Quantum mechanics for everyone: Hands-on activities integrated with technology

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Quantum mechanics is frequently taught toward the end of the first year of physics if it is taught at all. Many physics instructors believe that quantum mechanics is a very abstract subject that cannot be understood until students have learned much of classical physics. We are challenging this belief by creating instructional materials for quantum mechanics that can be integrated throughout the first physics course. In addition, we have transferred some of the materials and the basic approach to higher-level courses. The result is a hands-on approach to learning and teaching quantum mechanics for a broad spectrum of students. We describe some of our materials and the results of using these materials with students. © *2002 American Association of Physics Teachers.*
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I. INTRODUCTION

For the past several years the Physics Education Research Group at Kansas State University has been conducting research on student learning of contemporary topics in physics and developing teaching materials based on this and other research. One result of this effort is several sets of instructional materials for different types of students. Each set of materials is based on an understanding of how students learn physics in general and quantum physics in particular. All of our materials involve interactive instruction and include hands-on activities as well as interactive computer visualizations.

Our educational approach is similar for all levels of students. It is based on evidence that students learn by doing; most do not learn effectively by sitting in lectures.[1] Experiments come before the theory. Students do something first, so they have something to think about and explain. Application of the new concepts comes immediately after the theory. The applications are hands-on and interactive. We use an approach (called the Learning Cycle) that was developed by Robert Karplus many years ago,[2] and follow this format in everything that we do.

We first applied our approach to high school and introductory college students with little science or math background and a low interest in science. We have now expanded our target group to include undergraduate science and engineering students, medical students, advanced undergraduate physics students, and in-service teachers. Our overall goal is to teach quantum mechanics to students who do not normally study it and to increase the intuitive understanding for students who normally are introduced to quantum mechanics primarily from its mathematical foundations.

II. SELECTED HISTORY OF VISUALIZING QUANTUM MECHANICS

We are not the first to attempt to teach quantum physics through visualization. In fact, we have drawn our inspiration from many others who have used technology that was available in their day. Max Born provided animated flip charts in the margins of his book that was written for the nonspecialist.[3] On each page was a slightly different picture.

When the readers flipped through the pages rapidly, they saw a moving picture that helped them visualize some of the concepts that Born described.

About 20 years later a group at Lawrence Berkeley Lab created a series of short films that showed the time development of wave functions and wave packets as they interacted with various potentials. These films were created by having computers calculate until they could draw a complete picture for a single movie frame on a CRT.[4]

French and Taylor[5] introduced qualitative sketching of wave functions in their textbook that was part of the MIT Introductory Physics series. They used the principles of quantum physics to teach the students a series of rules for sketching wave functions for any potential. The students completed these sketches prior to solving the equations.

Eisberg[6] exploited the capabilities of early programmable calculators to engage students in interactively using technology to visualize wave functions. Students would enter a program into their calculator so that it would solve Schrödinger's equation for a potential. As the numbers for position and wave function magnitude were displayed, the students would plot a graph by hand.

A concerted effort to use personal computers for quantum and many other areas of physics was undertaken by the Consortium for Upper Level Physics.[7] The programs provide interactive visualizations that physics students can use to visualize the concepts. Unfortunately, these MS-DOS programs have yet to be converted to a modern user interface and operating system.

For advanced studies one of our favorite visualizations is *The Picture Book of Quantum Mechanics*[8,9] and its companions *Quantum Mechanics on the Personal Computer*[10] and *Quantum Mechanics on the Macintosh*.[11] These books and software contain many two- and three-dimensional representations of the development of wave functions in time and space.

Today, a Web-based search would reveal many programs that illustrate various aspects of quantum physics. Many of these programs have been created to demonstrate and teach a concept that its authors found particularly difficult to explain in other ways. Only a few of them are part of larger teaching-learning packages such as the ones that we have been creating.

