UNIVERSITY of CALIFORNIA
SANTA CRUZ

PRESENTING FUNDAMENTAL CONCEPTS IN PHYSICS TO THE GENERAL PUBLIC THROUGH VISUAL REPRESENTATION

A thesis submitted in partial satisfaction of the
requirements for the degree of

BACHELOR OF SCIENCE

in

PHYSICS

by

Nina McCurdy

20 March 2009

The thesis of Nina McCurdy is approved by:

Professor Zack Schlesinger
Technical Advisor

Professor David A. Williams
Technical Advisor

Professor David P. Belanger
Thesis Advisor & Chair, Department of Physics

Abstract

Presenting fundamental concepts in physics to the general public through visual representation

by

Nina McCurdy

This paper presents two separate projects both of which explore ways of communicating concepts in physics to a general audience through visualizations.The first project discussed is an interactive designed to convey information about light, magnetic fields and gamma ray astronomy. This was done through a combination of slides, interactives and visualizations. The second project discussed is an animation designed to communicate fundamental concepts of quantum mechanics. Although this was non-interactive, it aimed to inspire meaningful discussion within an audience. For each project, the product, creation process and design process is discussed.

Contents

List of Figures

To my Grandmother,

Marie Whiteside,

The only one more elegant than quantum mechanics.

Acknowledgements

I would like to thank Professor Zack Schlesinger and Professor David A. Williams, not only for giving me the opportunity to do these projects, but for being so utterly supportive throughout my work with them. I would also like to thank the team at the Adler Planetarium, providing me with such an incredible opportunity. Last but not least, I would like to thank Adriane Steinacker for being such a wonderful mentor over the past four years, and for believing in my unusual ambitions.

0.1 Introduction

This paper describes my recent attempts to communicate concepts in physics and astronomy to people with little to no background in math or physics. The introduction addresses the question of whether it is possible to intuitively grasp such concepts as energy eigenstates and electromagnetic radiation through other means. Swiss psychologist Jean Paiget [13] and cognitive linguists George Lakoff [7] argue that we learn first through physical experience and language.

We spend the first 8-12 months of our lives processing the images that surrounds us. We develop an intuitive way of differentiating smooth from sharp, soft from hard and big from small with respect to the objects within our immediately reach. Eventually we develop analytic perspective. By comparing unknown objects to those whose properties are known to us (general size, smoothness, sharpness) we can draw conclusions about things outside of our immediate vicinity[13]. At some point, we learn the words associated with such intuitive differentiations[7].

As adults our visual recognition and our language recognition seem almost interchangeable. A blade is sharp and a cushion is not. Language, however allows us to extend beyond our visual limitations. The imagination pieces together various images contained within our visual library to form creatures and universes that have never been realized by nature. Language allows us to transfer these synthesized universes from one person's imagination to the another's. This communication is limited however, by the vocabulary of the "imaginer" and the visual library of the listener. This is where visual arts come in.

Visual arts, for example, allow us to take our imagined creatures and integrate them into our visual reality. Munchs' "The Scream" is as concretely part of my visual database as an image of my Grandfather in his pajamas, or evening light hitting a Maple tree. So in the same way that we grasp the concept of a tree by looking at it, we can begin to grasp the concept of a never-ending staircase, or a creature that is half man, half lion. Being able to understand and analyze things that cannot necessary be found in nature (or are not detectable to the human eye), is crucial to the development of science.

When learning the language of math, we begin by describing relevant concepts both verbally and visually. When learning arithmetic, we work primarily in apples, or goldfish. When learning fractions, we use our favorite kind of pizza. We eventually veer away from food and rely primarily on symbols for visual aid. In addition, we develop an entirely new alphabet. Eating two apples becomes subtracting (or adding) “two”.

Once we have gained a pretty good grasp of our mathematical alphabet, we speak almost entirely in mathematical phrases (aside from the occasional, “and so”, “but” or “recall”). In the same way that we learn to verbally express the difference between visuals as infants, we learn to associate mathematical phrases with the symbols they describe. Eventually (I am told) our fluency can reach a point where a mathematical description immediately leads to some kind of visual description and visa versa.

I spoke earlier of the necessity for visual art in communicating imagined universes. The same is also true for imagined mathematical universes. In addition to freehand representations, we have developed technologies to help us draw the creatures that we have come across in mathematical streams of consciousness. These drawings not only allow us the share our thoughts with our friends, but they also help us find new ways of describing them, mathematically.

In addition, these representations prove to be effective in communicating such mathematically synthesized creatures and universes to people who do not speak the language of math. On a much more elementary level, visual representation helps us communicate things that aren’t just imagined, but are very real. This is where I come in. For my senior research, I wanted to combine my two passions: Art and Physics, and saw Physics education as a perfect way of doing this. With the help of my mentors, I found two projects in this field.

In the first part of this paper, I will present a project that I completed with Prof. David A. Williams and the Adler Planetarium in Chicago. This project focused on the propagation of high energy gamma rays through interstellar space. The second part of this paper will be devoted to presenting a project that I completed with Prof. Zack Schlesinger. This project focused on the process of exciting an electron through the absorption of a photon. Spanning the subatomic to astrophysical spectrum, these two projects were unified in their common goal to present advanced concepts in physics to the general public through visual representations. For each project, I will begin by presenting background information on the relevant material. I will then discuss the processes of creation. I will end both parts by discussing the outcome of each project and where I plan on going with it in the future.

0.2 Gamma Rays from Deep Space

0.2.1 Background

The original motivation for creating an interactive was to teach the general public about The Very Energetic Radiation Imaging Telescope Array System (VERITAS). This observatory, which is part of the Fred Laurence Whipple Observatory located in Arizona, employs four large ground-based optical telescopes to study gamma rays and the astrophysical phenomena that produce them [10].

Gamma rays are highly energetic photons with energies ranging from 100 keV to several TeV's. Lower energy gamma rays, in the 100 keV range, are a produced through radioactive decay and are one of the three most common types of radiation (the other two being alpha and beta radiation) [1]. The team of scientist working at VERITAS however, are primarily interested in gamma rays in the GeV to the TeV range. Such energies are produced only by incredibly energetic astrophysical events such as gamma ray bursts, pulsars and certain active galactic nuclei (AGNs).

Gamma rays make up only a fraction of all the energetic particles streaming through interstellar space at all times and in every direction. The majority of these particles are protons and heavier atomic nuclei called charged cosmic rays [10]. Because these particles have mass and charge, they are susceptible to the interstellar and intergalactic magnetic fields through which they traverse. As a result, the trajectories of such cosmic rays are filled with bends and turns, making it nearly impossible to pinpoint their source/origin. Gamma rays, on the other hand are photons and therefore are not effected by magnetic fields.

Although charged cosmic rays bombard our atmosphere at a much higher rate, the fact that a gamma ray can travel incredible distances without any major change in its trajectory makes it a far superior candidate for probing the Universe.

While the summary above drastically simplifies the complex and sophisticated processes involved in VERITAS and makes no attempt to discuss the methods and techniques it employs, it represents a level of understanding I was hoping to communicate in my interactive. Introducing a lay audience to ideas which take many years to understand is a big challange. In order to do this successfully, a variety of preliminary steps needed to be taken. The first step entailed choosing a target audience.

The idea of identifying a target audience is fairly intuitive. When presenting information to a demographic, certain methods will be more effective than others. We decided to design an interactive that would appeal to 19 to 25 year olds with little to no background in physics. This decision would influence every step of the creation process; everywhere from the language used to present the material, to the visual style of the slides. The fact that I belonged to the target age proved to be very helpful throughout the project. I am fully in tune with the humor and aesthetic persuasion of my peers, and also nearly always within reach of a perfect test subject.

