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

Richard Steinberg, Michael C. Wittmann, Lei Bao, and Edward F. Redish
Department of Physics, University of Maryland, College Park, MD, 20742-4111
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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 the particle nature of light. Fig. 1b shows an example of how a student who had just studied about photons

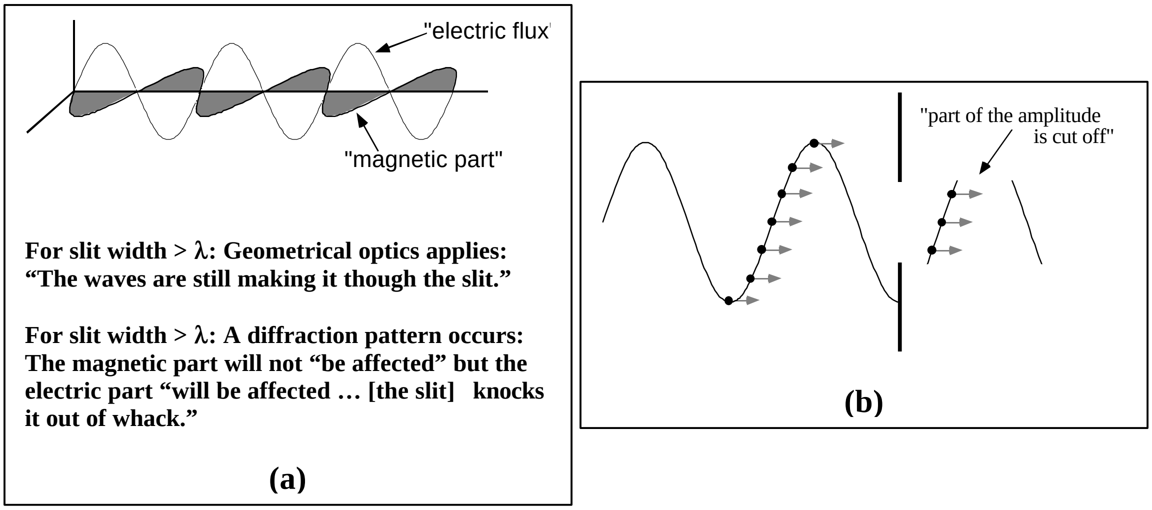

Figure 1. Typical student descriptions of light passing through a narrow slit: (a) Diagram and explanation given by a student who just completed introductory calculus-based physics. (b) Diagram drawn by student who just studied the photon.

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 …

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

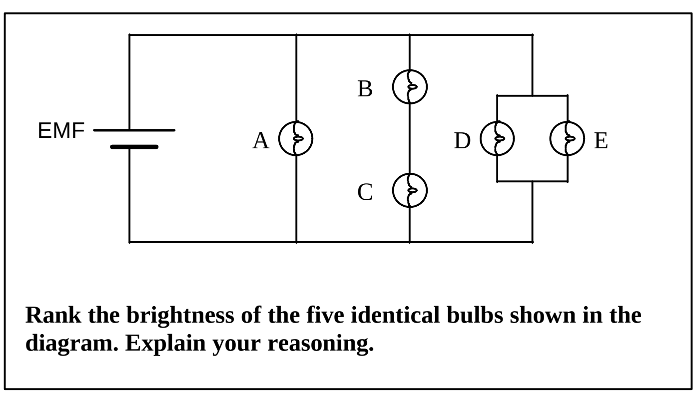

Figure 2. Part of an examination question given to introductory calculus-based physics students after they had finished studying dc circuits. Only 16% of the 94 students in the class gave the correct ranking (A=D=E>B=C).

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).

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

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 qbout a dozen 45-minute interview, we often have not gotten past question 3 and have never gotten to question 6.

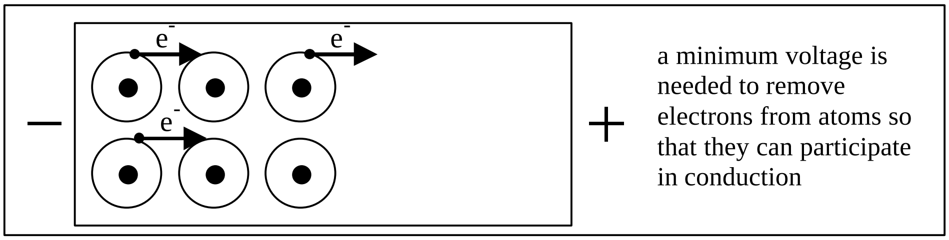

Figure 4. Typical student explanation about conductivity in the wire. This student explains that at some "minimum voltage" the electron is removed from the atom and contributes to conduction. The student was notable to contrast the behavior of conductors, insulators, and semiconductors using his model.

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.

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