Investigating Student Understanding of Quantum Mechanics: Models of Conductivity

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Advanced physics topics such as quantum mechanics (QM) are rarely studied in physics education research (McDermott and Redish 1999), yet are of fundamental importance for a large segment of the population due to the growing value of quantum technology in our society. Because quantum models of conductivity play a critical role in the understanding of such modern devices as pn junctions, LEDs, and transistors, the Physics Education Research Group at the University of Maryland has carried out an extensive investigation of student understanding of current and conductivity with advanced engineering students taking a QM physics course.

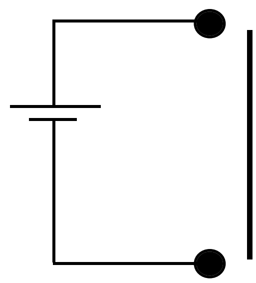
In developing a course in QM for upper level engineering students, we have used a cyclical process of research, curriculum development, and evaluation of our work in order to create a curriculum best matched to our population of students. More information on this curriculum can be found on the WWW (Redish et al. 2000).

Student Interviews: Detailed Pictures of Individual Responses

Conductivity provides an excellent context in which to describe how multiple (possibly contradictory) models are needed to adequately describe the physics of a situation. Our investigations sought to investigate student reasoning in such a situation.

Thirteen students were interviewed in detail on the subject of current flow (see Figure 1). Nine (group A) were interviewed before they had any instruction on microscopic models of conductivity. Four (group B) were interviewed after all (traditional) instruction in quantum mechanics, including several weeks of discussing QM models of conductivity. Students were asked

Present students with:



- battery
- wires
- steel wire
- copper wire
- aluminum
- rubber band
- wood
- Styrofoam
- and more...

Figure 1: Interview situation. Students were provided with a battery with two leads, and a variety of substances which could be placed between the two leads. They were asked to describe what would happen in each case, with the interviewer able to follow up with probing questions.

to describe what would happen when a variety of materials were placed between two leads connected to a battery. An example of a correct response would be to state that in a metal, there are free electrons in a conduction band, and these electrons are free to move about the material when an outside voltage is placed on it. In such a situation, the electrons flow through a lattice of atoms, colliding with them, and reaching a steady state average speed (this is the semi-classical Drude model).

Of the thirteen students, a majority (five of nine in group A, two of four in group B) described current according to a model summarized in Figure 2. In this model, an applied electric field acts on individual atoms in such a way that electrons from the outer shell of the atom are torn off. As one student stated, "just the [electrons] on the most outer shell would move. They'd get pulled off the atom ... by the electric field." This is the origin of free electrons in a conductor.

Once an electron is torn off the atom, another electron, torn from a different atom, can come in and take its place (i.e. fill the "hole" created by the first electron's departure). One student who described this model stated, "You have an electron being absorbed [by an atom], and then another electron emitted, so you kind of have a chain reaction going through the circuit." At a later time in the interview, he described the process as the "electron transfer" from atom to atom. Another student similarly described the transfer of electrons from atom to atom, stating "[the electron] is going in, attaching itself, there are too many, so one jumps out, attaches itself, and so on."

These students did not have a coherent model of free electrons existing in the material, so they built a model of conduction that could account for both their existence and their motion. During the interviews, it was often noticeable that students were inventing responses to situations they had never considered before. Many students spontaneously produced very similar responses, though. This indicates that students are creatively thinking about the physics using basic reasoning elements which they are able to combine on the spot to produce responses which seem relevant and reasonable and that many students use the same basic reasoning elements to arrive at an incorrect response. (These findings are similar to results from investigations in other areas of physics (Hammer 2000, Wittmann 2001).)

