Quantum Mechanics for Everyone:
Hands-On Activities Integrated with Technology

Dean A. Zollman, N. Sanjay Rebello, and Kirsten Hogg

Kansas State University

Frequently, quantum mechanics is taught toward the end of the first year of physics – if it is taught at all. The reason for delaying the study is that quantum mechanics is a very abstract idea without much practical purpose. Therefore, students cannot understand it until they have learned all the rest of physics. We are challenging that way of thinking by creating instructional materials for quantum mechanics that can be integrated throughout the first physics course rather than just tacked on at the end. In addition, we have transferred some of the materials and the basic learning 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 here some of our materials, as well as results of using these materials with students.

Introduction

For the past several years the Physics Education Research Group at Kansas State University has been completing research on student learning of contemporary topics in physics and developing teaching materials based on that and other research. The result of this effort is several sets of instructional materials for different types of students. Each set of materials is based on knowledge of how our 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 students. It is based on the evidence that students learn by doing; they do not learn by sitting in lectures. Concrete 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. And, those applications should be hands-on and interactive in some way. We use an approach (called the Learning Cycle) that was developed by Robert Karplus many years ago.[1] Basically we follow this format in everything that we do. This instructional format has proven to be quite successful for almost any level of instruction.

Initially, the students for whom we were aiming were high school and introductory college students. They have little science or math background and a low interest in science. Now, we have expanded our target audience to include undergraduate science and engineering students, medical students, advanced undergraduate physics students, and in-service teachers. For many of these students we must have hands-on activities if they are to study quantum mechanics (or anything else) effectively. For others, the active engagements with conceptual ideas provide a foundation upon which to understand better the quantitative aspects of quantum science. Our general goals, then, are to teach quantum mechanics to students who do not normally study it and to increase the intuitive feeling for those students who normally are exposed to quantum mechanics primarily from its mathematical foundations.

To reach our goals we use highly interactive computer visualizations as well as hands-on activities with real "stuff." Computer visualizations are still hands-on. The students' hands are on the keyboard and the mouse; their minds are on the content. The students must think and manipulate; they are not just watching animations or simulations.

We have put all of this material together in a set of packages that include written materials. Some people tend to believe that if you use the computer, everything will be on the computer. We do not do it that way. The students complete written materials that we have called "InGagements" for Interactive Engagement. In every InGagement students are expected to read, write, do activities, and work with the computers – all in one integrated approach.

Selected History of Visualizing Quantum Mechanics

We are certainly not the first to attempt to teach quantum science through visualization. In fact, we have drawn our inspiration from many others who have used technology that was available in their day. Max Born [2] provided animated flip charts in the margins of his book that was written for the non-specialist. On each page was a slightly different picture. When the readers flipped the through 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 high-speed (for that time) computers calculate until they could draw a picture on a CRT. Then, a camera shutter was opened, an electron beam followed a path prescribed by the computer, and a single frame of the film was created. Repeating this process many times eventually led to a series of short films on wave packets. [3,4]

French & Taylor [5] introduced qualitative sketching of wave functions in their textbook that was part of the MIT Introductory Physics series. They used the basic principles of quantum physics to teach the students a series of "rules" for sketching wave functions for any given potential. The students would complete these sketches prior to mathematically solving the equations. This approach helped build the students' intuitions.

Eisberg [6] exploited the capabilities of the, then, new programmable calculator 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 these 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 programs have yet to be converted from their MS-DOS version 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 2- and 3-dimensional representations of the development of wave functions in time and space.

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

Why Teach Quantum Mechanics to Non-Physicists?

Some physics educators have stated that quantum mechanics should not be taught at the introductory level.[12] They claim that the topic is too abstract for students with limited skills in using formal reasoning. Yet, we believe that we must do our best to bring an understanding of this topic to a broad audience.

Quantum mechanics was the most important development in 20th Century physics and it has dominated physics and technology for well over a half a century. Thus, at the beginning of the 21st Century it is time to allow all interested people access to these ideas.

Further, many experts predict that within the next 10 years miniaturization of electronics will reach the quantum mechanics limit. It would be nice if people who are trying to take the next step – development or business – understood what that meant.

Finally, many other very complex and abstract processes – the election of an American President, for example – fill our lives. Perhaps an appreciation of quantum physics can help us understand the role of measurement in these events.

Device Orientation

Sometimes quantum mechanics is taught in such a way that students learn the mathematics of quantum mechanics and never know what it is good for. We do not want this situation, so we introduce devices whose operation can only be explained with quantum mechanics. Students should recognize these objects and see them in their everyday lives. Light emitting diodes (LEDs), for example, are everywhere. Although many students do not know the name "LED," they have seen light emitting diodes in their computers, remote controls, etc. By examining the properties of LEDs the students learn that LEDs are different from other light sources. Then, with the help of computer visualizations they understand how the light emitting properties are related to the quantization of energy in atoms.

We occasionally use devices about which students may have heard and may have seen in pictures, 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. Although some students could build one, most will not be able to build such a device. Thus, in this case, we use the combination of a simulation and an interactive program.

We also use a variety of solid light sources. Infrared detector cards are a rather interesting example. They are a fairly recent development – at least fairly recent for inexpensive versions. TV repair people need to know if a television remote control is emitting infrared. How can they do that? It is rather simple if they have a video camera. The camera responds to IR and shows a bright spot where the IR is emitted. So, every TV repairperson needs a video camera, and he/she can find out if infrared light is coming from the remote control. But that approach is rather expensive. Another way to detect IR is with rattlesnakes, which have infrared sensitive eyes. So, every TV repairperson could have a rattlesnake, but that is rather expensive in a different way. However, one can buy a little card that responds to IR by emitting visible light. (For example, Radio Shack part #276-1099.) Thus, it absorbs low energy light and emits higher energy light.