III. DEVICE ORIENTATION

Sometimes students learn the mathematics of quantum mechanics and not its conceptual basis or applications.[12,13] We do not want this situation, so we introduce devices whose operation can be understood conceptually and can be explained only with quantum mechanics. Students should recognize these devices and see them in their everyday lives. Light emitting diodes (LEDs), for example, are everywhere. Although many students do not know the name, they have seen light emitting diodes in their computers and remote controls. By examining the properties of LEDs, students learn that LEDs are different from other light sources. As described below, they then understand with the help of computer visualizations how the light emitting properties are related to the quantization of energy in atoms.

We occasionally use devices about which students may have heard or read, but they have probably not encountered. The scanning tunneling microscope is the best example. We do not expect students to use a scanning tunneling microscope because of its cost. Instead, we use a simulation and an interactive program to give students a feel for the working of a scanning tunneling microscope.

IV. THE ORIGINAL VISUAL QUANTUM MECHANICS MATERIALS

Our instructional materials for high school and nonscience students at the college level are called *Visual Quantum Mechanics—The Original*.[14] These materials are divided into four major, but relatively short, instructional units and two units for background review. We have considered the physics prerequisites carefully and have included only those that are absolutely necessary. Thus, we have designed the units so that each one can be used in various times within a physics course—not just at the end. Each unit can be completed in about 6–12 h of classroom instruction. The units also can be integrated into an existing curriculum because the prerequisites are topics covered in a standard physics curriculum. The instructional units are as follows.

Solids & Light—Students use LEDs and gas lamps to understand the concepts of discrete energy levels, energy bands, transitions, and spectra. The emphasis is on how observations lead to the conclusions about energy in atoms.

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

Waves of Matter—Students explore the creation of a model to explain the discrete energy states, and learn about the wave nature of particles, wave functions, Schrödinger's equation (qualitatively), and wave packets.

Seeing the Very Small: Quantum Tunneling—Using a simulation of the scanning tunneling microscope as the pedagogical vehicle, students learn about quantum tunneling, the factors that influence it, and some of its applications.

Potential Energy Diagrams—We use magnets placed along a track and toy cars or dynamics carts to review energy conservation and explore potential energy diagrams of different shapes.[15]

Making Waves—A basic review on some properties of waves. Because students have difficulty understanding that interference is the property that determines if a phenomenon is a wave,[13,16] we focus on it.

Table I. List of instructional units for visual quantum mechanics—The Next Generation.

Historically important experiments	Quantum basics
Franck-Hertz experiment	Electron diffraction
e/m experiment (two versions)	Matter waves
Photoelectric effect	Sketching wave functions 1, 2, and 3
	Waves and their interpretation
Classical background	Probabilities and wave functions
Energy diagrams	Boundary conditions
Classical probability[a]	Exploring tunneling
Scattering and Rutherford's experiment	Motion of a wave packet
	Bound states and binding energy
Applications and model building	Uncertainty principle
Light emitting diodes	Motion of a wave packet
Investigating nanospaces (STM)	Wave functions and energies in atoms
White LED	
Hydrogen spectrum	Quantum orbitals[b]
Spectra of light sources	Shape of the wave function[a]
Fluorescence	
Quantum model of conductivity[a]	
Solar cell	

[a]Adopted from a similar instructional unit developed at the University of Maryland.
[b]Based on software developed at Boston University.

The backbone of our Learning Cycles is paper-and-pencil worksheets that students use to guide themselves through the learning process. The instructional materials are constructed so that the teacher is a necessary part of this process. The teacher helps students understand, asks questions to guide the learning and, occasionally, provides explanations. Thus, a critical part of the interactive environment is the teacher–student relation.

V. VISUAL QUANTUM MECHANICS—THE NEXT GENERATION

Undergraduate physics majors typically complete a one-semester "Modern Physics" course during their second year of study. This course usually has a prerequisite of two semesters of calculus-based physics. For these students we have developed a slightly different approach. We called these instructional materials The Next Generation because they were derived from the original Visual Quantum Mechanics materials developed for high school students. We still use interactive engagements, but the instructional unit is smaller than in the original materials. Each Next Generation unit requires about 1 or 2 h of study time. We designed these units to be completed in a tutorial setting,[17] where students work in small groups using equipment such as LEDs, lamps, light sticks, paper-and-pencil exercises, and computer visualizations. By making the units short, we hope to have created an environment in which instructors who teach with many different formats and textbooks can use them.