During my two week internship at the Adler, as well as the month that followed my return to Santa Cruz, I interviewed people in my target group to get a sense of what they already knew, and what they found the most perplexing about gamma-ray physics. The data that I extracted from these conversations were then used to design the K.U.D for the project. The K.U.D.[3] is a standardized method of designing curricula, used in a variaty of education settings. The method is rooted in the idea that a lesson plan should revolve around three main questions: what material are the students expected to know (K) prior to the lesson; what concepts do the students need to understood (U) by the end of the lesson; and how will the students demonstrate (D) their understanding of these concepts. The outline that we came up with for the interactive (see Fig. 0.1.) is a slight variation of the K.U.D method, in that it includes an "Essential Question" column and a "Resources" column. Also, the information in the "Know" column is not what we expect the audience to know prior to using the interactive (as described above), but rather what we expect them to know after viewing the information section (the first six slides) of the interactive.

The essential question (column 1) that we hoped to answer through the interactive was, "Why do VERITAS scientists study gamma rays and [charged]cosmic rays?" The most general answer to this question (column 2) is that studying cosmic rays helps us understand the objects that produce them. More specifically however, we hoped to convey the understanding that because gamma rays travel in straight lines, their sources are much easier to pinpoint than sources of charged cosmic rays, whose paths are perturbed by intergalactic magnetic fields. Making such a claim, to an 18 to 26 year old with no background in physics, would require us to back track a fair amount. Introducing the charged cosmic ray and gamma ray "particles" seemed like a good place to start. Familiarizing the audience with the most relevant and fundamental differences between them, would naturally follow. These fundamental differences are outlined in the bottom half of the "Know" column of Fig. 0.1.

The top portion of the "Demonstrate" (D) column reads "Participants will state the understand". In terms of an interactive, this simply means that at some stage in the program the user will be asked to apply his/her newly acquired knowledge to complete a task. While the D component of the interactive gives the subject a chance to show/test his/her understanding of the material, it also gives us an opportunity to measure the success of our program. If we find that after going through the interactive, the majority of users make the right move or choose the right answer on the first or second try, we can deem the program a success. For our "D" we thought it would be fun to put the user in the shoes of a VERITAS scientist, and have them pinpoint the sources of gamma rays and charged cosmic rays. This component will be described in greater detail in the next section. Essentially our K.U.D. guided us in plotting the trajectory of our lesson plan.

VERITAS Web Visualization KUD – Propagation of Gamma Rays Through Space

Essential Question	Know	Understand	Demonstrate	Resource
Why do VERITAS scientists study gamma rays and cosmic rays?	• There are many more cosmic rays emitted from energetic sources than gamma rays. • VERITAS studies energetic centers of distant galaxies that house supermassive black holes. These areas emit lots of energy and high-energy particles. • Gamma rays are what VERITAS scientists use to study distant energetic objects because they are easier to trace back to the emitting object than cosmic rays.	Studying gamma rays helps us understand how gamma rays <u>and</u> cosmic rays are produced in energetic objects.	Participants will state the Understand.	Surrounding information for propagation interactive on VERITAS website.
How do gamma rays travel through space?	• Photons are particles of light. • Gamma rays are very energetic photons of light. • Gamma rays travel through interstellar space at the speed of light. • There are phenomena that affect the energy of gamma rays as they travel through space. • Studying gamma rays can also tell scientists about the area between the galaxies through which gamma rays travel.	Gamma rays travel in a straight line from their source.	Users will be able to choose the straight-line source of gamma rays, when given several options for sources.	Web visualization: the propagation of gamma rays through space
How do cosmic rays travel through space?	• Cosmic rays are very energetic charged particles that have mass. • There are phenomena that affect the energy and direction of travel of cosmic rays through space.	Cosmic rays do not travel in a straight line through space.	Users will indicate that they cannot identify the source of cosmic rays when given options for sources.	Web visualization: the propagation of cosmic rays through space.

Figure 0.1: The second draft of the VERITAS K.U.D

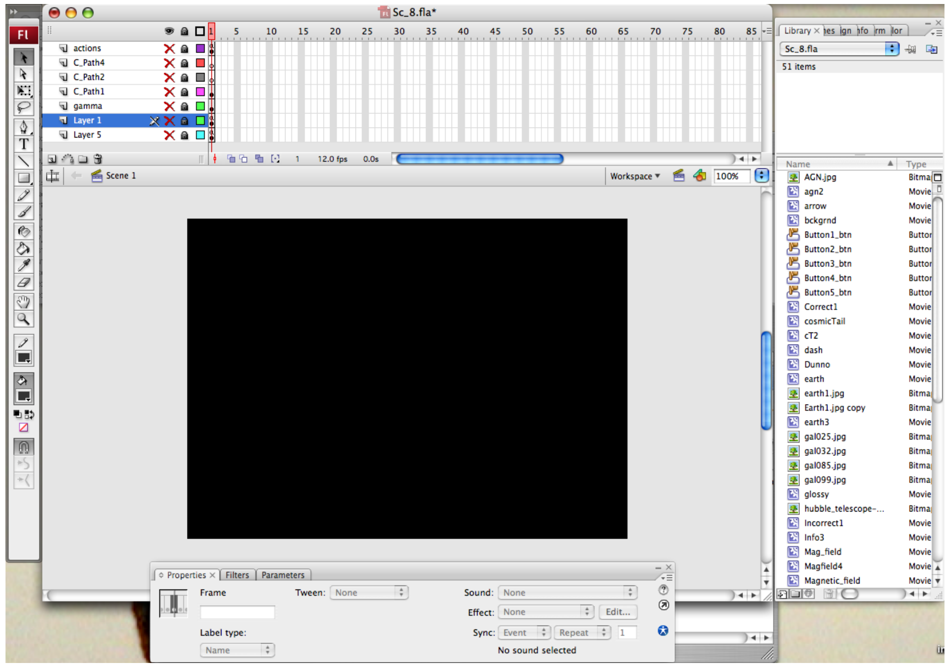

Figure 0.2: Adobe Flash CS3 Professional workspace environment

After finishing all of the necessary preliminary steps, I was finally ready to start designing some slides.

0.2.2 The Creation Process

The entire project was created on Adobe Flash CS3 Professional. Each scene was designed, for the most part, in the stage or workspace environment shown in Fig. 0.2. This included a tool bar Any actual animation/interaction however was scripted into the scene through a corresponding actionscript file. Actionscript 3.0 is an object oriented language based on ECMAscript [1] and designed specifically to target applications which run through the Adobe Flash platform.

My overarching goal was to write a program that would simulate the experience of riding a gamma ray through space. Being essentially new to the world of programming, my work was obviously cut out for me. The first few months were spent staring at forums and error messages

[1] ECMAScript European Computer Manufacturers Association is an international standardized programming language for scripting

Figure 0.3: Randomly generated deep space

and completing tutorial after tutorial. After many hours of this, I built up enough of a vocabulary to complete menial tasks: "put that there...make it bigger...and so on an so fourth". With this vocabulary, I was able to create an image of deep space (shown in Fig. 0.3).

The code for creating this picture consisted almost entirely of random number generators. Over 1000 galaxies, randomly chosen from a library of images, were assigned random values for their scales, positions, opacities and rotations. Every time the program was tested, a new image was created. After generating deep space after deep space, the code finally put out an image that I could work with. Fig. 0.3 appears as the background for all but two slides in the interactive. Although I was very pleased with the progress I had made, I continued chugging through endless tutorials. Eventually, I was simulating fire, water and rain. I had everything I needed to visualize gamma rays shooting through space (this would undoubtedly work its way into the interactive). As briefly mentioned in the introduction, finding a balance between clarity, aesthetics and scientific accuracy proved to be one of the largest challenges I encountered during the creation process. Simply attempting to visualize gamma rays, shooting through space at the speed of light, demanded an imaginative negotiation of clarity, depth and truth. The most natural tendency was to represent

Figure 0.4: Our gamma ray

it with a streak of electromagnetic radiation, like a shooting star. However, it needed to differ from a shooting star in some immediately recognizable way. In a meeting with the VERITAS team, we agreed that a purple streak of light, like the one shown in Fig. 0.4, would do the trick. In the final product, Fig. 0.4 can be seen streaking though the background in two of the introductory slides. In addition the image was the basis for designing the visuals used in the "ride a gamma/cosmic ray" component discussed towards the end of this section.

As mentioned earlier, the majority of each slide was designed in the "stage" environment. The rules and methods of the Flash workspace are very similar for any Adobe design program (e.g. Photoshop and Illustrator). Although I was still learning actionscript, I was able to create almost the entire storyboard without writing a single line of code.

