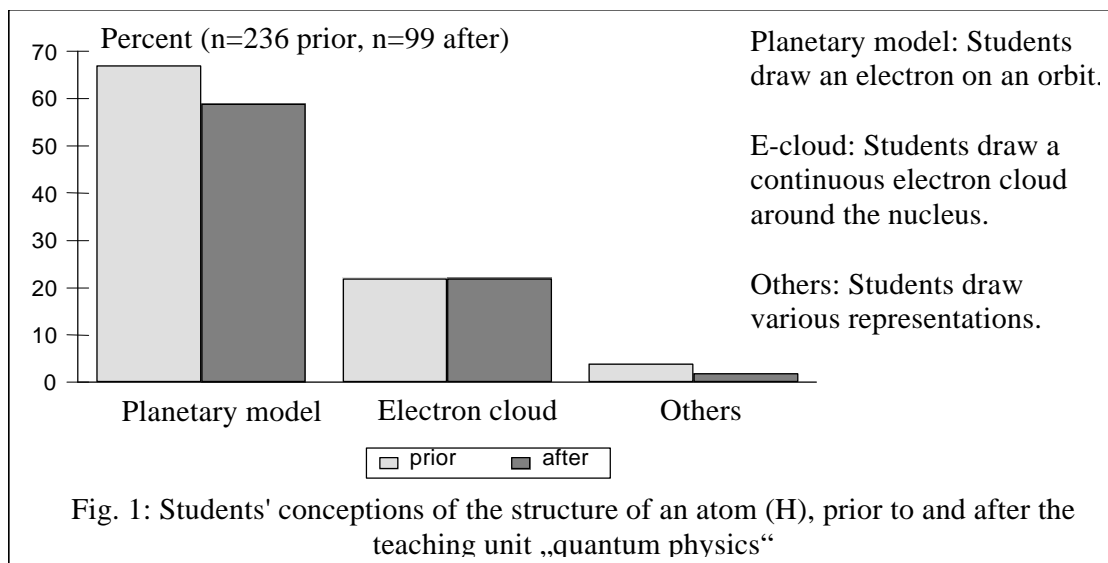
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In physics education, teaching often uses semiclassical models and concepts. The atomic model of Bohr and the concept of dualism are part of many textbooks for upper school grades. However, for more than 70 years we know that a new modern theory describes the behaviour of atoms, molecules and matter very well. Only quantum mechanics is able to describe the characteristics of matter consistently.

Consequences for teaching physics at upper school grades were drawn. An introduction to quantum physics was designed which omits all analogies to classical physics. In the evaluation of the teaching unit, students' conceptions were recorded both at the beginning and the end of the teaching. Students in the test groups dispensed with visualized conceptions and reached an understanding which is more suitable to modern physics.

## THE CURRENT SITUATION

The diagram in Fig. 1 has been the starting point of the developmental work on a new concept for an introduction to quantum physics at high school level. Fig. 1 shows that prior to the traditional teaching unit "quantum physics" the planetary model is the dominating model in students' mind. After this unit, the situation is almost the same. There are some reasons responsible for this result:



One of students' main misunderstandings at the end of lower secondary school is the idea that particles like atoms and molecules have the same macroscopic characteristics as the material that they constitute.

Students transfer macroscopic properties to the particle world.

Almost all textbooks for upper grades introduce the planetary model (Bohr) to students.

Many teachers use it in order to explain the characteristic features of the atoms' spectrum. Their justification for using the Bohr model is twofold:

The Bohr model, because of its descriptiveness, can be easily understood and provides explanations for many observations.

(b) The Bohr model was of enormous significance in the process of developing modern physics. Students should be introduced to this important stage.

In physics, the Bohr model was replaced 70 years ago by quantum mechanics in which the description of the atom dispenses with all visualizations. The traditional approach used by most of the teachers is criticized on the grounds that, in being oriented to historical development, the teaching over-emphasizes the conceptions of classical physics. The usage of mechanical models, which is implied in this, sets up an additional obstacle to an appropriate understanding of quantum physics. Thus:

“In school physics, the subject matter of modern theories is described with methods and conceptions of classical physics which, for this purpose, are insufficient. In so doing, all the unnecessary contradictions and difficulties are introduced into the school, which even the most outstanding physicists of the semi-classical epoch in physics (c. 1900-1925) had to grapple with because they had not yet fully uncovered the causes of these difficulties.” (Brachner/Fichtner 1974, p. 84; translation by the author of the present paper.)

## **CONDITIONS OF LEARNING MODERN PHYSICS**

Problems of elementarization (that is, of reducing more difficult concepts into simpler terms) become central to didactic reflection in quantum physics more than in any other topic. Although there are no universal principles of this process as yet, there is one principle which can nevertheless be deduced from all the investigations in psychology of learning: So the student is not forced to reorientate his basic conceptions, simplified models should be constructed in such a way that they are capable of being extended. This applies in particular to such models which, because they approach concepts of everyday life, are very attractive to students. The more these conceptions are strengthened in class the more impossible it is to overcome them, whereas in quantum mechanics such concepts have to be overcome.