We have divided the instructional units into several different major groups. Table I shows the groups and gives a short descriptive title of each of the units.

VI. VISUALIZATIONS, HANDS-ON ACTIVITIES, AND STUDENT LEARNING

In all of our materials we focus on enabling students to make observations and develop mental models consistent
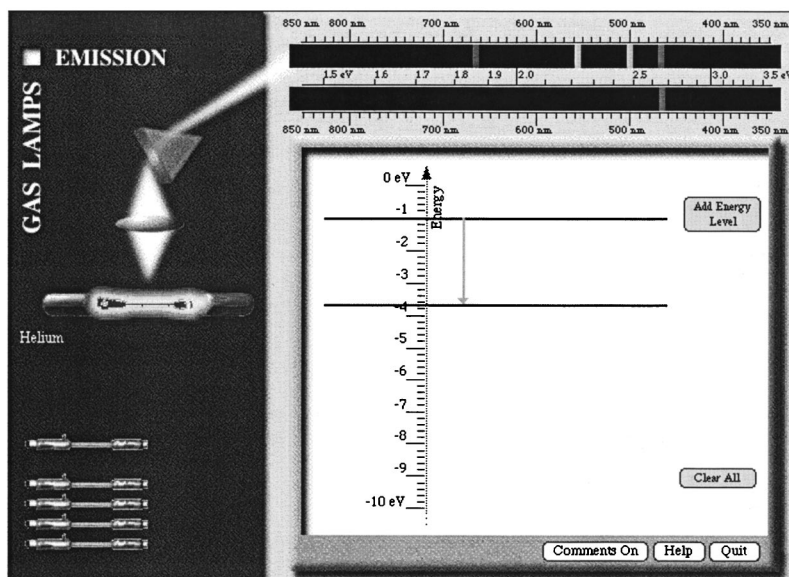
Fig. 1. The Emission module in the *Spectroscopy Lab Suite*. Students drag the light source on the right to the power supply. Then they build an energy level model of the atom to match the observed spectrum.

with quantum principles. Then, the students should be able to explain these observations and apply the models to other, related situations.

In any aspect of contemporary physics an important consideration is how one represents the atom. Building on the work of Fischler and his colleagues,[18,19] we have assiduously avoided the use of the Bohr model of the atom. They found that students who studied and used the Bohr model intensively were very reluctant to embrace a quantum mechanical model in later instruction. Thus, we focus on an energy level model in the early learning units of both The Original and Next Generation materials.

Energy Levels & Spectra. Early units focus on spectroscopy and its role in providing evidence for energy quantization. After observing the response of LEDs of different colors to changes in voltage and the spectra from both LEDs and gas spectral tubes, the students are ready to build an energy level model of the atom, as described below.

At this time in their studies, the students treat spectra as an empirical observation. They are asked to apply their knowledge that light is a form of energy and their observation that the atom emits only specific energies of light to construct energy level diagrams and explain the transitions in the atom that result in the emission of light. [We use spectroscopes from Project STAR (http://www.starlab.com/psgi.html) which are calibrated in both wavelength (nm) and energy (eV), so the students can read the energy of the light directly from the experiment. We introduce electron volts as a unit of energy and work primarily with the energy of the photons rather than wavelength or frequency.]

In the initial stages of our development, we observed that students would equate a numerical value of an energy level with the energy of a photon in each spectral line that they were observing. For example, if they observed a gas with spectral lines of energies 1.8, 2.1, and 3.0 eV, students would construct an energy diagram that had levels at each of these energy values and would not include any transitions.