The plan for the first few slides was to introduce gamma rays and charged cosmic rays separately, and then discuss the fundamental differences between them. The next few paragraphs will present and discuss the slides created with this in mind.

Another aspect of the interactive, includes the three silhouetted audience members shown in the lower left hand corner of Fig. 0.5. These characters resemble those of the 90's TV show "Mystery Science Theater". Their purpose is to echo the "thought bubbles" of the user (also shown in Fig. 0.5).

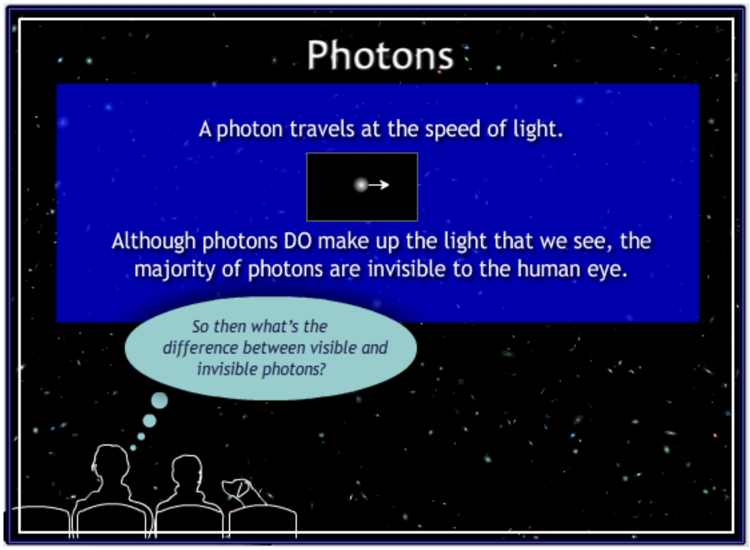

Figure 0.5: Introducing Photons

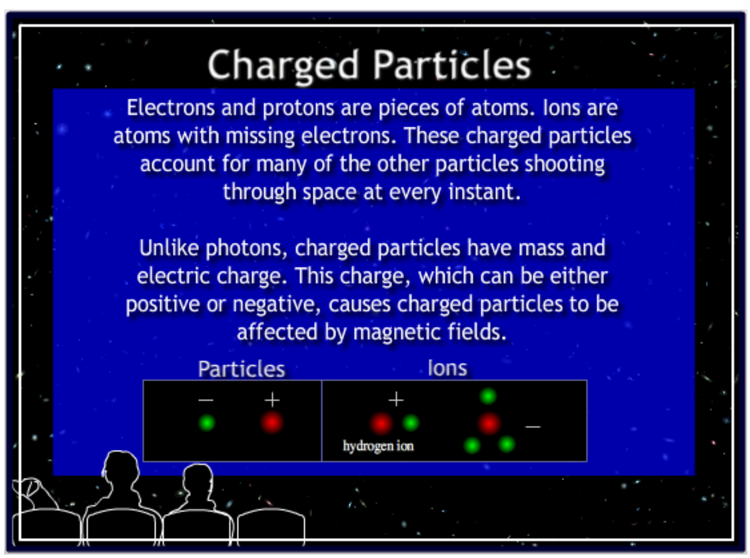

Figure 0.6: Introducing Charged Particles

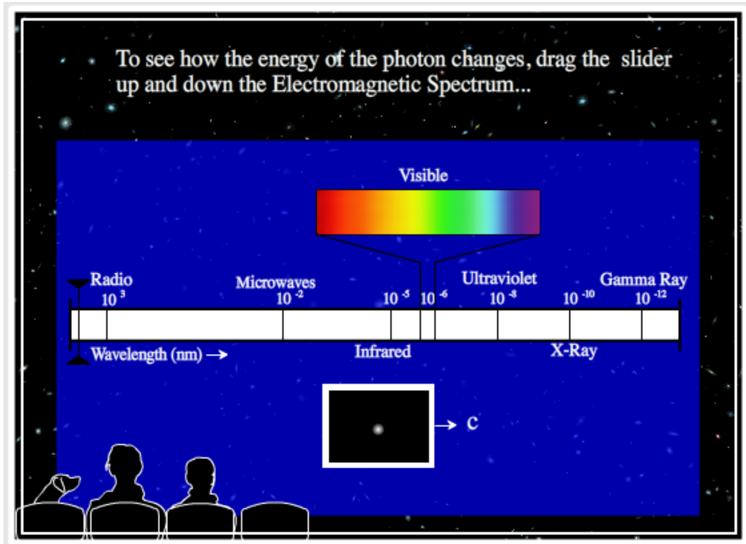

Figure 0.7: Slide1: The Electromagnetic Spectrum Interactive

Early in the development stages I found that, when presenting my slides to my peers, I felt compelled to confirm with them the key ideas of each scene. It soon became clear to me that my verbal confirmations needed to somehow be integrated into the slides. When targeting people of all ethnic and socioeconomic backgrounds however, finding the right character can be very tricky. By using silhouettes, this complication was avoided altogether. These characters not only play an integral role in guiding the user through the presented material, but they also make the entire interactive more playful and less intimidating.

The next slide, shown in Fig. 0.7 follows directly after Fig. 0.5 and continues the introduction of a photon. The main goal of this slide was to convey two things: that photons compose all forms of electromagnetic radiation, and that gamma rays are the most energetic form of this radiation. The notion that photons make up the radio-waves we ultimately hear, the light we use to see the world, and the X-rays that we take to view our broken bones was very unfamiliar to our target audience. Understanding this notion was a thrilling part of my science education and I was excited to have to opportunity to put my own spin on the presentation of it. The slide works as follows: as the user moves the slider to various frequencies on the spectrum, the photon bounces up

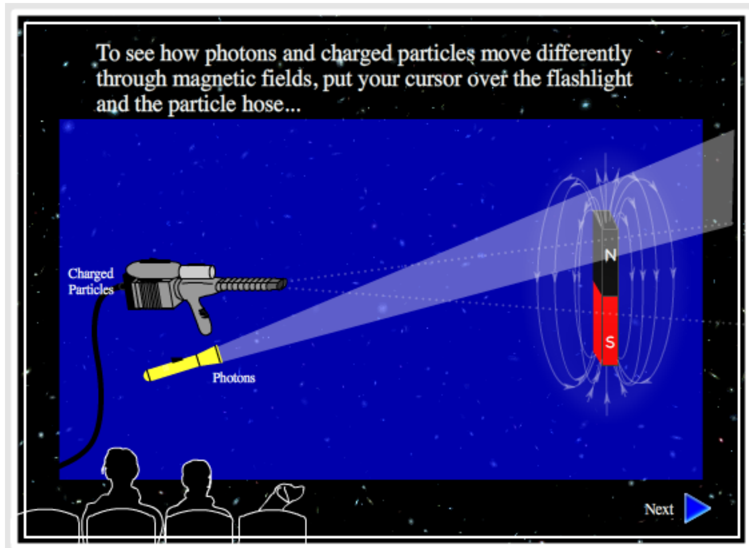

Figure 0.8: Scene3: The effect of magnetic fields on photons and charged particles

and down at a proportional speed. I saw this correlation as a way of allowing the user to “feel” the different energies of the photon.

In the final product, this slide was for the most part removed. Although it very clearly presented the range of energies (and the various associated wavelengths) at which a photon can exist, it referenced a concept that proves again and again to be quite perplexing to a general audience. Although the wave-particle dual nature of a photon is something that every physicist either makes peace with or continues to obsess over, it can be quite disorienting when presented the first or second time.