Students who have been shown the efficiency of Bohr’s atomic model will have little success in surmounting this illustrative model. To resort temporarily to mechanical aids for the sake of illustration would be to conceal the fundamental difference between the students’ concepts encouraged by this model and the correct physical description. An electron’s orbit is not simply an auxiliary device which is almost correct and can thus function for a while as a comprehensive aid. Every single argument supported by the concept of orbit makes the necessary change in thinking more difficult, delays the due process of discarding mechanical models, and finally renders this process impossible. Such an opinion can be drawn rather clearly from observations about the stability of students’ conceptions.

The only way to respond didactically to this situation is to lay the foundation for the intended understanding as early as possible, while avoiding the encouragement of concepts which contradict this understanding. The latter, however, occurs if one emphasizes the efficiency of illustrative concepts over a longer period of time while not confronting the students with modern ideas until near the end of the teaching unit: the result is then a kind of confrontation, which rather ‘concedes’ the failure of the theory which has been treated until then, instead of presenting the explanatory possibilities of the newer approach.

## **A NEW CONCEPT IN INTRODUCING QUANTUM MECHANICS**

The results shown in Fig. 1 and other findings demonstrate that most students hold the following conceptions about the basic ideas of quantum physics after teaching:

The atom is described as a planetary system (Bohr).

Photons have particle characteristics.

Students have a naive dualism conception. Whether light shows its wave-like or its particle-like nature, depends on the experiment we use to detect it.

The notion of a quantum object’s trajectory is not put into question.

Consequently, a concept which prevents the students from attempting to understand the phenomena of quantum physics in terms of classical physics, will have to proceed from the following basic decisions:

One should avoid reference to classical physics.

The teaching unit should deal first with electrons (not with photons when introducing the photoelectric effect).

For the explanation of observed phenomena one should use the statistical interpretation and avoid dualistic descriptions.

The uncertainty relation of Heisenberg should be introduced at an early stage (formulated for ensembles of quantum objects).

When dealing with the hydrogen atom, Bohr’s model should be avoided.

By choosing the demonstration of a diffractive, or interference pattern which is composed of stochastically distributed individual processes, not only do we dispose of the problem of dualism but come directly to modern conceptions. Therefore, the teaching unit presented here begins by observing and discussing such figures which the students are already familiar with in wave optics. It is the purpose of this unit to consciously break with previous ideas and conceptions in order to emphasize the “curious” behaviour of quantum objects. Entirely consistent with this intention would be to describe this behaviour

even as “mysterious”, as often happens in English literature of high didactic standard, that is to say, not just in popular descriptions (for examples see Squires 1986, Feynman et al. 1965).

In order to describe this strange behaviour of quantum objects, electrons are more suitable than photons. This follows from the hypothesis which states that students are more likely to associate photons with classical particles than to imagine electrons as being some sort of matter-waves. Although the double-slit experiment cannot be demonstrated experimentally with electrons, this disadvantage will have to be tolerated for sake of the advantages in teaching this approach. Besides, this disadvantage is not so great since there are good films available which cover this topic.

The didactic reflections (as already mentioned) resulted in the following macrostructure of the teaching unit:

Electron diffraction

De-Broglie relation  $p = h/\lambda$

$p$ : momentum of the electrons (treated classically before hitting the crystal).

$\lambda$ : wavelength related to the luminous phenomenon in the electron tube, if being interpreted as interference pattern.

Details see next section.

Double-slit experiment with electrons, Film – Original treatise of Jönsson

Details see next section.

Heisenberg’s uncertainty principle

There does not exist an ensemble of quantum objects whose mean variation both of their momentums’  $x$ -components and of their  $x$ -positions cannot be very small at the same time:  $\overline{\Delta x} \cdot \overline{\Delta p_x} \geq h/4\pi$ .

Consequence: The quantum objects have a localization energy.

Quantization of energy for a square-well potential and for the hydrogen atom

$$W_n = h^2 \cdot n^2/8ml^2.$$

This quantization is derived by considering an analogy: in the double slit experiment the electrons have shown a distribution on the screen which is similar to an interference pattern. In a square-well potential the distribution of the probability of finding an electron will presumably be similar to standing waves. This hypothesis is confirmed by the results of the experiments which are carried out in the following part of the teaching unit.

Quantization of energy for the hydrogen atom:  $W = W_L + W_{pot}$  ( $W_L$ : energy of localization,  $W_{pot}$ : potential energy).

Franck-Hertz experiment and spectroscopic analysis

The Franck-Hertz experiment as a confirmation of the quantization. The mercury atoms absorb energy only in distinct portions  $\Delta W$ . This energy is emitted as radiation with a frequency that is connected with  $\Delta W$  via  $h$ , where  $h$  has the same value as in the De Broglie relation:  $\Delta W = h \cdot f$ . Spectrum, energy level scheme. The equation  $\Delta W = h \cdot f$  can be read from right to left: influenced by light with the frequency  $f$  the atoms gain energy in discrete lumps  $h \cdot f$ . Absorption lines.

Quantum objects of light: photons

(exterior photoelectric effect, Taylor experiment: stochastic distributions in double-slit experiments).

Problems of interpretation

What is the meaning of  $\lambda$ ? ‘Waves of chance’. Causality in modern physics. Copenhagen interpretation.