We designed a computer visualization program to enable students to overcome this difficulty. *Spectroscopy Lab Suite* provides a set of simulated experiments, similar to the real experiments that the students have completed, and a means for students to build energy models that can explain their observations.[20]

In the *Emission* module of *Spectroscopy Lab Suite*, students build a spectrum by creating an energy level model diagram of a gas atom. The program confronts the issue of whether the energy of the light is related to the energy levels or energy differences (see Fig. 1). The top spectrum in Fig. 1 represents the observed spectrum, while the bottom one is the result of the students' energy level model. By comparing the two, the students obtain the necessary feedback on their model. After using this program, almost all students are able to overcome their earlier learning difficulty.

Many students draw an energy level diagram with all the transitions starting at one energy level and with the energy differences corresponding to the energies of the spectral lines. Others have different initial states with one final state (see Fig. 2). We challenge students to state which model is correct based *only* on the evidence that they have observed. When they realize that they can only state the difference between the energy levels from the spectral data, we discuss the limitations of scientific models and how these models are refined as more information becomes available.

By using the *Emission* module of the *Spectroscopy Lab Suite*, students construct an energy level model that matches their observations and realize that a spectral line can be cre-
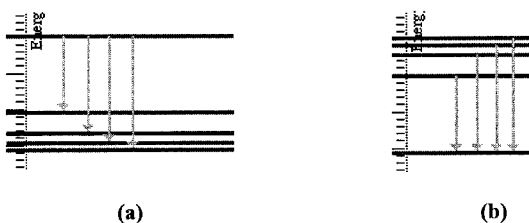

(a)   **(b)**

Fig. 2. In one class students will frequently create two variations of the energy level model. (a) shows all of the transitions beginning at the same initial state, and (b) indicates that all transitions end on the same state.
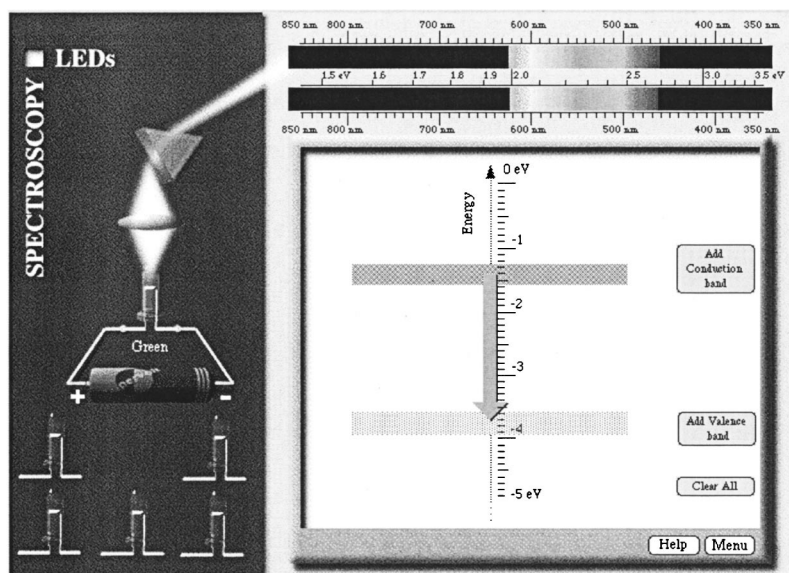
Fig. 3. The LED module in *Spectroscopy Lab Suite*. Students explore how the energy bands and gaps are related to the spectrum of a LED by building a model to reproduce and observe spectra.

ated only by transitions between two discrete energy levels. Thus, they learn that the energy of the emitted light is equal to the change in energy within the atom. More importantly, they see that only certain discrete energy levels are needed to explain the observed spectrum. From knowledge of energy conservation and the data presented by the spectrum of a gas, students can discover that energy states in atoms are quantized. This critical discovery follows from empirical results and an explanation in terms of energy — no knowledge of wave functions or the Bohr atom is needed.