The Star Trek Transporter is also a quantum mechanical device. If one reads the Star Trek Users' Manual,[13] one finds that the Transporter has a component called a Heisenberg Compensator. When Michael Okuda, a writer for Star Trek was asked, “How does the Heisenberg Compensator work,” he responded, “It works very well, thank you.”[14] Because Werner Heisenberg is one of the founders of quantum science, we must assume that this Compensator is related to his Uncertainty Principle. In one of our units we ask students to address this fantasy device in terms of basic quantum mechanics principles.

These and several other devices are introduced to students. In each case we show how the devices are related to quantum mechanics. Further, the students learn how the devices work at the atomic level.

The Original Materials

The instructional materials for high school and non-science students at the college level are called *Visual Quantum Mechanics - The Original*.[15] These materials are divided into four major instructional units. Each instructional unit is relatively short. We have considered the physics prerequisites very carefully and include only those that are absolutely necessary. Thus, we have designed the units so that each one can be inserted in various places within the physics course – not just at the end. Each can 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 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. 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 the project we realized the need for two units that would address topics in a traditional curriculum with which students seemed to have some difficulty.

Potential Energy Diagrams – These diagrams are a powerful representation that is utilized in quantum mechanics. We use magnets placed along a Pasco dynamics track and Hot Wheels cars to create and explore potential energy diagrams of different shapes. (Jolly, *et al*. 1998)

Making Waves – A basic review on some properties of waves and focusing on interference as the property that determines if something is a wave.

The "backbone" of our Learning Cycles has been 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 the 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.

VQM - The Next Generation

In a typical curriculum undergraduate physics majors in the U.S. complete a one-semester "Modern Physics" course during the 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 still use the InGagements, but the instructional unit is a smaller unit than in The Original materials. Each Next Generation InGagement requires about one or two hours of study time. We designed these InGagements to be completed in a tutorial setting where students work in small groups and move among regular equipment, paper-and-pencil exercises, and computer visualizations. By making the InGagements short, we hope to have created a situation in which they can be used as part of the instruction in courses with many different formats and textbooks.

We have divided the InGagements into several different major groups. Table 1 shows the groups and gives a short descriptive title of each of the InGagements.

Visualizations, Hands-On Activities & Student Learning

Representation of an Atom: Building on the work of Fischler[16,17] and his colleagues, we have assiduously avoided the use of the Bohr model of the atom. Fischler found that students who studied the Bohr model and used it intensively were very reluctant to embrace a quantum mechanical model in later instruction. Thus, we focus on an energy level representation in the early learning units.

In the first units this model is used simply to represent changes in the energy of individual atoms, or a group of atoms in a solid, when they emit or absorb light. Later units include the study of potential energy diagrams in classical situations such as a low-friction cart on a track.[18] With an understanding of these energy diagrams students can expand the use of energy diagrams when studying wave functions qualitatively or complex light emission.

Prior to the study of classical potential energy diagrams, many students mistake the vertical axis in an energy diagram as representing a 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. With the instruction they begin to understand that the energy axis can be used to represent how energy in the atoms changes rather than a physical distance.

Energy Levels & Spectra: In both VQM - The Original and The Next Generation we have learning units which focus on spectroscopy and its role in providing evidence for energy quantization. Because light emitting diodes are such a common device in the students' lives, they are the starting point for learning. We can convince students that the

LED is related to contemporary physics because they can read statements that come with some LEDS such as a "genuine White Light Super Bright LED … utilizes an advanced Quantum Well technology.[19]" After observing how different colors of LEDs respond to changes in voltage and observing the spectra from both LEDs and gas spectral tubes, the students are ready to build an energy level model of the atom.

At this time in their studies, the students are treating spectra as an empirical observation. 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 must have only certain values of energy -- discrete energy levels. Students are, thus, able to use empirical data and conservation of energy to grasp one of the fundamental concepts of quantum physics.

Students construct energy level diagrams to explain the transitions in the atom. In the initial stages of our development we observed that students would conclude that the energy level that is responsible for a spectral line had a value that was identical to the energy of a photon in the spectral line that they were observing. For example, if they observed a gas with 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. They would not include any transitions. While this model assigned only certain discrete levels to the atoms, it was not an accurate representation of the atomic process.

We designed a computer visualization program to enable students to overcome this difficulty in understanding. *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 which can explain their observations.[20]

In the *Emission* module of *Spectroscopy Lab Suite* students build a "spectrum" for a gas by creating an energy level model diagram of a gas atom. This representation includes determinations of both the values of the energy levels and the transitions between these levels. (See Figure 1.) The top spectrum in Figure 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. Thus, the program confronts 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. Others have different initial states with one final state. (See Figure 2.) We challenge students to state which model is correct based *only* on 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.

Thus, by using this program, students 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 of

20th Century physics 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 levels, students segue into solid atoms in an LED. 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. The *LED* module of *Spectroscopy Lab Suite* (Figure 3) enables students to interactively explore the relation between energy bands and gaps and the spectrum of an LED. Students manipulate the sizes of the bands and gaps to create models which 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 change the voltage across an LED. However, this time the experiment is performed virtually with half of the screen devoted to the "experiment" and the other half showing the changes in the energy bands as the 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 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 the 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 their attention to electrons. They can observe a real experiment if the equipment is available, view pictures in books, or watch a video.[21] The real experiment is, however, somewhat complex. It involves a crystal through which the electron passes. Thus, once we establish that interference occurs with electrons, we introduce an idealized program to investigate the wave nature of electrons further. This program enables the students to control variables in a two-slit experiment involving electrons, nucleons, pions, and photons. (Figure 4)

The first purpose of this program is to enable students to discover, qualitatively, the 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 deBroglie's equation but to be able to use phrases such as the wavelength increases as the energy decreases.