Detailed descriptions of the experiments, information about the scientific background, and proposals for the teaching process are included in a teachers’ guide which was sent to all high schools in Berlin. In some physics groups this teaching unit was evaluated with the possibility of drawing data from the processes as well as from the outcomes.

## THE STRANGE BEHAVIOUR OF ELECTRONS

Details of the first two sections of the teaching unit are to give an impression of the didactical principles which are guidelines on the instructional structure of the unit.

In the electron diffraction tube (Fig. 2), the rings on the screen show a pattern that is already known from experiments with light. Students have their difficulties to understand this phenomenon because for them electrons are classical particles. Some statements made by students confronted with this structure show their confusion.

There are interferences! This looks like Newton's rings.

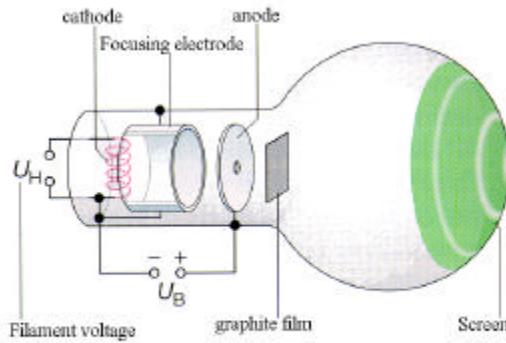


Fig. 2: Electron diffraction tube

Electrons obviously move wavelike.

One particle activates the next.

(Counterargument of another student: Actually, the tube is evacuated.)

If the electrons are not waves before hitting the crystal they couldn't cause interferences.

Electrons and light are different things. For me, these rings cannot be explained.

It is plausible to assign a wavelength  $\lambda$  to these rings. It is not necessary to speak of electron waves. The variation of the accelerating potential

difference in the tube results in the De Broglie relation  $p = h/\lambda$ ,  $p$  is momentum of the electrons treated classically before hitting the crystal,  $\lambda$  is wavelength related to the luminous phenomenon in the electron tube, if being interpreted as an interference pattern (Fig. 3).

The 'double-slit' experiment with electrons cannot be demonstrated in reality. There are several good films available.

High intensity: the distribution of the intensity is similar to interference patterns with light. Therefore one

can conclude: electrons are not classical particles. Low intensity: statistically distributed singular events. Therefore electrons cannot be described as a wave. Electrons are quantum objects (Fig. 4).

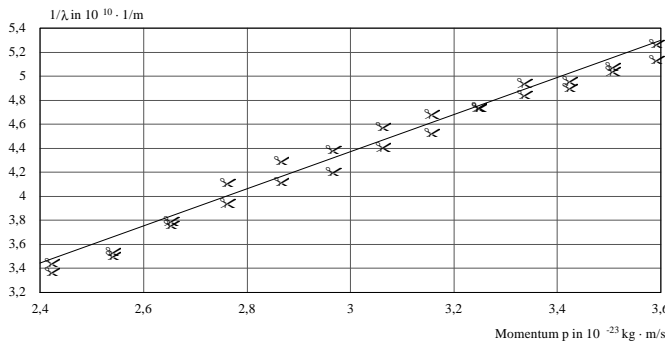


Fig. 3: Electron diffraction. The inverse wavelength (assigned to the pattern on the screen) plotted against the electrons' momentum

An interesting experiment with classical particles is a part of the teaching unit: Thousands of small pellets pass a double slit and fall into segments where the distribution can be observed (Fig. 5). Students' statements show that they now

attribute

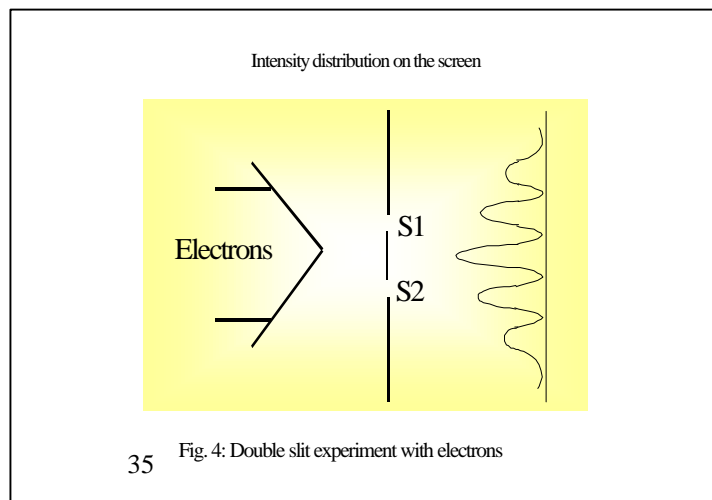
## STUDENTS' STATEMENTS PRIOR TO THE EXPERIMENT

I expect an interference structure.

If this model is correct, then an interference pattern must appear.

- Actually, I expect an interference pattern. Why otherwise one should have constructed this model?

Actually, electrons are particles, therefore these particles should be



35 Fig. 4: Double slit experiment with electrons

comparable with electrons. the electrons' behaviour also to classical particles. For them, electrons are still classical particles, so pellets have to have the same behaviour.

## EVALUATION OF THE TEACHING UNIT

The teaching unit was tested in a total of eleven physics courses of several high schools in Berlin. It was a central decision for the evaluation process to choose a multidimensional approach which allowed to trace a single student's learning processes as well as learning outcomes of groups. Therefore, research followed the steps below:

A questionnaire was given to students in all 11 courses, and interviews were carried out on two courses before the start of the lessons to find out what conceptions the students then held.