It is important to note that the most common incorrect student descriptions of conduction lead to incorrect predictions about the physics. Many students were not able to interpret Ohm's Law ($V = IR$) correctly, nor to apply it in a microscopic setting. These students stated that there was a cut-off or threshold voltage required before current flowed in a wire. This was consistent with their model, but incorrect when describing the physics. In other situations, though, these same students had no problems correctly applying Ohm's Law. Students seemed to reason independently when describing macroscopic quantities (such as current or resistance) and microscopic quantities (such as average electron speed).

Though most of the interviewed students had completed introductory electrical engineering courses which included discussion of conduction and valence bands and microscopic models of

Figure 2: Electron hopping model. Students described the particle moving from bound state to bound state by jumping from one atom to the next.

current, only two in group B and none in group A brought up band diagrams to account for free electrons or the existence of insulators.

A striking result of the interviews was student inability to discuss semiconductors. Only two students from group B (post-instruction QM class) were able to use band diagrams to describe semiconductors. Many used the electron-jump model described above. One student explicitly used the electron-pull-off idea when he described the difference between doped and undoped semiconductors. He stated, "I think the doped ones are better conductors because I think it takes a lot of energy to remove the silicon electrons, but if you add electrons from a different metal, like aluminum, which require less energy to be removed, then you'd get more current using less energy."

One should note that most students were upper level undergraduate electrical engineers, and all stated that they had discussed semiconductors in previous classes. A reasonable explanation for their responses in these interviews would be that they were unfamiliar with the physics of semiconductors and had so far learned to deal only with specific examples in their engineering classes.

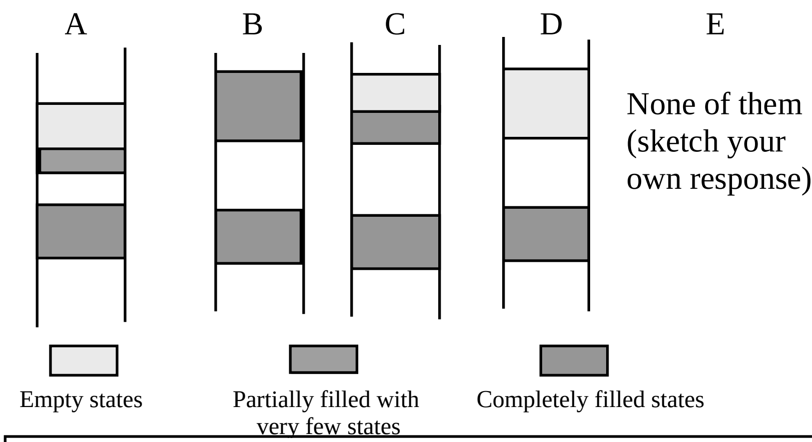
Curriculum Development

A natural response to our findings was to design curriculum materials specifically to help students understand the source of free electrons in a metal. We were inspired by the tutorials developed for the introductory physics sequence at the University of Washington (McDermott et al. 1998). Our materials use specially designed questions and relevant software tools to help students observe, discuss, and build an appropriate understanding of the physics. In the three tutorials, students begin by building a model of band diagrams and discussing polarization of a metal. They discuss a quantum model of conductivity, focusing on band diagrams for conductors, semiconductors, and insulators and the different behaviors of the charge carriers in each case. Only then do they describe free electrons as particles flowing through an atomic lattice. The tutorial helps students evaluate when this model is appropriate, and when the band diagram model is appropriate. This skill is assumed in many other curricula, but we have made it an explicit part of instruction. Tutorials were taught in the place of one lecture (of three) a week.

Evaluation of Student Performance: Comparison of Three Classes

Student performance on identical examination question (see Figure 3) was compared for three different classes. One class ("traditional" in figure 4) had only traditional instruction, with no specially designed materials. Lecture topics included Fermi energies and models of heat and current conduction. Two classes had modified instruction (using tutorials). The first class (modified 1) used an early version and the second (modified 2) the final version of the curriculum materials described above.