After a few more experiments, including a variation in mass, we introduce the deBroglie equation. We have not actually derived the equation experimentally but have given a feasibility argument for it. While this approach is not historically accurate, it seems to provide students with a gentler introduction to an abstract concept than stating deBroglie's hypothesis and then using interference experiments to verify it.

Students frequently assume that the spreading of the electron beam is due to the electron's electrical charge. They argue that like charges repel so the Coulomb interaction is causing the patterns. One could address this misconception 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 neutrons with all other variables identical. Because the interference patterns are identical, charge must not be a factor.

To connect the matter waves to probability we return to the experiment illustrated in Figure 4. Setting the particle flux to a few per second, the students watch the pattern develop. After a few particles have hit the screen, as shown on the left side of Figure 4, we have the students stop the "experiment." Now, we ask them to predict where the next electron coming from our electron gun will appear on the screen. The students quickly fall into discussing 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. Thus, we can introduce the wave function and its probabilistic interpretation based on the students' experience with indeterminacy.

With wave functions we emphasize conceptual understanding by having students manipulate graphic 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 easily be very inexact with paper and pencil, and sometimes they need to be exact. So, we have created a program, *Wave Function Sketcher* (Figure 5) that allows the students to vary the wave function and match boundary conditions. We have discovered some interesting ways in which non-science students use *Wave Function Sketcher*. First, if we tell the students that the wave function is smooth, they will make it smooth to many derivatives. The idea that two functions just stick together 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 that 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. Thus, we rely heavily on programs such as *Wave Function Sketcher* even when the students have the mathematical ability to find the analytical solutions. For the advanced undergraduate physics students we have created a different form of the *Wave Function Sketcher*. As shown in Figure 6 it uses the common 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* program, students also learn the relationship between the wave function and the potential energy diagram. They are also expected to learn why the wave function model concludes that only certain energies are allowed in an atom. Using the program with a square well potential energy, students pick an energy and try to match the boundary conditions on both sides. The quickly discover that such a matching is not possible for most energies. This activity needs to have a short duration because 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. This activity allows them to see why the wave model of matter leads to the conclusion that an electron bound in an atom can have only certain energies. Further, InGagements provide the opportunity to experiment with different potentials for which Schrödinger's Equation is solved automatically.

The matter waves model 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. (Figure 7a) Then the step is changed to a barrier and boundary conditions matched again. Quantum tunneling naturally follows. (Figure 7b) 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 scanning tunneling microscope (STM). The *STM Simulator* program is 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 an STM operation.

Does Visual Quantum Mechanics Work?

Field tests of *The Original* units have been conducted in high schools and universities throughout the U.S. and in several other countries. Actually, we do not know all the places that it is being used because all the material is on the web and people download it. We have given materials to people in Southeast Asia and throughout various parts of Europe as well as the U.S. Most of The Original units have now been translated into Hebrew.[23] Thus, the materials, except for the new Advanced Visual Quantum Mechanics, have been thoroughly field-tested.

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 results back to us. Students' attitudes toward these materials are very positive. They frequently make comments like, "I really like this better than our regular physics. Can we keep doing it?" (We don't tell the instructors that!) Our staff has observed teachers using the materials in a variety of different schools. The students are positive; they interact with the materials and each other; and they seem to be learning. Most of the teachers also have positive attitudes; a few do not. We certainly have the problem that many teachers in the U.S. do not have a very strong background in quantum mechanics. Even though we are approaching quantum mechanics in a much different way than it is normally taught, some teachers still feel uncomfortable. Building the teachers' confidence is very important. We are working on that aspect now by building a Web-based course for high-school science teachers.

Student learning was also rather good. We have been revising all of the materials in hopes of making it even better. During our observations of the teaching, we noticed that the hands-on component for both the real experiments and the visualizations was important. We had some teachers who decided that it is too much trouble to have the students work in a hands-on mode with all of these programs. So, they just demonstrated the programs to the students. In these cases both the student learning and attitudes went down. Hands-on activities make a difference. Of course we should not be surprised because we built the material for the students to use -- not for the teacher to talk about.

Moving to the Web

While we did not originally design our instructional materials to run on the Web, we have moved toward providing some instruction in that mode. Some reasons for Web-based instruction have been accidental; while others are intentional. On the accidental side, several years ago we selected Macromedia Director as our primary programming environment. Fortunately, Macromedia released Shockwave at about the same time that we began field-testing. Thus, all of our Director programs are now useable on the Web as long as the user installs the Shockwave plug-in. (The programs can be found on our Web site, http://www.phys.ksu.edu/perg/vqm/.) Director is not a good environment for programs that crunch numbers. So, we now use a combination of Director and Java. With these choices we can simultaneously develop software that runs under both Macintosh and Windows operating systems and interactively on the Web.

While these computers programs can be used interactively on the Web, no Web-based instructional materials were originally developed for them. We did not see an easy way to create Web-based substitutes for the hands-on activities. Thus, we made the programs available on the Web but did not know how people would use them in that environment.

To meet a need for instructing in-service teachers, we have now created a Web-based version of most of our InGagements from the Original materials. These materials provide a means for participants to complete the InGagements and submit their results to an instructor for comment. The overall structure and philosophy is identical to the in-class material. Thus, the participants in the Web-based version combine completing on-line "forms" with real experiments and interactive computer visualizations.

Conclusions

Based on a large number of field tests and a rather 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.