Video recordings were taken of all 32 lessons in six courses in order to discover correlations between students' conceptions and their answers given during the lessons, and to obtain additional verifications for the conceptions which had been collected from the students.

Five weeks after the end of the teaching unit a second questionnaire was given. From these data the conceptions which students held after the end of the lessons were worked out. With the help for students' interviews from three courses we wanted to make sure the information gathered in this way was correct.

We gave the same questionnaire to the students before and after the teaching unit in 14 further courses (control group), which introduced quantum physics in the conventional way of the Berlin syllabus. This was done to help us correctly value the conceptual patterns shown in the courses in which the new teaching concept had been tested.

All questions were assigned to the range of topics which make up the subject-matter for teaching quantum physics in school: light, atom-electron, particle-body, and students' ideas on the philosophy of science. The questions themselves were different in type: open questions, e.g. 'What really is light?'; word-pair associations, e.g. 'electron-real body'; drawings, e.g. 'What do you think a real hydrogen atom looks like?'

In total, written statements were gathered from 270 students of which just under 150 belonged to the test group (taught through the new teaching unit) and more than 120 belonged to the control group (taught along customary lines). The verbal answers given by the students during the teaching unit and in the interviews were transcribed from the videotapes. The transcripts also include notes on students' play of features and gestures as remarks.

The results of the research consisted of four steps:

Overview of students' conceptions before the beginning of the teaching unit.

Comparison of students' conceptions of the two groups (test and control group) five weeks after the lessons.

Perceptions in the process of change: a comparison of students' conceptions before and after the teaching unit (whole data of all students).

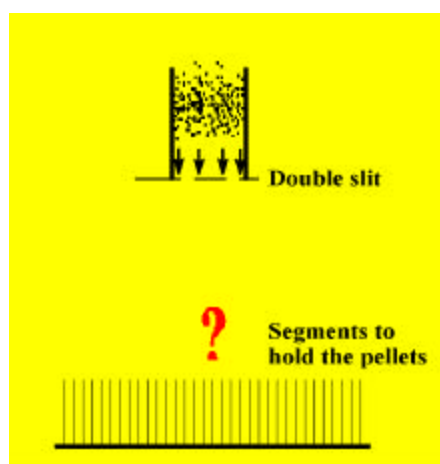
Design of ideas' networks from all data of one student from the beginning of the teaching unit up to the second questionnaire and interview.

In the following, some examples will be given for each of the four steps.

### STUDENTS' CONCEPTIONS BEFORE THE TEACHING UNIT

One of the items in the questionnaire referred to the topic 'atom-electron'. Some of the open answers given by the students before the beginning of the actual lessons about the introduction to quantum physics were:

*... because the electron is tightly placed on an atomic shell, i.e., there is a distance between the shell and the nucleus so that the electron cannot get to the nucleus.*



**Fig. 5: Double slit experiment with classical particles**

The electron is acted upon by the centrifugal force and the attractive force of the atom. Both forces are in equilibrium (Bohr's atomic model).

The electron is separated from the nucleus by its high velocity (centrifugal force).

As a result of the high angular velocity of the electrons, the resulting centrifugal force prevents the electron from falling into the nucleus under the influence of the attractive force.

Because the charges of electrons and protons neutralize each other.

The electron is negatively charged while the nucleus is positively charged. Again, the electron is subject to a kind of centrifugal force which keeps it in its orbit. Therefore they rather repel each other.

Electrons are fixed in their shells.

From these answers, typical patterns could be constructed which show students' conceptions:

**Circle (circular orbit):** conceptions of electrons which fly round the nucleus with (high) velocity in fixed, prescribed orbits. In this conception the centrifugal force and the Coulomb (electric) force are brought into equilibrium. The students use their experience with roundabouts first to explain the movement of the planet, and then second to explain the process in atomic shells, without regard to reference systems (63% of 240 students in both groups).

**Charge:** students have a fixed conception of the repulsion between charges. They often explain the properties of charges incorrectly. The charges of both the proton and the electron cause a distance between the two particles (23% of 240 students in both groups).

**Shell:** conception of a firm casing (shell, ball) on which the electrons are fixed or move (8% of 240 students in both groups).

In conclusion it can be noticed that the students already possessed a fixed idea of an electron in an atom, being strongly based on a mechanistic conception. The question is, therefore, whether normal teaching, including the treatment of Bohr's atomic model as an explanation of the quantization of energy levels, does imply the reinforcement of already existing thought patterns.

## CHANGE OF STUDENTS' CONCEPTIONS

A comparison of the conceptions of the students from the two groups (test and control group) after the lessons demonstrates that different changes in conceptions have taken place. First of all, another conceptual pattern could be constructed from students' answers:

**Loc. (localization energy):** the stability of atoms was regarded by the students as connected with the Heisenberg uncertainty principle. According to this conception, the mere restriction of space results in a rise of the kinetic energy of the electrons, the loci of which are subjected to a statistical distribution. At the same time the students dispensed with statements about single electrons which they thought of as inconceivable.