Energy Bands in Solids. Having studied gas atoms with discrete individual energy levels, students segue to the emission of light by the atoms in a solid state LED. Similar to the way that they learned about the energy level diagram for an atom in a gas, they observe the spectrum of a LED, and try to create an energy level diagram to match the spectrum. 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 a LED. The *LED* module of *Spectroscopy Lab Suite* (see Fig. 3) enables students to interactively explore the relation between energy bands and gaps and the spectrum of a LED. Students manipulate the sizes of the bands and gaps to create models that match the observed spectra of various LEDs. Thus, again the model building is connected directly to spectra that the students have observed.

After an introduction to *N*- and *P*-type materials, the students repeat the experiment that began this study. They use a computer program in which they can change the voltage across a LED, just as they did in the real experiment. While one half of the screen shows the set up for the LED experiment and allows the student to vary the voltage applied to the LED, the other half displays the changes in the energy bands of the LED as this voltage changes.

In these activities the students learn that empirical evidence alone can lead to the conclusion that individual atoms can be represented by a model that has discrete energy states. The model can then be modified and extended based on the observation of continuous spectra emitted by atoms in LEDs. These models provide evidence of quantized energy, but do not provide a model that can explain why energy is quantized. For that step we must introduce wave functions.

Wave Functions. For both high school and introductory physics students we begin the study of the wave nature of matter with an experimental observation—electrons can behave as waves. After the students have discussed how interference patterns indicate wave behavior and have observed the interference of light, we turn to electrons. They can observe a real experiment if the equipment is available, view pictures in books, or watch a video.[21] Once we establish that interference occurs with electrons, we introduce a program with an idealized experiment to further investigate the wave nature of electrons. This program enables the students to control variables in a two-slit experiment involving electrons, nucleons, pions, and photons (see Fig. 4).

The first purpose of this program is to enable students to discover the qualitative relation between the wavelength associated with an object and other physical properties such as energy, mass, and momentum. We do not expect students to obtain de Broglie's equation, but to be able to use phrases such as the wavelength increases as the energy decreases. By asking students to vary different parameters (such as type of the particle and its energy) and to observe the diffraction pattern in the program, students are able to learn the qualitative relationship between the wavelength and momentum of the particle. We then introduce the de Broglie equation. Although this approach is not historically accurate, it provides students with a gentler introduction to the de Broglie relation than a strictly mathematical approach.

Our research has uncovered some conceptions that needed to be addressed. Students would frequently state that the diffraction of the electron beam must be due to the electron's electrical charge. They would argue that like charges repel so the Coulomb interaction is causing the diffraction patterns. This misconception could be addressed logically by discussing the lack of a uniform distribution of the electrons. However, the students seem more convinced by completing and comparing two simulated experiments. We have them compare the patterns created by protons and by neutrons with all other variables identical. Because the interference patterns are identical, students conclude that charge cannot be a factor.

To connect the matter waves to probability, we return to the experiment illustrated in Fig. 4. Setting the flux to a few
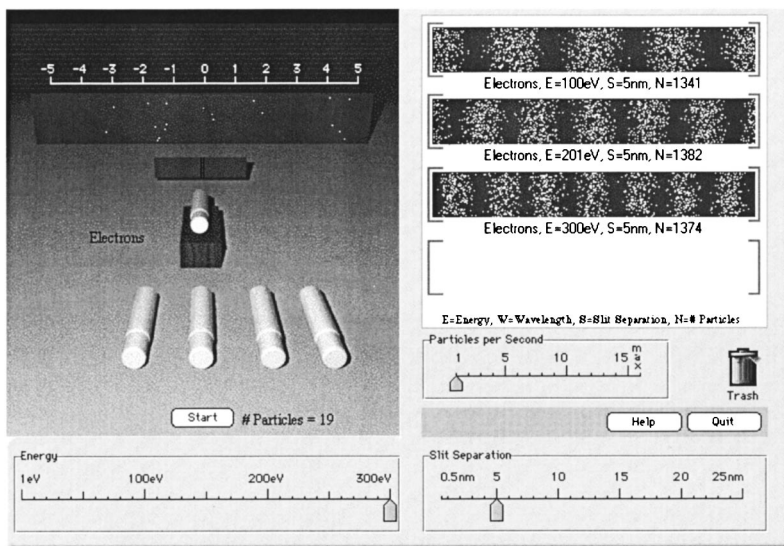
Fig. 4. A simulated electron interference experiment. As the energy increases, the distance between minima decreases. By comparing this behavior with that of light, the students conclude that the wavelength decreases as the energy increases.