Studies with our own students at Kansas State University provided us with information about the relative difficulty in helping students learn abstract concepts through hands-on activities and computer visualizations. They also can point to ways in which we could 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.

Our materials are also 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 feel that we have built a foundation for providing instruction in the most important aspects of 20th Century physics to a broad range of 21st Century students.

Acknowledgments

Primary support for the work described here has been provided by the National Science Foundation. Additional funding has come from the Department of Education's Eisenhower Professional Development Program and the Howard Hughes Medical Institute. The development of *Visual Quantum Mechanics – The Original* teaching materials profited from significant work by Lawrence Escalada and Michael Thoresen. Lei Bao assisted in the development of *The Next Generation* materials, while Waldemar Axmann is the primary author and programmer for *Advanced Visual Quantum Mechanics*. Chandima Cumaranatunge programmed most of the visualizations described in this paper. Rami Arieli has provided valuable feedback and suggestions for improvement while he has been creating the Hebrew translation. We have profited greatly from input from undergraduate students and teachers at many other universities and high schools where the Visual Quantum Mechanics materials have been tested.

Historically Important Experiments	Quantum Basics
Franck-Hertz Experiment e/m Experiment (2 versions) Photoelectric Effect **Classical Background** Energy Diagrams Classical Probability* Scattering & Rutherford’s Experiment **Applications & Model Building** Light Emitting Diodes Investigating Nanospaces (STM) White LED Hydrogen Spectrum Spectra of Light Sources Fluorescence Quantum Model of Conductivity* Solar Cell	Electron Diffraction Matter Waves Sketching Wave Functions 1, 2 & 3 Waves & Their Interpretation Probabilities & Wave Functions Boundary Conditions Exploring Tunneling Motion of a Wave Packet Bound States & Binding Energy Uncertainty Principle Motion of a Wave Packet Wave Functions & Energies in Atoms Quantum Orbitals** Shape of the Wave Function*

Table 1. List of InGagements for Visual Quantum Mechanics – The Next Generation

* Adopted from a similar instructional unit developed at the University of Maryland
** Based on software developed at Boston University

References

[1]Robert Karplus, "Science Teaching and the Development of Reasoning," in J. Res. Sci. Teach. **14**, 169-175 (1977).
[2]Max Born, *The Restless Universe* (Harper & Brothers, New York, 1936).
[3]Kurt Gottfried, "Quantum Physics Series, Films 1-10, Film Review," Am. J. Phys. **46**, 315-316. (1978).
[4]Abraham Goldberg, Harry M. Schey, and Judah L. Schwartz, "Computer-Generated Motion Pictures of One-Dimensional Quantum-Mechanical Transmission and Reflection Phenomena," Am. J. Phys. **35**, 177-186 (1967).
[5]Anthony French and Edwin Taylor, *An Introduction to Quantum Physics* (W. W. Norton & Co., New York, 1978).
[6]Robert Eisberg, *Applied Mathematical Physics with Programmable Pocket Calculators* (McGraw-Hill, New York, 1976).
[7]Daniel F. Styer, Ian D. Johnston, John R. Hiller et al., *Quantum Physics, Consortium for Upper-Level Physics Software,* **Second ed.** (John Wiley & Sons, New York, 1996).
[8]Siegmund Brandt and Hans Dieter Dahmen, *The Picture Book of Quantum Mechanics* (John Wiley & Sons, New York, 1985).
[9]Siegmund Brandt and Hans Dieter Dahmen, *The Picture Book of Quantum Mechanics,* **Third ed.** (Springer Verlag, Berlin, 2001).
[10]Siegmund Brandt, *Quantum Mechanics on the Personal Computer* (Springer-Verlag, Berlin, 1989).
[11]Siegmund Brandt, *Quantum Mechanics on the Macintosh* (Springer-Verlag, Berlin, 1990).
[12]Arnold Arons, *A Guide to Introductory Physics Teaching* (John Wiley & Sons, New York, 1990).
[13]Rick Sternbach, *Star Trek: The Next Generation Technical Manual* (Pocket Books, New York, 1991).
[14]"Reconfigure the Modulators!," Time **144**(22), (1994).
[15]Dean Zollman and KSU Physics Education Group, *Visual Quantum Mechanics* (Ztek, Lexington, KY, 2001).
[16]Helmut Fischler and Michael Lichtfeld, "Modern physics and students conceptions," International Journal of Science Education **14**, 181-190 (1992).
[17]Helmut Fischler and Michael Lichtfeld, "Learning quantum mechanics," in *Research in Physics Learning: Theoretical Issues and Empirical Studies*, edited by R. Duit, F. Goldberg and H. Niedderer (Institute for Science Education, Kiel, Germany) 240-258, (1992).
[18]Pratibha Jolly, Dean Zollman, N. Sanjay Rebello et al., "Visualizing motion in potential wells," Am. J. Phys. **66**(1), 57-63 (1998).
[19]Dick Smith Electronics, *Flyer included with a white LED* (Australia, 2000).
[20]N. Sanjay Rebello, Chandima Cumaranatunge, Lawrence Escalada, et al., "Simulating the spectra of light sources," Computers in Physics **12**(1), 28-33 (1998).

[21] Jürgen Kirstein, "Interaktive Bildschirmexperimente," Ph.D., Technical University, 1999.
[22] N. Sanjay Rebello, Konstantin Sushenko, and Dean Zollman, "Learning the physics of the scanning tunnelling microscope using a computer program," Eur. J. Phys. **18**, 456-461 (1997).
[23] Rami Arieli, (translator) *Visual Quantum Mechanics* (Hebrew) (Weizmann Institute of Science, Rehovot, Israel, 2001).