In Fig. 6 the changes in students' conceptions concerning the stability of an atom are given.

Within the range of topics discussed here, a clear dependency on the teaching experienced by the students can be observed: 68% of the students in the test group oriented themselves toward the conception of localization energy (*Loc.*) while the students of the control group persisted in the conception of *circle* and *shell*.

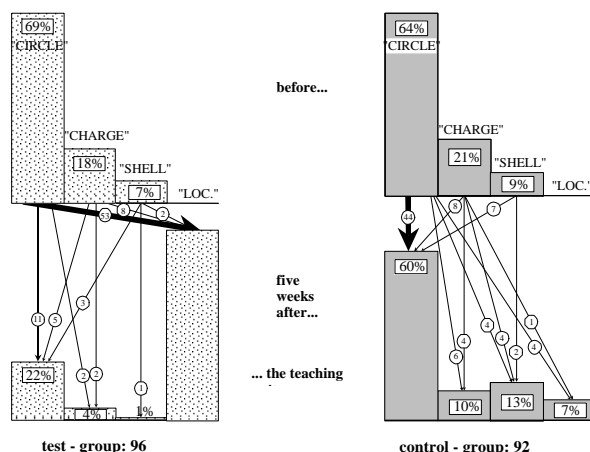


Fig. 6: Change of students' conceptions of an atom's stability.

## SUMMARY OF THE EVALUATION

The example given illustrates the trend of the results of the investigation. A teaching approach, for example like the one introduced here, which, from the outset, considers possible conceptions of students in detail and consciously provides room for these conceptions to develop in class, will achieve an increased cognitive conflict situation which will then, in turn, lead the students to grapple with the subject. In this way, the students became conscious of their own conceptions and began to question them. The students became conscious of their own conceptions and began to question them. The results of the control group pointed to an incorporation of the 'new' phenomena into the 'old' mechanistic ideas. Here, the different ideas in quantum physics were merely acquired verbally and were forgotten again afterwards. This statement is supported by Fig. 7. Here, for all items of the various topic areas, the conceptual changes are rated, summarized, and reproduced separately for test group and control group.

### STUDENTS' NETWORK STRUCTURES

Students "react to things on the basis of meanings which these things have for them" (Blumer 1976, p. 81; translation by the

author of the present paper). This approach proceeds from the theory of symbolic interactionism (adapted from Mead, Schütz), according to which, meanings are built up on the basis of a correlation between a "stock of commonplace knowledge" and "situational experience" (Schütz/Luckmann 1979; p. 133; translation by the author of the present paper).

On the basis of this interaction, a research approach is formulated, which constructs cognitive networks of students from the interpretation of students' ideas together with their meanings. These networks themselves, according to this assumption, reflect students' conceptions.

The following figures point out network structures of two students, both constructed before and after the lessons. The initial sets of single ideas were deduced from the total data set of all students' answers before and after the lessons. The single answers show students' main ideas. The ideas themselves are interconnected through various features demonstrating the connection of meanings (following Klix 1976, his adaptation by Norman and Rumelhart 1975):

R: represents a relation between general ideas and sub-ideas. Features which form a general idea can be transferred to the sub-idea (..is a..).

CM: typifies characteristic features of an idea through the use of other ideas (..heard..;..has..).

AM: typifies active features which characterize an idea (..can..).

N: points out that a character of an idea consists in establishing another idea (shown with..).

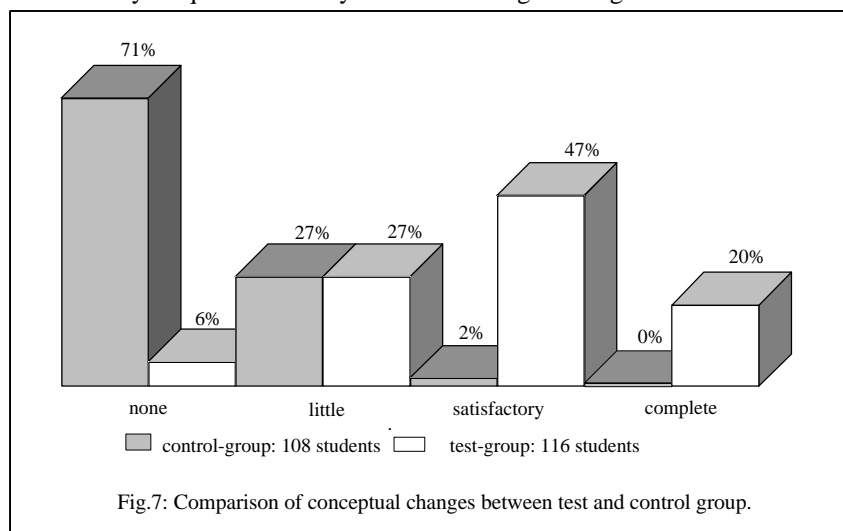
ZO: illustrates a relation between two ideas without itself being a characteristic feature (..will be assigned..).

TI: signifies partial identity of two ideas (..is like..).

WI: contradiction: no further relation between both ideas (..it cannot be..).

Fig. 8 and 9 show the networks of a student from the group which throughout the lessons received an introduction to quantum mechanics according to the new concept (see Berg et al. 1989); whereas Fig. 10 show the networks of a student who was enrolled in a course which followed the regular Berlin syllabus.