particles per second, the students watch the pattern develop. After a few particles have hit the screen, as shown on the left-hand side of Fig. 4, we have the students stop the experiment. Then, we ask them to predict where the next electron coming from the electron gun will appear on the screen. The students quickly begin to discuss the location in terms of probability. They can indicate some locations where the electron will rather definitely not appear and several where it is very likely to appear, but they cannot give a definitive answer. In this way, we introduce the wave function and its probabilistic interpretation based on the students' experience with not being able to predict accurately where the next electron will appear on the screen.

We emphasize conceptual understanding of wave functions by having students manipulate graphical images in accordance with their knowledge. For example, we ask students at all levels to sketch wave functions qualitatively. Following procedures that appeared in French and Taylor,[5] some sketching is done with paper and pencil. However, we find that students can be inexact with paper and pencil, and sometimes they need to be exact. So, we have created a program, *Wave Function Sketcher* (see Fig. 5), that allows

students to vary the wave function and match boundary conditions. The idea that a wave function needs to be continuous is motivated by pointing out that the wave function is directly related to the probability of finding a particle, and that it is physically not possible to have two probabilities of finding a particle at any given point.

We have observed some interesting ways in which non-science students use *Wave Function Sketcher*. First, if we tell them that the wave function is smooth, they will make it smooth to many derivatives. The idea that two functions can be continuous, but not necessarily smooth does not occur to them. Second, we use the word decreasing for exponential decay. When we used decay, we found that students immediately think of radioactive decay. They interpret decay to mean that the electrons are radioactively decaying in the region where the total energy is less than the potential energy. So, we use the phrase decreasing wave function.

With all types of students we strive for conceptual understanding and rely heavily on programs such as *Wave Function Sketcher* even if the students have the mathematical abil-
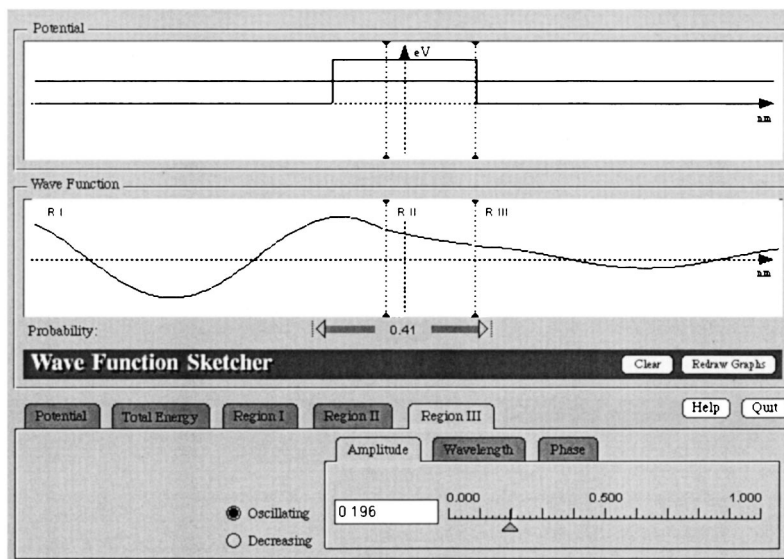