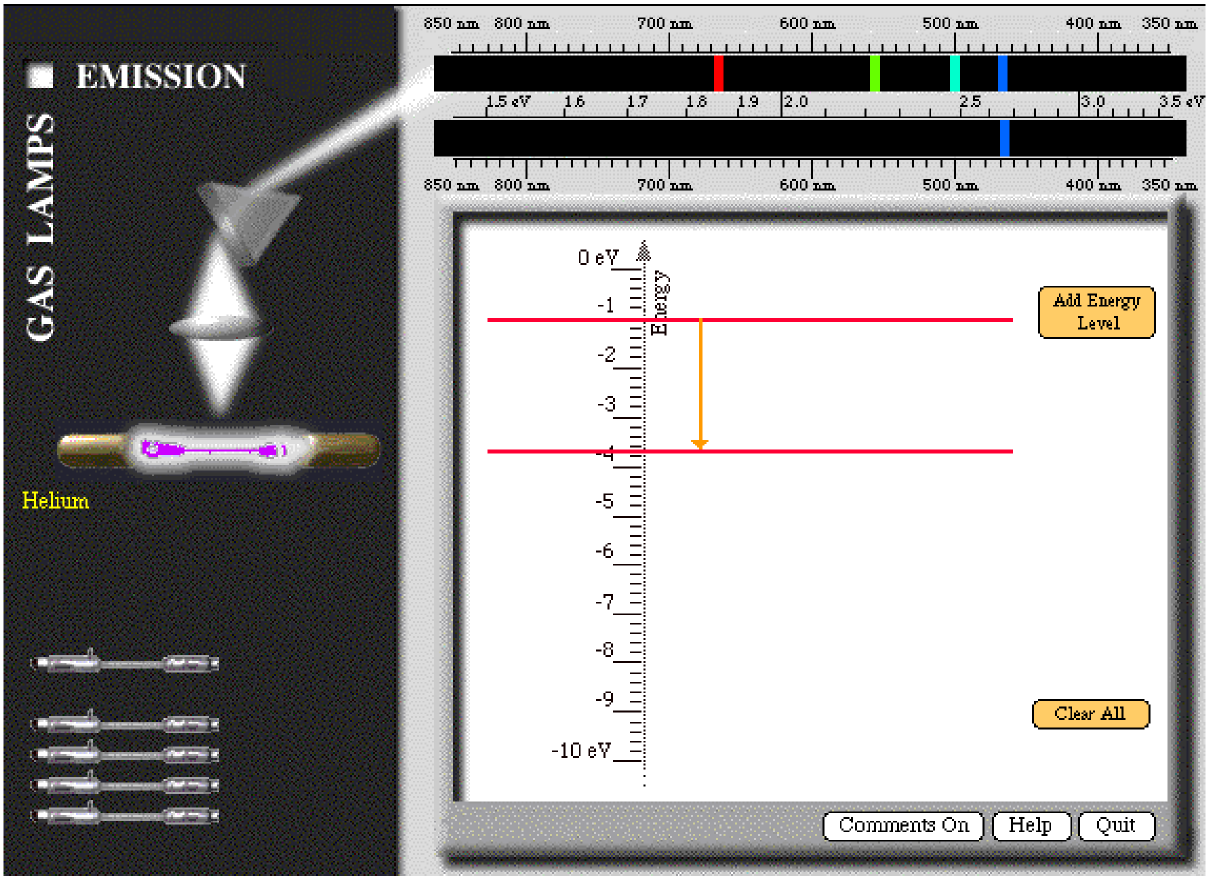


Fig. 1. The Emission module in the *Spectroscopy Lab Suite.* Students drag the light source on the right to the power supply. Then, they build an energy level model of the atom to match the observed spectrum.

(a) **(b)**

Fig. 2. In one class students will frequently create two variations of the energy level model. Fig. 2a shows all of the transitions beginning at the same initial state while Fig. 2b indicates that all transitions end on the same state.