In Fig. 8 and 9 the two networks give an impression of the development of ideas and their meanings. The students was able to change his basic ideas in atomic-physics (see Fig. 8) to the new idea of the quantum (see Fig. 9). For him the quantum is something new without a relation to the classical wave or real particle. In the other case (see Fig. 10) the student was fitting the new ideas into the old network. The photon





became a real particle, and the electron is still on a fixed prescribed orbit around the nucleus now under oscillation.

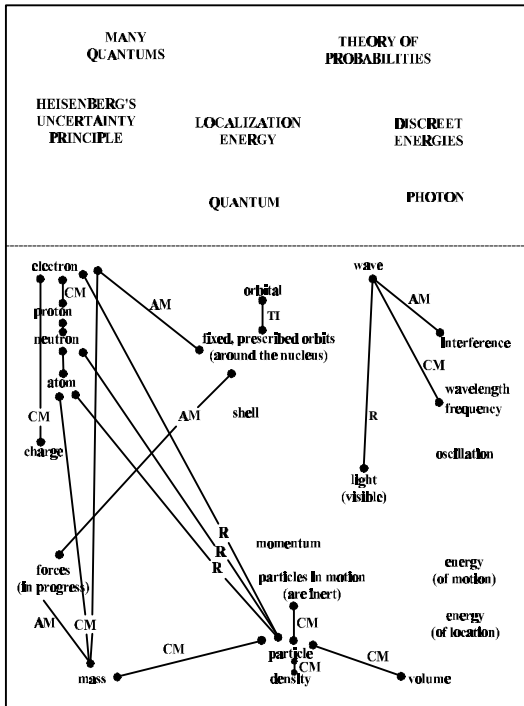


Fig. 8: A student's cognitive network before the lessons - test group

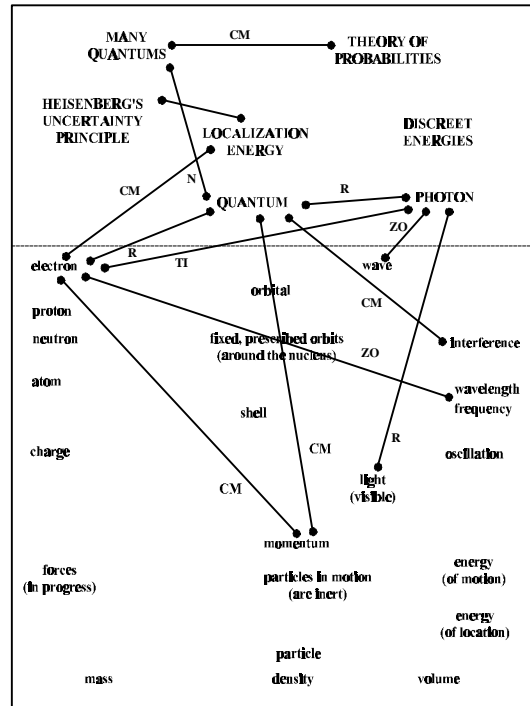


Fig. 9: A student's network of ideas (test group): five weeks after the teaching unit

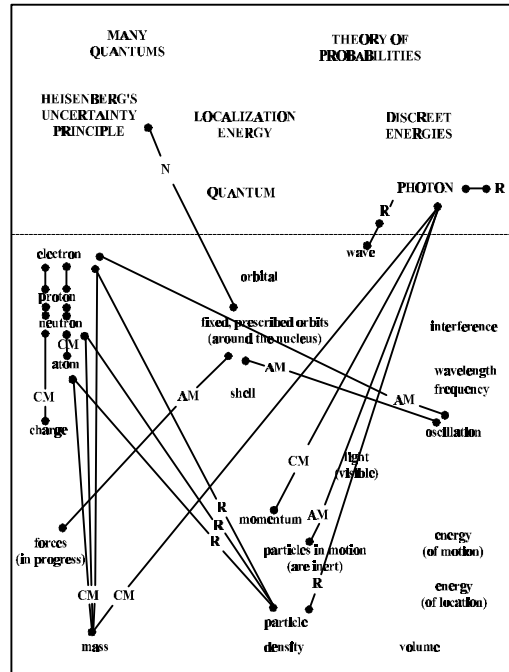


Fig. 10: A student's cognitive network after the lessons - control group

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# THE INFLUENCE OF STUDENT UNDERSTANDING OF CLASSICAL PHYSICS WHEN LEARNING QUANTUM MECHANICS

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## INTRODUCTION

Understanding quantum mechanics is of growing importance, not just to future physicists, but to future engineers, chemists, and biologists. Fields in which understanding quantum mechanics is important include photonics, mesoscopic engineering, and medical diagnostics. It is therefore not surprising that quantum is being taught more often to more students starting as early as high school. However, quantum mechanics is difficult and abstract. Furthermore, understanding many classical concepts is prerequisite to a meaningful understanding of quantum systems.

In this paper, we describe research results of two examples of the influence of student understanding of classical concepts when learning quantum mechanics. For each example, we describe difficulties students have in the classical regime and how these difficulties seem to impair student learning of quantum concepts. We briefly discuss how these difficulties can be addressed.