The next slide, presented in Fig. 0.8, draws on the information presented in the slides before it. The main goal of this slide was to convey the idea that while paths of charged particles are distorted by magnetic fields, those of photons are left undisturbed. Although this concept doesn’t appear to be too difficult for people in our target audience to grasp, it is crucial in understanding why VERITAS scientists choose to study gamma rays rather than the more prevalent, charged particles. The slide works as follows: when the curser is placed over the flashlight, a stream of “photons” shaped as little white spheres shoot straight through the lines of the magnetic field created by the magnet. Placing the cursor over the particle gun however, causes charged particles (i.e. electrons, protons and ions) to curve about the stage according to the equation

$$F = q\vec{v}x\vec{B} \tag{0.1}$$

where q is the charge of the particle, v is the velocity of the particle and B is the field of the magnet. The fact that the force of a magnetic field, acting on a charged particle, is perpendicular to both the field and the initial velocity of the particle, made designing this slide slightly tricky. I needed to find a way to arrange the magnet and the particle gun such that both the bending of the particles and the magnetic field lines were visible. My first attempt to solve this is presented in Fig. 0.7. Making the magnetic field spherical, however, does not change that fact that charge particles shot towards the magnet will be deflected either in or out of the screen. In the final product, the magnet will be rotated 90 degrees causing its magnetic field to point, for the most part, into the screen. Upon entering the magnetic field, negatively and positively charged particles will be deflected downwards and upwards, respectively.

The next part of the project was devoted to creating the gamma ray/cosmic ray rides. The general idea was that the user is relocated to the middle of deep space. After staring out into space, he/she notices a bright purple light growing larger. It soon becomes clear that a collection of gamma rays are headed right towards him/her. As they approach, time slows to a still and the user hops onto the center-most ray. The camera then rotates one hundred an eighty degrees until the user is facing the direction in which the gamma/cosmic ray is traveling. At this point, time speeds back up and the user rides the ray through interstellar space until he/she and the ray reaches Earths atmosphere. In the case of the gamma ray, user's journey to Earth is direct. In the case of the cosmic ray however, the user spirals through space in a somewhat chaotic fashion.

This was by far the most programming intensive part of the entire project. The first program that I wrote, created the illusion of zooming through space by moving images of galaxies radially outward from the center of the screen. The second and final program that I wrote employed

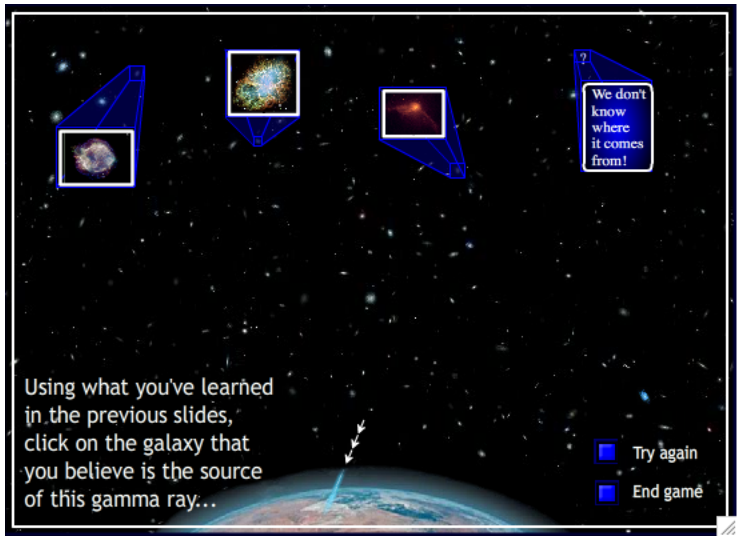

Figure 0.9: Pinpoint the source of this gamma ray

a class called PaperVision3D. Using this class allowed me do distribute images of galaxies through a three dimensional environment and then send a camera through the space. This produced a much more convincing simulation.

This part was designed to be the more entertaining component of the interactive, and also to clear up any confusion created in the previous slides. The last part of the interactive addressed the "Demonstrate" component of the K.U.D.

This portion consisted of two slides (shown in Figs. 0.9 and 0.11) in which the user was asked to pinpoint the source of either a gamma ray (Fig. 0.9) or a cosmic ray (Fig. 0.11). The ray (cosmic or gamma) was animated to repeatedly pierce Earth's atmosphere at a clearly defined angle. If the previous slides were successful in conveying the important distinctions between photon propagation and charged particle propagation, the user would choose the correct source simply by extending the line of the gamma ray back to the picture of the galaxy M87 (Fig. 0.10). Pinpointing the charged cosmic ray source however, would be a different challenge altogether.

Hopefully by this point, the user would feel confident in the fact that the propagation of a charged particle though space is turbulent and anything but direct. He/She should therefore

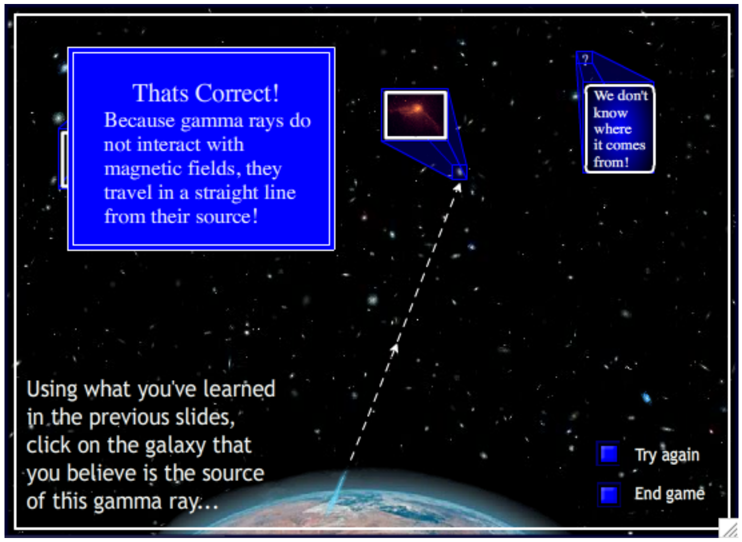

Figure 0.10: The correct source of this Gamma ray

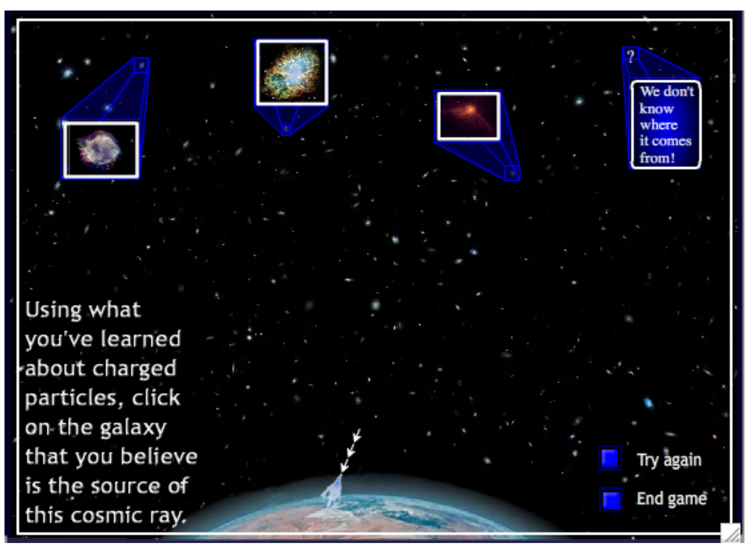

Figure 0.11: Pinpoint the source of this cosmic ray

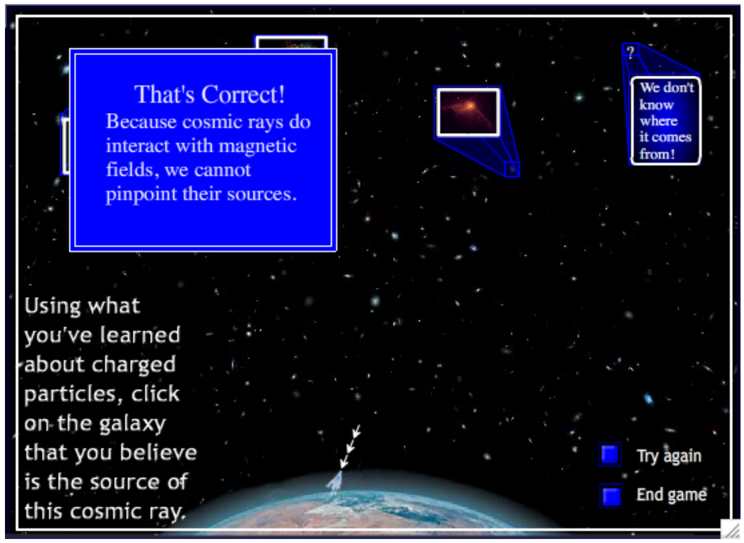

Figure 0.12: The correct source of this cosmic ray

conclude that the charged cosmic ray could have just as easily come from any of the possible sources, and that he/she really doesn't know where it came from (Fig. 0.12). Rather than simply telling the user that he cannot determine the source of the charged cosmic ray, this slide pushes him/her to experience the challenges of the VERITAS scientists first hand.