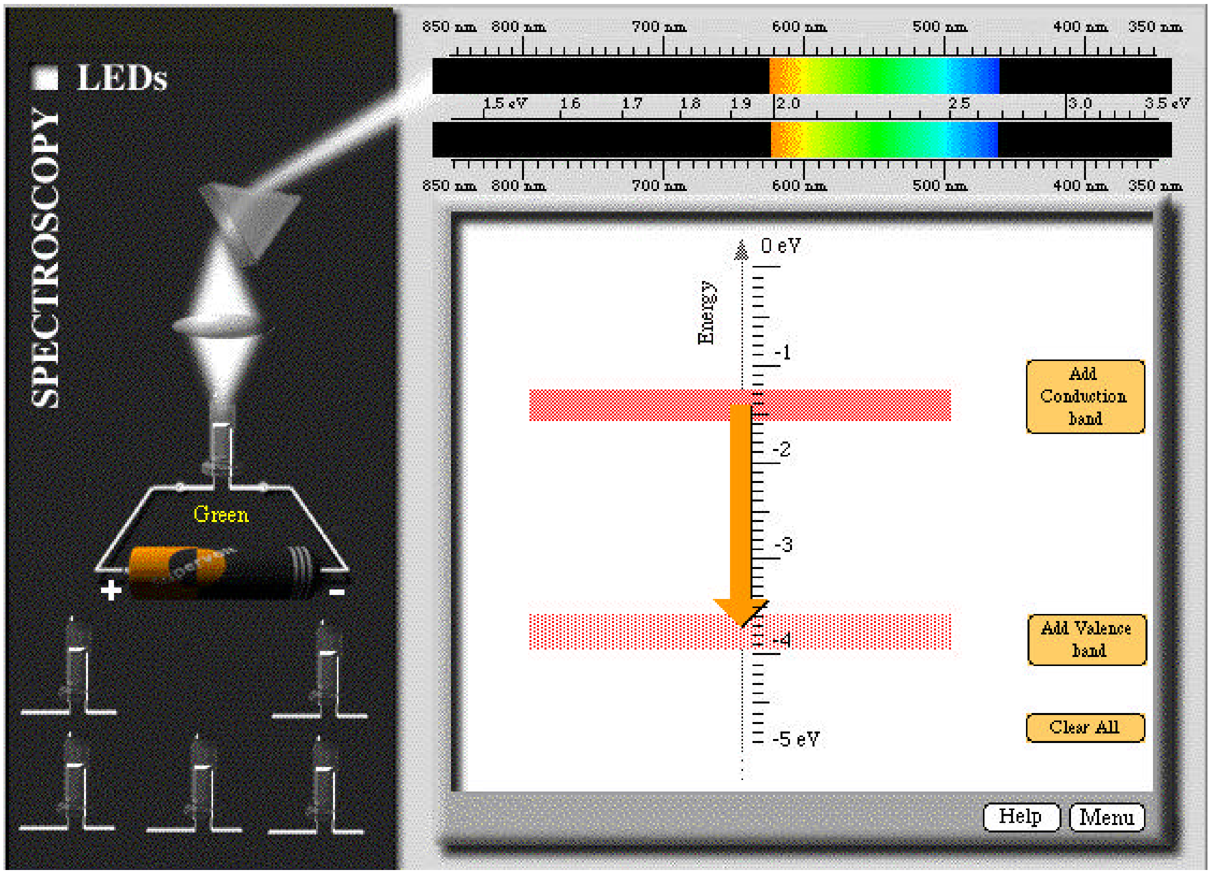


Fig. 3. The LED module in *Spectroscopy Lab Suite.* Students explore how the energy bands and gaps are related to the spectrum of an LED by building a model to reproduce and observe spectra.

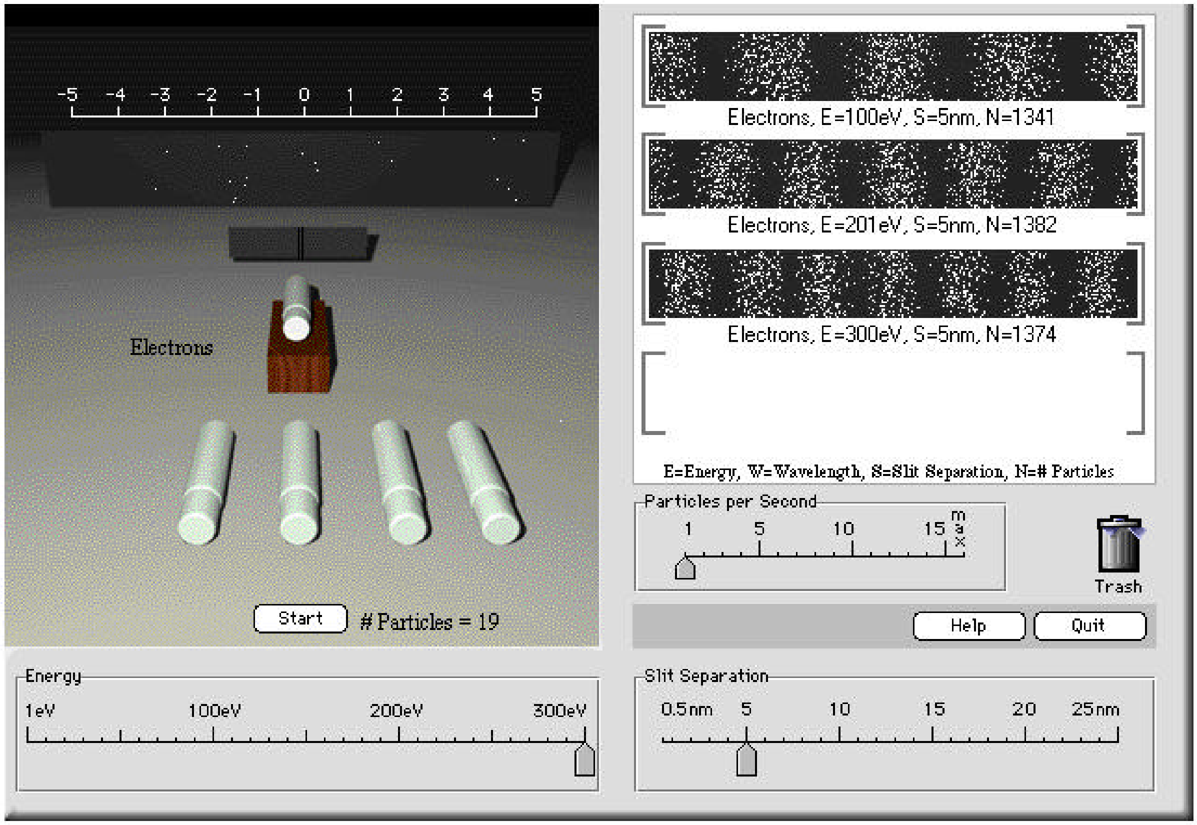


Fig. 4. A simulated electron interference experiment. As the energy increases, the distance between minima decreases. By comparing this behavior with that of light the students conclude that the wavelength decreases as the energy increases.