Obviously the examples described in this paper are not intended to be exhaustive. Instead, we have two objectives. The first is to highlight the importance of having a strong conceptual base when learning more advanced topics in physics. The second is to illustrate the importance of continuously and systematically probing student learning by using the tools of physics education research.

## PHYSICS EDUCATION RESEARCH

The results described in this paper come from systematic investigations of how student learn physics. Research tools include classroom observations, free response and multiple-choice diagnostics, videotaped and transcribed individual demonstration interviews, and many other methods. Due to space limitations, we will only cite the results of a few studies and provide references where further details can be found. An overview of the field of physics education research can be found in a recent issue of *Physics Today* (Redish & Steinberg, 1999).

## FROM PHYSICAL OPTICS TO PHOTONS

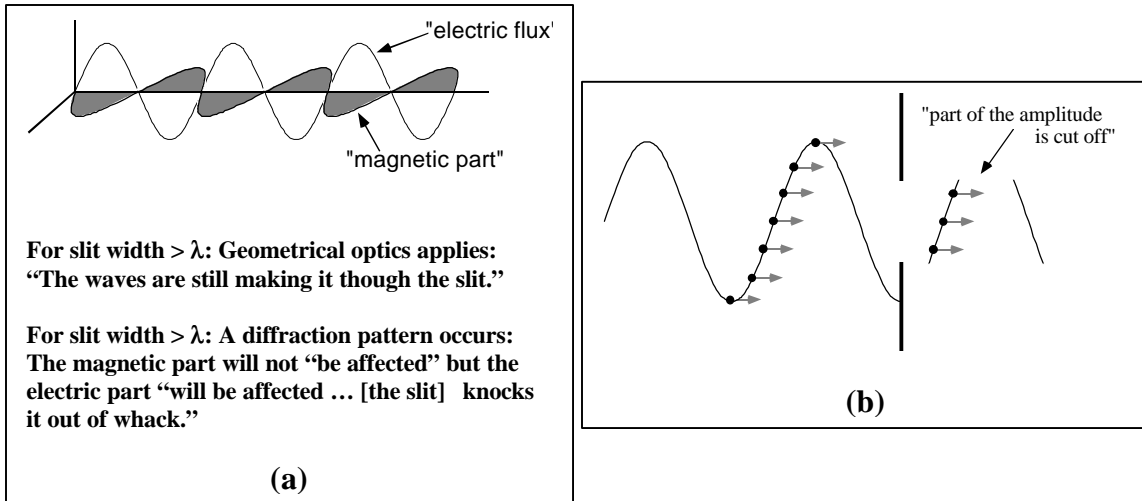
Before studying modern physics and quantum mechanics, students first typically study mechanical waves and then physical optics. The reasons behind this are logical. The wave properties of matter, wave-particle duality, and atomic spectroscopy make no sense if one does not understand superposition, wave representations, and diffraction. In this section, we describe how student difficulties interpreting the wave nature of light can propagate when they are introduced to the concept of a photon.

### **Students struggle with learning physical optics ...**

Difficulties that students have learning models of light have been reported (Ambrose et al., 1999). Clearly, most students do not develop a reasonable wave model for the behavior of light. For example, about half of the students who had just completed the introductory calculus-based physics course believed that the amplitude of a light wave is spatial (as opposed to electromagnetic). Many students speak of waves “fitting” or “not fitting” through a narrow slit while trying to describe diffraction. Fig. 1a shows a student response in an interview when asked to describe the behavior of light passing through a narrow slit. His response was typical.

### **... and then they study photons**

When studying more advanced topics in physics that follow physical optics, students appear to take with them difficulties such as the one exemplified in Fig. 1a. This can lead to misinterpretations of, among other things, the quantum nature of light (Steinberg, Oberem, & McDermott, 1996). Instead of correcting the way they think about light, many students incorporate the new physics they are learning into their faulty model. Many introductory students think of the amplitude of light as a spatial quantity. It appears that these students then simply have photons moving along sinusoidal paths when they learn about



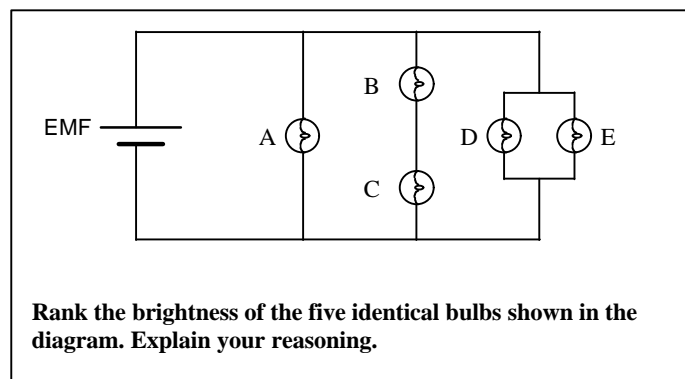
**Figure 1. Typical student descriptions of light passing through a narrow slit: (a) Diagram and explanation given by a student who just completed introductory calculus-based physics. (b) Diagram drawn by student who just studied the photon.**

the particle nature of light. Fig. 1b shows an example of how a student who had just studied about photons describes the behavior of light as it passes through a slit. Other students had photons traveling up and down along the sinusoidal path.