As mentioned earlier, in addition to solidifying the user's understandings, these slides provide an opportunity for us, the creators, to see which parts of the interactive worked, and which parts need to be improved.

0.2.3 Plans for final product

If all goes as planned, the final product will be available on the Adler Planetarium website. It will be one of three interactives/simulations, the other two of which will focus on the creation of gamma rays and the detection of secondary particle showers on earth. Together, the three pieces will trace the path of a gamma ray from its creation at distant sources, through its propagation through interstellar space and to its detection right here on earth.

This project has been an invaluable experience for me in that is has in every way launched my career in the field of science education. It has given me a taste of some of the greatest challenges associated with the art of teaching. When I started this project, the concept of programming gave me chills. After eight months of staring at tutorials, forums and error messages, I am finally beginning to understand a language!

The American computer scientist Alan Curtis Kay once said "To get the medium's magic to work for one's aims rather than against them is to attain literacy" [11]. I am realizing more and more, that the primary medium for visualizing physics is programming. I am familiar with the feeling of connectedness with one's medium. I have felt it with a variety of materials, all of which could be sculpted with my fingers. I hope that one day I feel this connectedness with programming, which is just to say that I hope to one day become literate.

Thus concludes my presentation of the gamma ray interactive. The second half of this paper will present an animation created to teach the general public about certain properties of quantum mechanics.

0.3 A Little Bit of Quantum Mechanics

0.3.1 Background

It is my understanding that the primary goal of science is to create a language that very accurately describes the things that occur around us. While the complexities of nature are reflected in the plethora of page-long formulas and lifelong derivations, the fundamental relations are relatively simple and incredibly elegant. A person's concept of beauty and comfort is derived from the way he/she views the world, the colors he/she is surrounded by, and the sounds he/she falls asleep to. We are all precisely tuned to a range of vibrations which once processed, allow us to define our individual places in the universe. Through mathematics, the rhythms of nature are transposed into sines and cosines and non-linear expressions. It is not surprising then, that the visualization of a mathematical representation of nature would convey something as beautiful and comforting as a crashing wave or a shooting star. From the rhythm of space time, to the dynamics of a morning cup of coffee, to the electron shells of an atom, these patterns and rhythms exists on all scales, whether or not they are visible to the human eye.

In this project, we were interested in the patterns and rhythms that appear when an electron is excited from a lower to a higher energy level in an infinite square well potential. In order to study this however, we needed to first translate the excitation into the language of science.

Derivation

In this next section I will present the mathematical derivation of the time-dependent first order perturbation of a two level system. We must, of course, begin with the Schrödinger equation,

$$i\hbar\frac{\partial\Psi}{\partial t} = H\Psi \qquad where \qquad H = -\frac{\hbar^2}{2m}\nabla^2 + V, \tag{0.2}$$

where m is the mass of the particle and V is the is the potential of the system.

At first glance, this elegant relationship may look like any first order time differential equation. Anyone whose taken a course in quantum mechanics, however understands at the very least the magnitude of information that is contained within it.

The general solution to eqn.(0.2), which can be obtained by separation of variables, is

$$\Psi(\mathbf{r}, t) = \psi(\mathbf{r})e^{-iEt/\hbar}. \tag{0.3}$$

As you can see, the wavefunction $\Psi(\mathbf{r}$,t) has been separated into a spatial component $\psi(r)$ and a time component $e^{-iEt/\hbar}$.

In a two-level system, an electron can exist in either one or both of the states ψ_a or ψ_a at any given time t. The complete wavefunction of the electron Ψ(x,t) can be expressed as a linear combination of the two possible wave functions ψ_a and ψ_b:

$$\Psi(x, t) = c_a(t)\psi_a e^{-iE_a t/\hbar} + c_b(t)\psi_b e^{-iE_b t/\hbar}. \tag{0.4}$$

That the coefficients c_a and c_b evolve through time is characteristic of time dependent perturbations. In addition to the time-dependent phase factors, $e^{-iE_a t/\hbar}$ and $e^{-iE_b t/\hbar}$, of the two individual wave-functions, time-dependent perturbations cause the mixture/ratio of the two available states to evolve with time as well.

Taking the absolute value of eqn.(0.4) gives us the probability density,

$$|\Psi(x,t)|^2 = |c_a(t)\Psi_a(x,t)|^2 + |c_b(t)\Psi_b(x,t)|^2$$

$$+(c_a(t)\Psi_a(x,t))^* c_b(t)\Psi_b(x,t) + c_a(t)\Psi_a(x,t)(c_b(t)\Psi_b(x,t))^*. \tag{0.5}$$

Simplifying this gives us

$$|\Psi(x,t)|^2 = |c_a(t)|^2\psi_a(x)^2 + |c_b(t)|^2\Psi_b(x)^2$$

$$+[c_a(t)^* c_b(t)e^{i(E_a-E_b)/\hbar} + c_a(t)c_b(t)^* e^{-i(E_a-E_b)/\hbar}]\Psi_a(x)\Psi_b(x). \tag{0.6}$$

The next step is to derive c_a(t) and c_b(t) and plug them into our probability density equation. For our animation, we were interested in simulating the excitation of an electron, from a lower to a higher energy level, through the absorption of radiation. This process calls for the following boundary conditions:

$$c_a = 1 \quad , \quad c_b = 0 \quad at \quad t = 0; \tag{0.7}$$

$$c_a = 0 \quad , \quad c_b = 1 \quad at \quad t = t_1. \tag{0.8}$$

At $t_0 = 0$, the electron is completely in the lower energy level E_a. At a later time t_1 the electron is completely in the higher energy level E_b. Using perturbation theory, we can find out where the electron is in the time between t_0 and t_1.

By plugging eqn.(0.4) into eqn.(0.2) and defining the hamiltonian as

$$H = H^0 + H'(t), \tag{0.9}$$

where H^0 is the unperturbed hamiltonian and $H'(t)$ is the time dependent perturbation, we can solve for the first order time derivatives of our coefficients.

$$\dot{c}_a = -\frac{\imath}{\hbar} H'_{ab} e^{-\imath\omega_0} c_b \qquad , \qquad \dot{c}_a = -\frac{\imath}{\hbar} H'_{ba} e^{\imath\omega_0} c_a, \tag{0.10}$$

where

$$H'_{\imath\jmath} \equiv \langle\psi_\imath|H'|\psi_\jmath\rangle \qquad and \qquad \omega_0 \equiv \frac{E_b - E_a}{\hbar}. \tag{0.11}$$

To solve for c_a(t) and c_b(t) in eqn.(0.10) we use what Griffith calls "successive approximations"[8].

First we solve for the case of no perturbation. This would result in the wavefunction obeying eqn.(0.4) for all time t i.e.

$$\Psi(x,t) = \psi_a e^{-iE_a t/\hbar} \tag{0.12}$$

We call this a zeroth order perturbation. To find the first order perturbation, we simply plug our zeroth order values for c_a and c_b into eqn.(0.10) and integrate with respect to t. This yields

$$c_a = 1 \qquad and \qquad c_b = -\frac{\imath}{\hbar}\int_0^t H'_{ba}(t')e^{\imath\omega_0 t'}dt'. \tag{0.13}$$

For the purposes of our simulation, a first-order approximation would suffice. The next step is to plug in our perturbation H'_{ab}, defined in eqn.(0.9) . For the case of excitation via absorption of radiation,

$$H'_{ab} = -\wp E_0 cos(\omega t), \qquad where \qquad \wp = q\langle\psi_b|x|\psi_a\rangle, \tag{0.14}$$

where E_0 is the maximum amplitude of the radiation, ω corresponds to the frequency of the photons being absorbed, and q is the charge of an electron. The fact that x shows up in the expectation value indicates that the radiation is polarized in the x direction.