Figure 4 shows results from the three different classes. The performance of students using the original tutorial materials (modified 1) was only marginally better than students in the traditional class. This result led to the final version of the tutorials. We find that students participating in these tutorials were far more successful (while having the same amount of class time spent on the material) than in either of the other classes. We measured success both in terms of how many answered correctly and how many were able to correctly apply two different models in the question.



a. Consider the following band diagrams. For the each of the materials listed below the diagram, select the diagram that best represents the band structure of the material. For each material, **explain how you arrived at your answer.**

i. Conductor ii. Insulator iii. Semiconductor

b. A potential difference is placed across a resistor. Describe what, if anything, happens to the individual electrons in the material. Include a sketch in your explanation.

Figure 3: Final examination question

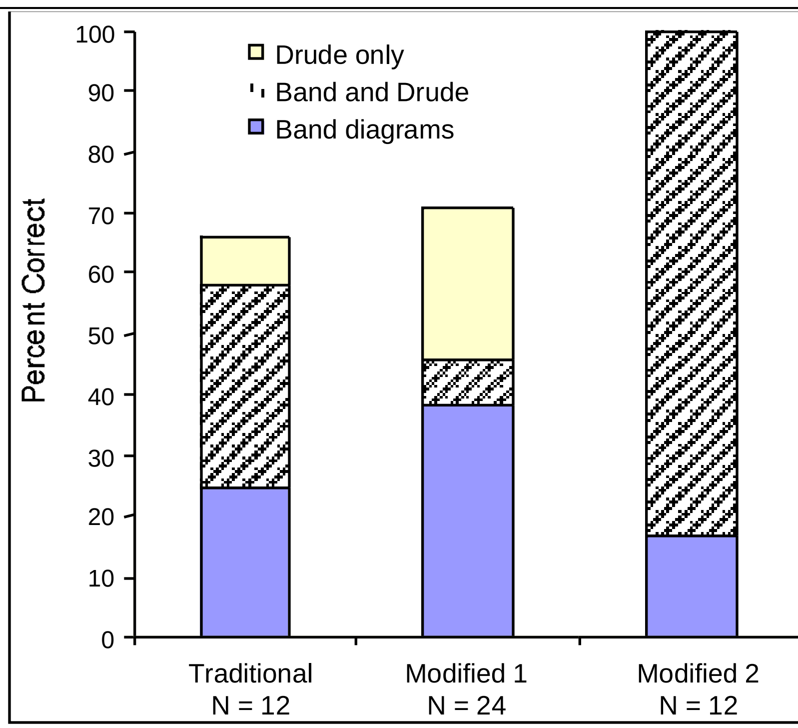


Figure 4: Student performance on final examination question.

Conclusions

Proper evaluation and investigation of student understanding leads to more than curriculum that helps student learn the physics. In addition, we are coming to a growing awareness of the nature of student thinking, and how students make sense of material they are learning. By recognizing the nature of student reasoning about the source of free electrons in a metal, we were able to develop appropriate materials to address their needs. Giving the students an opportunity to develop tools for understanding the difficult physics had a measurable effect on student learning. These materials form only a small part of an entire course we have developed, yet are representative of how research based curriculum development can create a more effective learning environment for students.

Bibliography

Hammer, D., 2000, Student resources for learning introductory physics. American Journal of Physics, Physics Education Research Supplement, 67, S45–S50.

McDermott, L.C. and Redish, E.F., 1999, Resource Letter PER-1: Physics Education Research. American Journal of Physics, 67, 755–767.

McDermott, L.C., Shaffer, P.S., and the Physics Education Research Group at the University of Washington (1998) Tutorials in Introductory Physics (New York: Prentice Hall).

Redish, E.F., Steinberg, R.N., and Wittmann, M.C., A New Model Course in Applied Quantum Physics, http://www.physics.umd.edu/perg/qm/qmcourse/welcome.htm.

Wittmann, M.C., 2001, The Object Coordination Class Applied to Wavepulses: Analysing Student Reasoning in Wave Physics. International Journal of Science Education,, in press.