### FROM CIRCUITS TO BAND DIAGRAMS

In teaching elementary quantum mechanics, band diagrams, and the fascinating properties of semiconductor devices, instructors typically assume that their students have a reasonable model of conductivity. After all, what sense can a MOSFET make if students do not have a functional understanding of current and voltage? In this section, we describe some of the difficulties that many students have when they study current and voltage in a college physics class and how these difficulties can limit understanding of students who are studying more advanced models for conductivity.

**Students struggle with learning current and voltage ...**



**Figure 2. Part of an examination question given to introductory calculus-based physics students after they had finished studying dc circuits. Only 16% of the 94 students in the class gave the correct ranking ( $A=D=E>B=C$ ).**

McDermott & Shaffer (1992) have documented difficulties students have when they study current and voltage in college physics. They found that many students do not know what a complete circuit is, do not have a model for current as a flow, and do not have a functional understanding of voltage. At the University of Maryland, in an introductory calculus-based physics class dominated by sophomore engineering majors (many of them in electrical engineering) we reproduced these findings. For example, in a class of 94 students that had just studied dc circuits, equivalent resistance, Ohm's law, and Kirchoff's laws, only 16% correctly answered the final examination question shown in Fig. 2. Student difficulties, such as the current being "used up" in bulb B before getting for bulb C, were essentially the same as those described by McDermott & Shaffer.

### **... and then they study semiconductor physics**

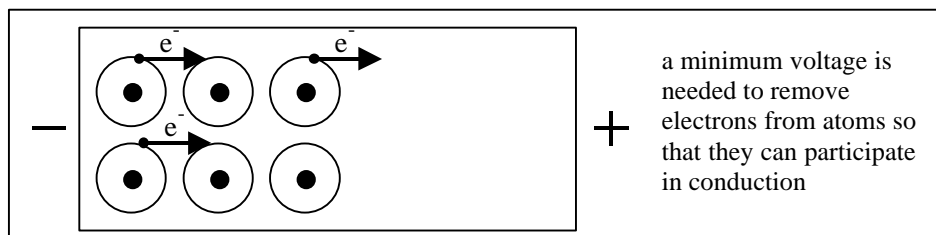
At the University of Maryland, we are exploring student understanding of microscopic models for conductivity after having taken several more advanced courses, including intermediate undergraduate electrical engineering courses. After all, it is often assumed that students overcome their difficulties as they revisit the same concepts in progressively more advanced contexts. We decided to administer one-on-one interviews using the protocol outlined briefly in Fig. 3. We thought this was a reasonable set of questions for this set of students. Unfortunately, of the 12 or so students we have interviewed so far, none of them have had a model for current suitable for accounting for the differences between conductors, insulators, and semiconductors. For example, about half of the students described conductivity similar to the student in Fig. 4. In explaining conduction in a wire, this student said that there is a "minimum voltage" necessary for there to be any current. (Note the qualitative similarities here with electrons being removed from a metal via the photoelectric effect.) Unfortunately, with this model, current first "kicks in" when there is a finite voltage and there is no mechanism to account for semiconductor physics. Other students describe differences in conductivity by the size of physical constrictions the electrons move through at the atomic level. Very few of the students interviewed invoked any kind of a drift velocity mechanism, charge carrier density, or band diagram. This is of particular concern since many of these students had studied how diodes and transistors work in great detail.

## **RESEARCH BASED CURRICULUM DEVELOPMENT**

At the introductory level, physics education research has guided the development of curriculum and instructional strategies with encouraging results (e.g. Redish & Steinberg, 1999). For example, having students work through materials where they can build their own models, strengthen their conceptual understanding, and exercise their reasoning skills has yielded marked improvement in instruction in both physical optics (Ambrose et al., 1999) and simple circuits (Shaffer & McDermott, 1992). We are now using this same paradigm in developing materials at the quantum level. Our preliminary results are encouraging (e.g., Steinberg & Oberem, 1999).

- 1. Describe the behavior of resistor wired to battery (real circuit elements in hand).**
- 2. Contrast the behavior in the resistor and in the wire.**
- 3. Contrast the behavior when the resistor is replaced with one of a different value. Explain why the 2 behave differently.**
- 4. Repeat for insulator.**
- 5. Repeat for piece of semiconductor.**
- 6. Repeat for diode.**
- 7. Repeat for MOSFET. (Have one in hand and let student do what s/he wants with the three leads.)**

**Figure 3. Brief outline of interview protocol administered to students who had finished introductory calculus-based physics and at least one more advanced course in physics or electrical engineering. In about a dozen 45-minute interview, we often have not gotten past question 3 and have never gotten to question 6.**



**Figure 4. Typical student explanation about conductivity in the wire. This student explains that at some “minimum voltage” the electron is removed from the atom and contributes to conduction. The student was notable to contrast the behavior of conductors, insulators, and semiconductors using his model.**

## CONCLUSIONS

Clearly there are many good reasons to teach quantum mechanics to a broad audience. However, the goal is not merely to turn this instruction into a vocabulary lesson or a mathematics exercise for the students. Instead, it is possible to have instruction in quantum mechanics be much more meaningful. In this paper, we have tried to show how recognizing what students understand about relevant classical concepts and how they build an understanding of quantum ideas can inform instruction.

## ACKNOWLEDGEMENTS

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