Plugging this into eqn.(0.6) and noting the definition of ω_0 in eqn.(0.11) leads me to the following expression:

$$\begin{aligned} |\Psi(x,t)|^2 = |c_a|^2\psi_a(x)^2 + \Big(\frac{qE_0\langle\psi_b|x|\psi_a\rangle sin[(\omega_0-\omega)t/2]}{\hbar(\omega_0-\omega)}\Big)^2\Psi_b(x)^2 \\ +|c_a|\frac{2qE_0\langle\psi_b|x|\psi_a\rangle}{\hbar(\omega_0-\omega)}sin[(\omega_0-\omega)t/2]sin[(\omega_0+\omega)t/2]\Psi_a(x)\Psi_b(x), \end{aligned} \tag{0.15}$$

where c_a is on the order of unity. Thus concludes the derivation of the time-dependent perturbed wave equation for an electron in a two-level mixed state of an infinite square well potential.

We are now ready to plug the above expression into Mathematica and see what kind of shapes it produced.

0.3.2 The Creation Process

This animation was designed specifically for non-science brains, i.e. artists, writers, activists etc... In particular, we wanted to create something friendly and approachable for people naturally averse to the language of math. We hoped however, that portions of the animation would appeal to people familiar with concepts of quantum mechanics as well.

The first part of this project was devoted to deriving the perturbation equations for our particular system (shown in the previous section). Once I had completed these derivations, I was able to begin creating my simulating. This was done entirely in Mathematica.

Initially, my goal was to animate the time evolution of eqn.(0.15). This entailed choosing appropriate values for things like the amplitude of the electromagnetic radiation E_0 and the width of infinite square well (a).

In order to excite an electron into a higher energy level, the frequency of the electromagnetic radiation being absorbed by the electron (ω) must be near the resonant frequency of transitioning electron i.e.

$$\omega_0 = \frac{E_n - E_{n-1}}{\hbar}, \tag{0.16}$$

where E_n is the level the electron begins in and E_{n-1} is the level that it is excited into. The formula for the energies is of course,

$$E_n = n^2 \frac{\pi^2 \hbar^2}{2ma^2}, \tag{0.17}$$

where m is the mass of an electron (on the order of 10^{-31} kg) and a is the width of our well. Therefore increasing the width of the well decreases the energy of each level, and visa versa. My initial tendency was to make choose a small a (on the order of 10^{-37} (nm)) that would make up for the $\hbar^2$ in the denominator. However, the effect of a on eqn.(0.15) also needed to be taken into consideration.

The other two constants that show up in the perturbation equations are the charge of an electron (q) which is on the order of 10^{-19} C, and E_0 which represents the square root of the intensity of the radiation. After fiddling around with different orders of magnitude for E_0 and a, I finally settled on 10^{-13} (unitless) and 10^{-2} (nm) respectively. These values made enough sense both visually (resulting in nice plots) and scientifically (a was on the same order as the bohr radius).

This is all to say that choosing the appropriate parameters turned out to be much more challenging than I anticipated. At this point I was able to animate the evolution of my probability density from the ground state to the first excited state. By changing around the appropriate variables (i.e. ω and energy level number (n)) I was able simulate an electrons' transition from the first to the second excited state; the second to the third excited state, and the third to the fourth excited state. These four simulations would be all I would need for my animation.

Time-dependent perturbation theory does a fine job of describing an electrons transition toward a higher energy state, but that is as far as it goes. While various sinusoidal oscillations in eqn.(0.15) cause the ratio of the mixture of the two states to evolve with time, the overall effect is periodic. In addition, the time independence of c_a, a consequence of working with the first order approximation, prevents the electron from ever being entirely in the excited energy state.

Rather than stepping up the order of our approximation, we decided to simulate the absorption of photons by interrupting the periodic repetition with appropriately scaled error functions. The effect of these error functions on the coefficients of the various terms in eqn.(0.4) are shown in Fig. 0.13. The blue line (c_0) is the coefficient for the ground state wavefunction. At around 14 seconds, c_0 exponentially drops to zero. c_{mixed}, which represents the coefficient of the third term in eqn(0.15), goes to zero at the same time. At this point, the electron is entirely in Ψ_1, and the only term that survives has the coefficient c_1. An inverted error function was used to change c_1 from sin-like function, to a steady value.

Although Mathematica was excellent for creating the frames of each animation, it lacked the components needed to turn these animations into presentable art forms. Because I had become

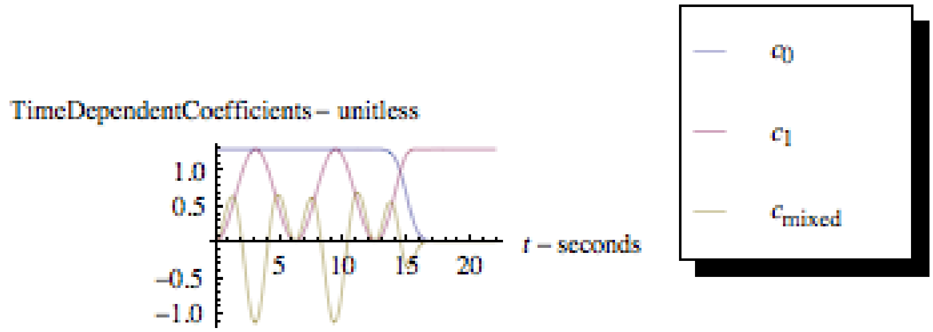

Figure 0.13: The effect of error functions on the coefficients terms in eqn.(0.4)

familiar with Flash CS3 through my gamma ray interactive project, I decided to use its workspace to make my movie.

Rather than discovering a clever way of importing the animations from Mathamatica to Flash, I took the tedious manual route. This entailed exporting one still frame for every tenth of a second of each animation. These images (gifs) were then imported into a flash library where they were placed manually, one by one, onto the workspace (or stage). Thankfully, my patience and persistence was rewarded with a beautiful reproduction of what became know as "the dancing blob".

At this stage it became clear that in order to give the audience the richest experience, I would need to give the dancing blob some context. The rest of my project was devoted to creating a larger animation that would introduce the relevant concept leading up to to the original animations. In short, this meant drawing pictures, animating letters, and attempting to find the best ways to instantly convey some of the most richly complicated concepts I've ever encountered. Now, where to start?

One of the first concepts covered in any introductory physics course is the infinite square well (I.S.W.)potential. While the mathematical description is slightly abstract, it clearly illustrates the idea of confinement. In addition, the I.S.W. paves the way for things like wave equations and

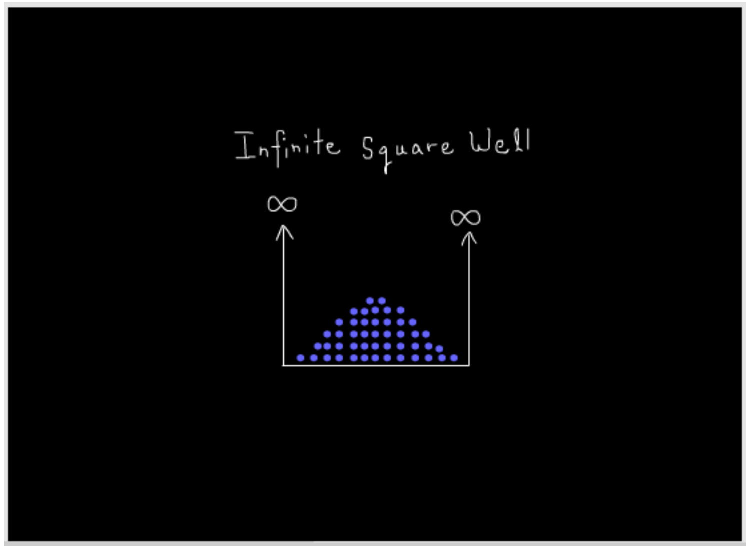

Figure 0.14: Introducing the probability density

energy eigenstates. This seemed like a good starting off point for the animation. From that point, all I would need to do is introduce the various probability densities and discuss the process of exciting an electron.