Fig. 5. A screen capture from *Wave Function Sketcher*. This version of the program is aimed at high school students and nonscience university students.
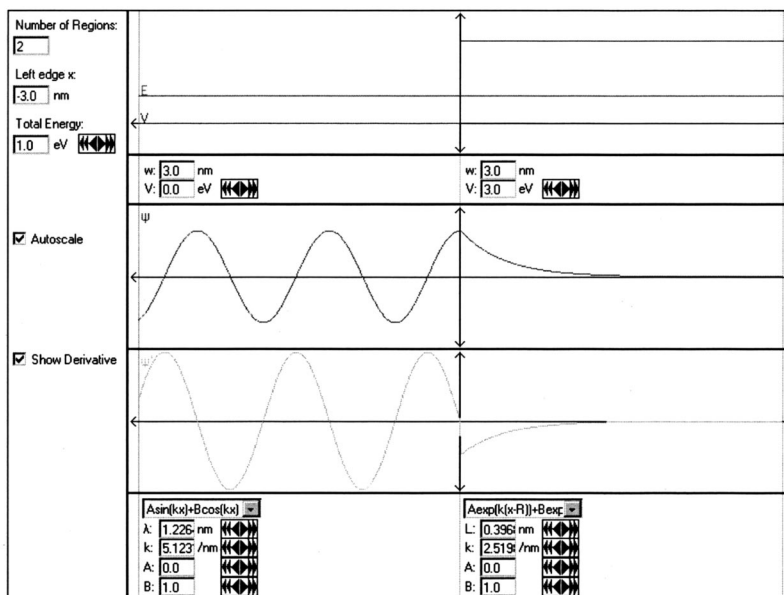
Fig. 6. A screen capture from the advanced version of *Wave Function Sketcher*. This program is for university physics students.

ity to find the analytical solutions. For the advanced undergraduate course, one of our graduate students, Wally Axmann, has created a different form of the *Wave Function Sketcher*. As shown in Fig. 6, it uses the mathematical language of physicists and includes the option to observe the behavior of the derivative as well as the wave function.

Through the *Wave Function Sketcher* programs, students also learn the relation between the wave function and the potential energy diagram. They learn why the wave function representation of an electron implies that only certain energies are allowed in an atom. Using the program with a square well potential, students choose an energy and try to match the boundary conditions on both sides. They quickly discover that such a matching is not possible for most energies. (This activity needs to have a short duration because student frustration can grow quickly.) We then give the students a set of parameters for which they can easily match the boundary conditions on both sides of the well. In this way they see why the wave model of matter leads to the conclusion that an electron bound in an atom can have only certain energies. Other instructional units provide the opportunity to experiment with different potentials for which Schrödinger's equation is solved automatically.

The use of matter waves to represent electrons in a bound
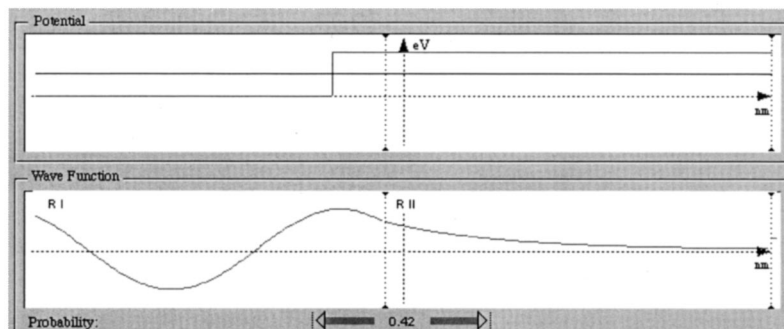
(a)
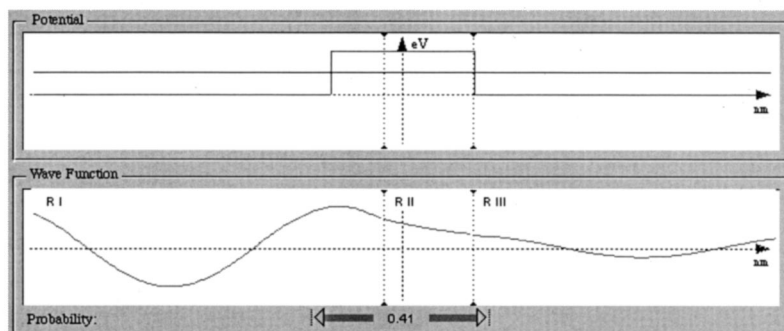
(b)