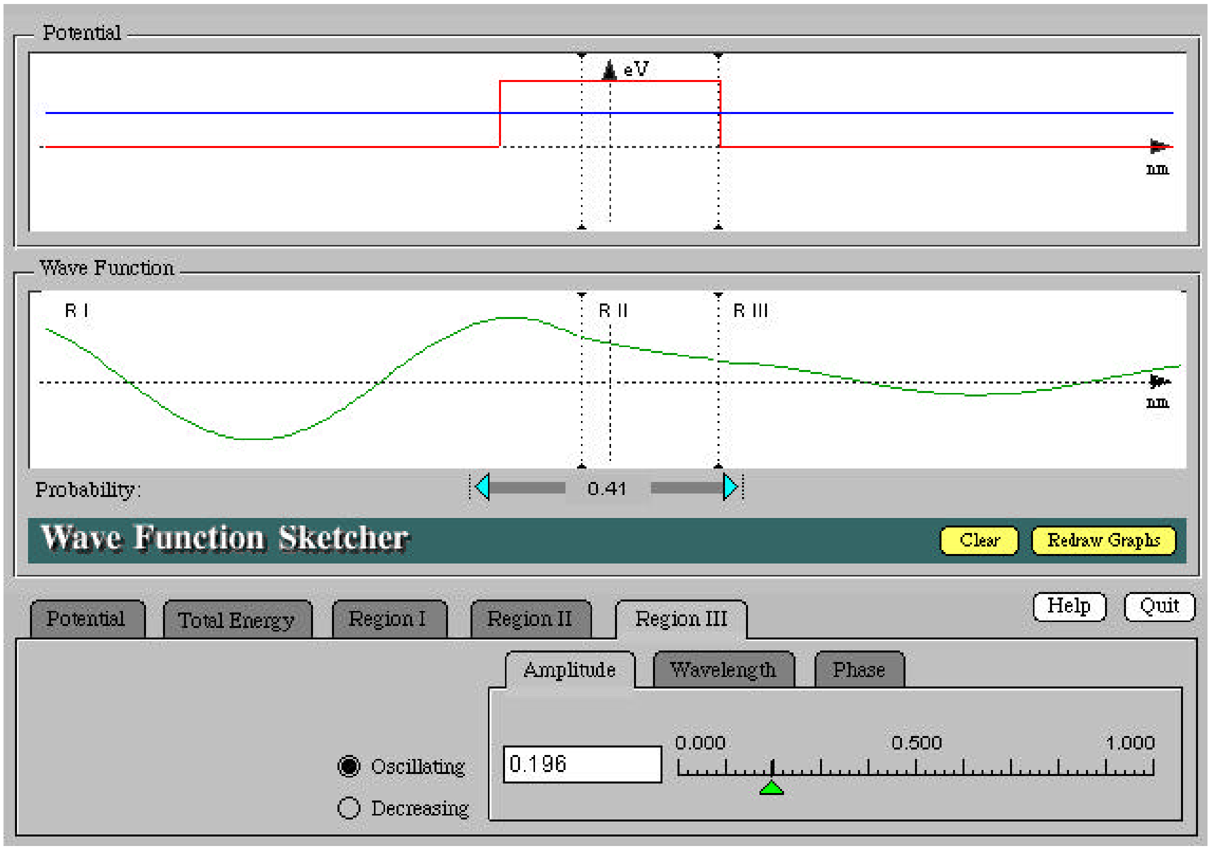


Fig. 5. A screen capture from *Wave Function Sketcher*. This elementary version of the program is aimed at high school students and non-science university students.