Figure 0.14 is a frame taken from the sixty-second second of the animation. What is shown is an infinite square well potential with electrons (shown as little blue dots) stacked on top of each other in the shape of the ground state probability density. This was one of my attempts to appropriately balance clarity and scientific accuracy. Popular science depicts and electron almost always as a particle. When thinking about quantum mechanics however, it is much more useful to think of an electron as a complex wave. Because Schrödinger's equation was undoubtedly beyond the scope of this animation, it was necessary to devise a new simple way of taking the audience from a single electron to its probability density. Describing the density as the shape that arises when many horizontal position measurements are plotted (frequency as a function of position) seemed to do the trick. The next step was to introduce the idea of quantized energy levels.

The conventional approach to visualizing the energy levels of such a potential is shown in Fig. 0.15[9]. While this depiction may seem clear to someone who is familiar with the problem, I felt

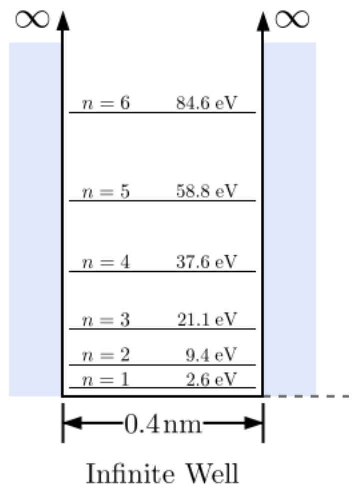

Figure 0.15: Conventional representation of the quantized energy levels of an I.S.W. potential

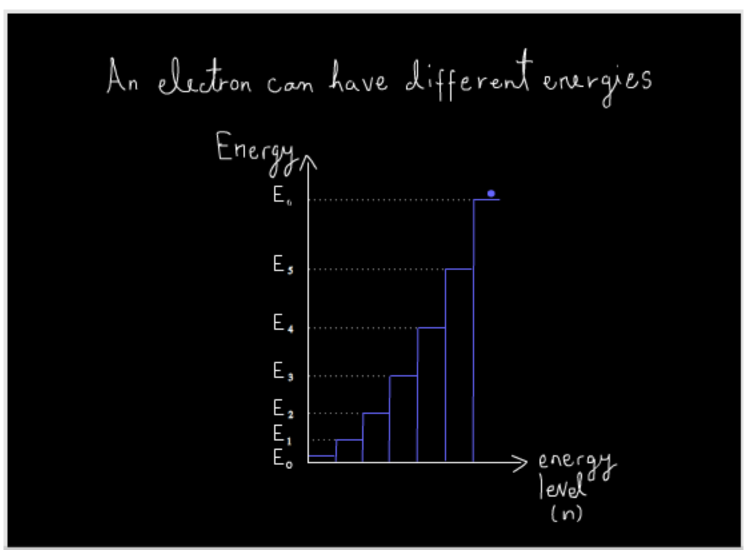

Figure 0.16: Alternative representation of energy levels

that presenting a step function (Fig. 0.16) would aid in introducing the idea of electrons jumping up and down in energies. As the step function is drawn into the scene, the concept of finite energy values is discussed. A moment later, an electron appears at the grounds state level E_0 which is only slightly above the horizontal axis. Each time the electron is excited into the next highest level, the new energy E_n and its associated energy level number n is introduced. Once the electron has been "excited" all the way into the sixth energy level, it rolls back down to the ground state. Not only does this last part pave the way for the next scene, but it give me a chance to say something about the reversed process of an electron emitting energy as it is de-excited into lower energy levels.

After introducing the quantized energy levels, I briefly familiarize the audience with the probability densities associated with the first three energy levels. This oriented them to the idea that more nodes indicates a higher energy. From there, I discuss the process of exciting an electron from the ground state to the first excited state, through the absorption of photons (displayed as a cone of white light). I then present the simulation of this transition, that I originally created in Mathematica. I then repeated this process for the other three transitions. Stills taken from these sections are presented in Figs. 0.17-0.20. In these figures, the cone of light is the same for all four transitions. While white light does contain photons of all frequencies, using the same image leads viewers to believe that the absorption of the same photon can lead to different excitations. In the final version of this animation, I plan on somehow differentiating the light used for each transition.

For the grand finale, I join the four clips together, simulating an electron incrementally making its way from the ground state, to the fourth excited state. Although this sequence of excitations is not something that naturally occurs in quantum, we took the liberty of bending the truth slightly the name of art. This stunning and elaborate dance, was accompanied by the glorious tones of Angela Hewitt playing Bach's Goldberg Variations.