Fig. 7. (a) The *Wave Function Sketcher* is used to match boundary conditions for a step potential. (b) The step is converted to a barrier and students match two boundaries. A discussion of quantum tunneling follows.

state has now enabled students to explain their conclusion that electrons in atoms have discrete energy levels. Because they have already connected the discrete energies to the observed spectrum, they can now show how matter waves explain the observed spectrum.

Quantum Tunneling. The *Wave Function Sketcher* can also be used to introduce quantum tunneling. The students begin with a step potential and sketch a wave function for a total energy just below that of the potential energy of the high side of the step [see Fig. 7(a)]. Then, the step is changed to a barrier and boundary conditions matched again. Quantum tunneling naturally follows [see Fig. 7(b)]. The *Quantum Tunneling* program then allows students to explore how tunneling depends on variables such as potential height, potential width, and total energy.

To introduce students to an application of this effect, we use the *STM Simulator* program, our most complex programming effort.[22] It enables students to see how quantum tunneling can be used to map atoms on a surface and to move atoms one at a time. In addition to a map of the surface, students can see wave function and energy diagrams related to the quantum mechanics basics behind a STM operation.

VII. CONCLUSIONS

Field tests of *The Original* units have been conducted in high schools and universities throughout the U.S. and in several other countries. However, most of our reports have come from the U.S. Approximately 175 different teachers in 160 different schools have used the materials in classes and reported their results back to us.

Based on a large number of field tests and a careful evaluation of student attitudes and learning, we have concluded that the Visual Quantum Mechanics materials have been successful in teaching some abstract concepts to students who have limited science and mathematics background.

Because we are approaching quantum mechanics in a much different way than it is taught normally, some teachers feel uncomfortable using our instructional materials. To meet the needs of these teachers, we have created a Web-based version of these materials. The overall structure and philosophy of the Web-based materials is identical to the in-class material. The participants use a hands-on materials kit, and interact with the computer programs on-line. The written activity sheets have been converted into online forms that the teachers can complete and submit for feedback from us. By completing the on-line material as a tutorial and receiving feedback before they teach quantum physics, the teachers increase their confidence level.

Our materials also are successful in teaching the conceptual ideas of quantum mechanics to students who have stronger science and engineering backgrounds. The combination of hands-on activities, pencil-and-paper exercises, and interactive computer visualizations seem to work well in a classroom environment where student–student and student–teacher interactions are taking place. Thus, we believe that we have built a foundation for providing instruction on the most important aspects of 20th century physics to a broad range of 21st century students.

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GORDON CONFERENCE ON PHYSICS RESEARCH AND EDUCATION: QUANTUM MECHANICS

The 2002 Gordon Conference on Physics Research and Education will focus on quantum mechanics and will be held on June 9–14, 2002 at Mount Holyoke College, South Hadley, Massachusetts. The goal of the conference is to bring together researchers who study and apply quantum mechanics, physics education researchers, and college and university level instructors of quantum mechanics for the purpose of promoting innovation in all aspects of teaching quantum mechanics throughout the undergraduate curriculum. The conference will include sessions and discussions about the desired content and outcome of courses, curriculum development using research on student understanding of topics in quantum mechanics, ways of approaching non-intuitive aspects of quantum theory, and the results of current research in physics that can be used to increase undergraduate student understanding of the concepts and applications of quantum mechanics. More information can be found at http://www.grc.uri.edu/programs/2002/physres.htm. Questions or suggestions about the Gordon Conference can be addressed to the organizers, Beth Ann Thacker (batcam@spudhammer.phys.ttu.edu), Harvey Leff (hsleff@csupomona.edu), or David Jackson (jacksond@dickinson.edu).