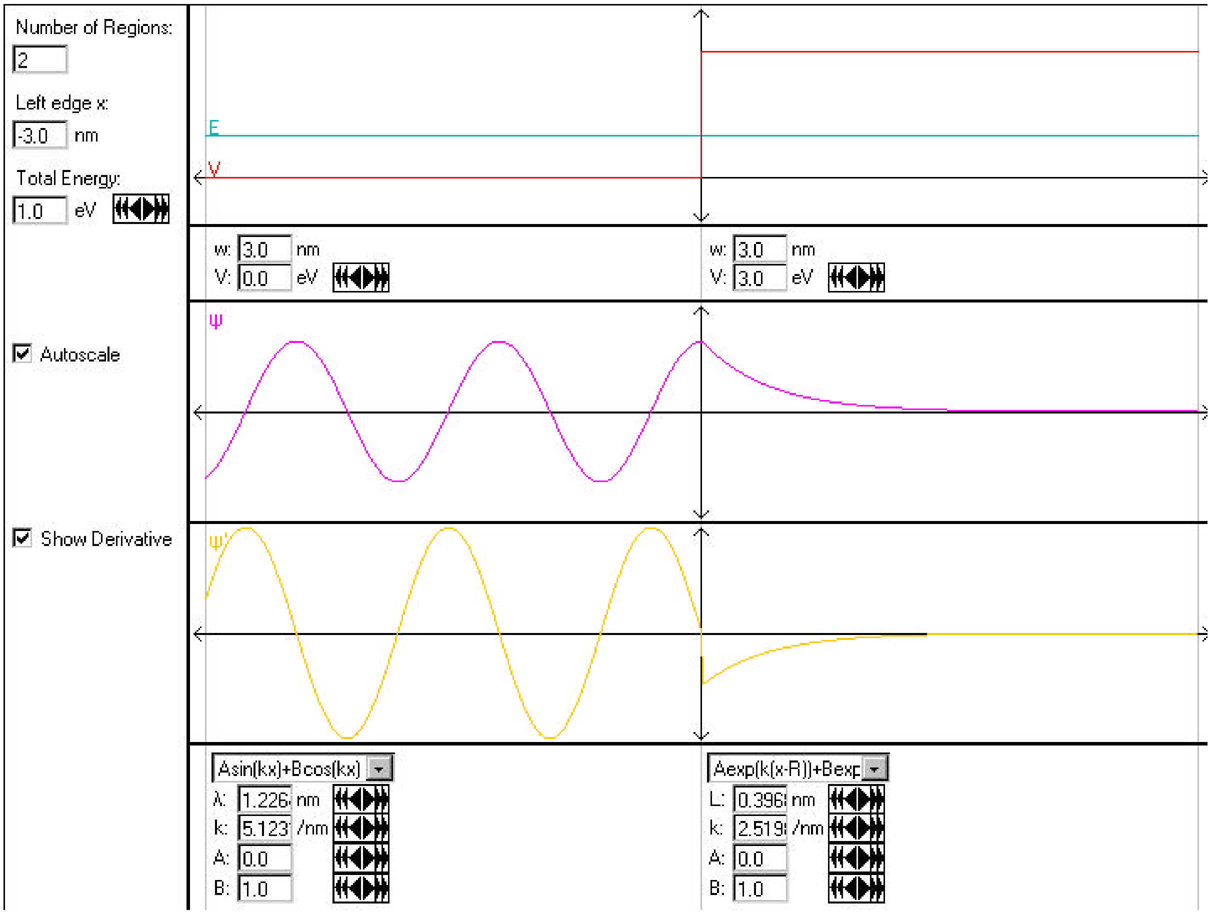
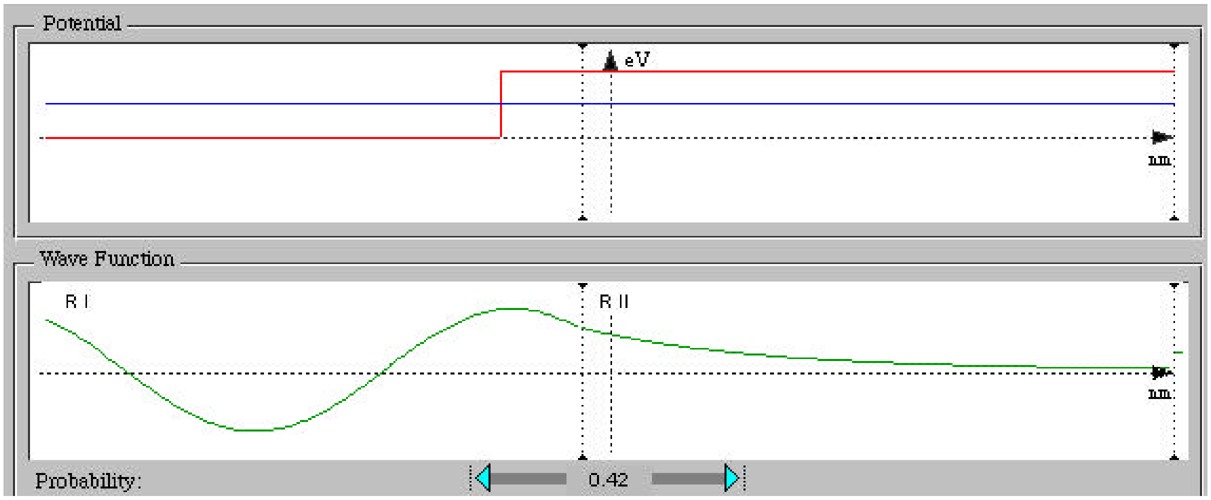
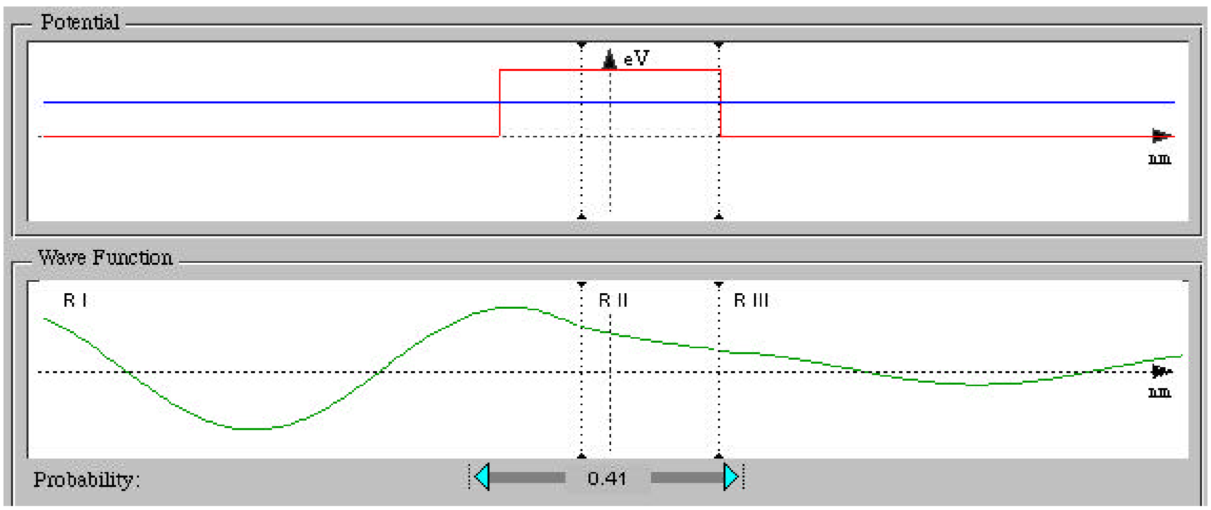


Fig. 6. A screen capture from the advanced version of *Wave Function Sketcher*.

This program is for the university physics students.



(a)



(b)

Fig. 7. (a) Students use the *Wave Function Sketcher* 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.