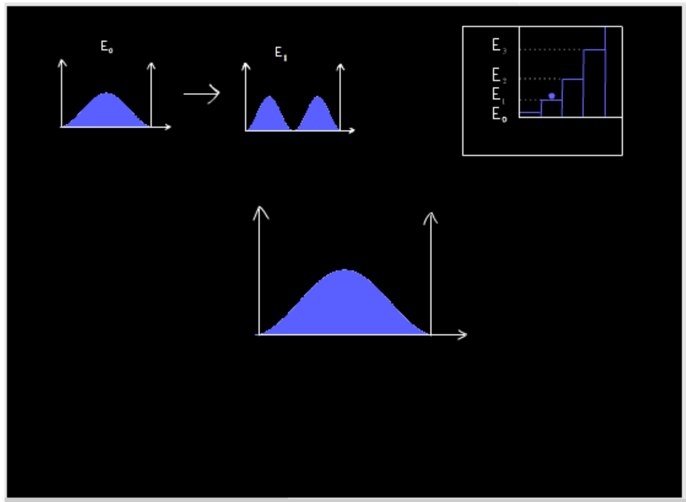

Figure 0.17: The excitation from E_0 to E_1

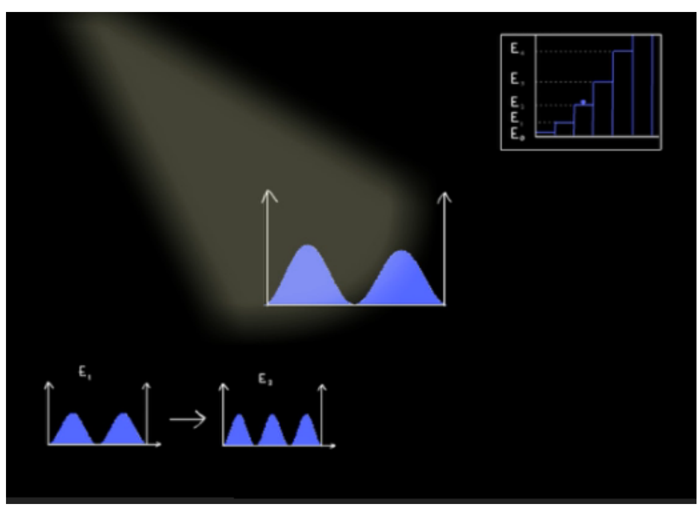

Figure 0.18: The excitation from E_1 to E_2

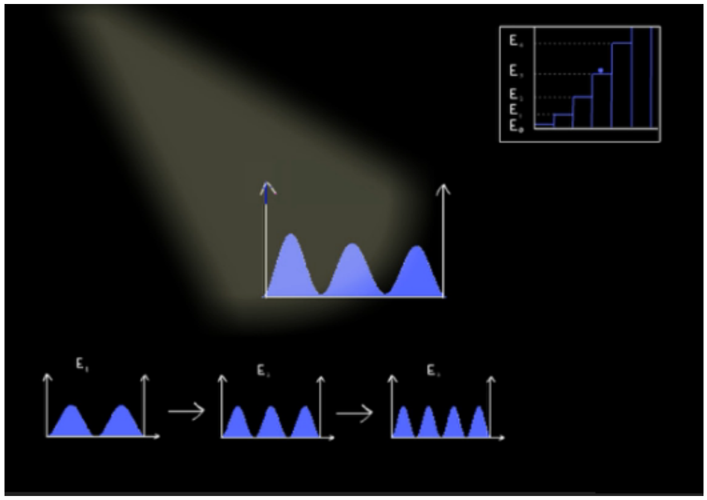

Figure 0.19: The excitation from E_2 to E_3

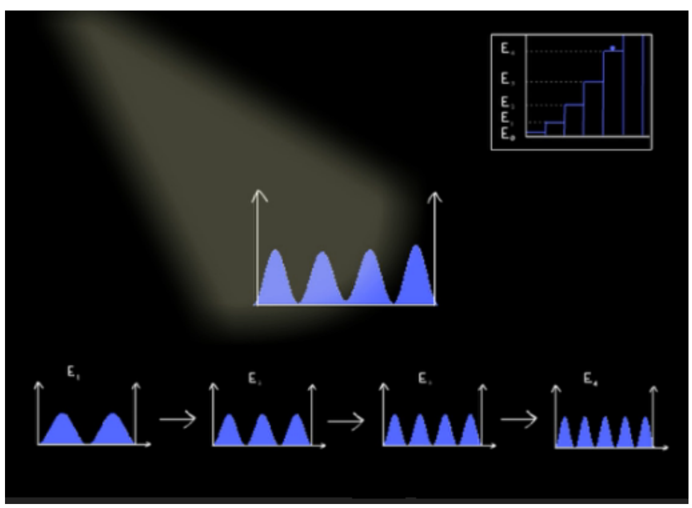

Figure 0.20: The excitation from E_3 to E_4

0.3.3 Plans for the Future

Science brains and non-science brains alike have responded very well to this animation. We hope to continue showing it to as many audiences as possible. In terms of our future plans, we feel that although this film gives a proper introduction to some properties of quantum mechanics, we anticipate that it will leave the audience engaged and interested. We have therefore decided to create more chapters that will extend their learning beyond the falsely represented electrons stacked up in rows, and into the realms of Shrödinger equations. The hope is that we may eventually be able to put together some sort of educational resource that can be used in a class setting.

We are also considering creating the same kind of animations, but for people in the field of physics. This may entail animating something like the characteristic transitions of the hydrogen atom. Whatever the case may be, "A little Bit of Quantum Mechanics" will hopefully be the first of many (of this kind of) teaching resources.

0.4 Conclusion

In conclusion I would like to stress the importance of conveying concepts in physics to the general public and the potential that comes with doing so through visualization. I will begin by discussing some to the major motivations echoed throughout the science education community.

In its mission statement, the Adler Planetarium in Chicago declares its commitment to "Inspiring young minds to pursue careers in science" [6] . This is by far the most inherent motivation. In order to insure the future of science, we need to inspire future scientists. In order to insure the future of science funding, we must continue generating the interest and support needed to keep research and scientific progress a national priority. It is therefore equally as important to reach out to those young minds that end up pursuing career in fields other than science.

"Exploring, explaining and protecting the natural world" [5] is what the California Academy of Sciences declares as its ultimate goal. In order to save our planet, we must reconnect to it. Taking a step in the direction of reversing things like climate change requires that we first understand things like carbon emission and global warming. This same kind of philosophy is used to deter people from smoking cigarettes and doing other harmful things to their bodies.

Science museums have brilliantly mixed entertainment with education and environmental activism. While watching the playful otters at the Monteray Bay aquarium is by all means exciting, one leaves with a sense of connection to the species. Reading about an oil spill is suddenly ten times more devastating. One experiences similar connections after visiting the indoor rainforest at the California Academy of Science, or the penguins at the Central Park Zoo.

Lastly, making science accessible to the general public is necessary in maintaining a separation of church and state. Although science continues to be seen as one of the leading sources of truth both in the classroom (evolution vs. creationism) and in the bedroom (pro-life vs. pro-choice) the threat of this being replaced by religious-based doctrines continues to grow[4]. Now more than ever, we need to provide people with the information and vocabulary required to assess the claims brought against things like teaching evolution in the classroom and ultimately to allow them to define their own position on such issues.

While I am undoubtedly committed to the outcomes discussed above, my passion lies in the potential that comes with presenting concepts in science, through visual representations. The great American physicist, Richard Feynmann once said, "Our imagination is stretched to the utmost, not, as in fiction, to imagine things which are not really there, but just to comprehend those things which are there"[12]. We have come to an odd era in our efforts to advance Physics . Our quest for one elegant theory of everything has lead theorists to develop mathematics so complicated, only a select few can wrap their heads around it. And while I do have an enormous amount of faith in physicists and in the field, I am excited by the original and innovative thought that may come from exploring a new perspective.

In an article addressing the fusion of science and the arts, author Jonah Lehrer calls for the synergism of the members of the two fields. "It's time for the dialogue between our two cultures to become a standard part of the scientific method. Art galleries should be filled with disorienting evocations of string theory and the EPR paradox. Every theoretical physics department should support an artist-in-residence"[12].

Although Lehrer's call for action may seem radical, it is motivated by the powerful progress that could come of it. A painter's understanding of colors may lead him to color-code an image of the galaxy M82 in a way that reveals something that has remained unnoticed for all these years. A sculptor may have a unique intuitive sense of the deformation of an object due to various surface or body forces. A photographer may have a very different take on wave particle duality. Visual artists are, in the most literal sense, applied physicists. They are constantly exploring the ways by which the laws of physics manifest themselves in everyday occurrences. While a glass blower may not know how to derive the Navier-Stokes equation, he has a deep intuitive understanding of centripetal forces, thermodynamics and fluid dynamics. "By heeding the wisdom of the arts, science can gain the kinds of new insights and perspectives that are the seeds of scientific progress"[12].

I have never thought of myself as a great physics thinker and I do not see myself making any major breakthroughs in field. Instead, I believe that my contribution to physics will come from my ability to communicate and translate between the field and the world of art.

Appendix A

Additional Components

A DVD containing the animation "A Little Bit of Quantum Mechanics" is included in this file.

The main slides from the Gamma Ray Interactive are contained within the text. The entire interactive, however will be added to this file in the near future.

Bibliography

[1] VERITAS Educational Website. 2007. VERITAS Science.12 Feb.2009 (http://veritas.adlerplanetarium.org/home.shtml).

[2] Redish, Edward F. "The Implications of Cognitive Studies for Teaching Physics" American Journal of Physics 62(6) (1994) :796-803.

[3] McTighe, Grant and Wiggins, Jay. Understanding by Design 2nd Expanded ed. Upper Saddle River, NJ :Pearson Prentice Hall, 2005.

[4] Gropp, Robert. "Teaching the Public about Science" BioScience. 56(2) (2006): 91.

[5] The California Academy of Sciences. 2008. About Us. 12 Feb. 2009 (http://www.calacademy.org/about/).

[6] The Adler Planetarium. 2001-2009. About Us.12 Feb. 2009 (http://www.adlerplanetarium.org/aboutus/index.shtml).

[7] Lakoff, George and Mark, Johnson. Metaphors we live by. Chicago, IL: University of Chicago Press,1980.

[8] Griffiths, David J. Introduction to Quantum Mechanics.2nd ed.Upper Saddle River, NJ :Pearson Prentice Hall, 2005.

[9] "MainPage." Wikimedia Commons:Finite-vs-Infinite-Square-Well-Energies.7 Mar 2009, 15:13

UTC. 19 Mar 2009 (http://commons.wikimedia.org/w/index.php?title=Main_Page&oldid=19012536).

[10] "Radioactive decay." Wikipedia, The Free Encyclopedia. 18 Mar 2009, 00:16 UTC. 19 Mar 2009(http://en.wikipedia.org/w/index.php?title=Radioactive_decay&oldid=277992751).

[11] The Painter's Keys.Mar 1, 2009. Alan Kay Art Quotes.Mar 1, 2009 (http://quote.robertgenn.com/auth_search.php?authid=3085).

[12] Lehrer, Jonah. "The Future of Science...is Art?" Seed Magazine 16 January 2008. 2 Feb.2009 (http://seedmagazine.com/content/article/the_future_of_science_is_art/).

[13] Atherton, J. S. "Learning and Teaching: Piaget's developmental theory".2005. 18 March 2009 (http://www.learningandteaching.info/learning/piaget.htm).