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Symmetry and Aesthetics in Introductory Physics: An Experiment in Interdisciplinary Physics and Fine Arts Education

A Dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in Education

by

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September 2007

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Dedication

To:

My father, Robert Krause,

who taught me that with hard work, anything is possible

~

My son, Devananda Rupa van der Veen,

who began teaching me before he was born

~

My husband, Dr. Steve Davis,

who is still trying to teach me not to take life so seriously

~~*~*

One dark, moonless night, Nasruddin Hoja was frantically searching, on his hands and knees, under a street lamp. One of his students happened to ride by on his horse, and asked, "Hoja, what are you doing on your hands and knees?" to which the Hoja replied, "I have lost my purse and I am searching for it."

The student asked, "Hoja, why are you only searching next to the lamp post? You could have dropped it anywhere!" to which the Hoja replied, "This is true, but on a moonless night, the only place I may hope to find it is under the light!" *– Traditional Ottoman Folktale*

You never know what you might be missing

if you only search under the light!

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I wish especially to thank Professor David Gross, director of the Kavli Institute for Theoretical Physics (KITP) at UCSB, for encouragement in developing a symmetry-based introductory curriculum, for graciously providing me with articles on symmetry, and conversations in his office at the KITP, and for inspiring my students (and myself) with a fascinating lecture on symmetry.

I wish to also thank Dr. Jean-Pierre Hebert, Artist in Residence at the KITP, for several insightful conversations regarding physics and art during the planning phase of my course, and for participating in the course as an unofficial mentor for myself and my students. Thank you also for providing an inspiring lecture, and for supporting my students’ physics works of art by coming to their installations, and for graciously inviting us to your studio.

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I offer most heartfelt thanks to the College of Creative Studies and Geology Department, under whose auspices I was able to teach my class. I wish to thank Professor Bruce Tiffney, Dean of the College of Creative Studies (CCS), who welcomed my course in Winter Quarter, 2007 under the auspices of his College, and also Ms. Leslie Campbell and Ms. Leslie Edgerton, administrators of CCS and the Geology Department, respectively, who facilitated the administrative aspects of arranging for me to teach this course. Without all of your help, this course would not have taken place.

I wish to thank my brother, Frederic Krause, for valuable discussions and insights from the viewpoint of a non-physicist, for the writer's perspective that a well-designed course should be like a good novel, always keeping students on the edge of their seats, wanting to find out what comes next.

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Education

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Most Recent Awards and Honors

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2004	Myra Sadker Curriculum Award, American University
2002	UCSB Instructional Improvement Grant
1999	First Place, NASA International Competition to name Chandra X-ray Observatory
1986	Smithsonian Institute/American Institute of Indian Studies grant for travel and advanced study of classical dance in India for nine months

Publications

van der Veen, J. (2006) Physicists and Firewalkers: The co-construction of community identity through narratives in ritual performances, invited paper, American Association for the Advancement of Science, June, 2006.

van der Veen, J. and Lubin, P. ,Labs for a Lambda-Dominated Universe, *in press*

van der Veen, J., Lubin, P., Natoli, P., Seiffert, M., (1998). Small Scale Anisotropies: The Final Frontier, invited feature article in *The Physics Teacher* , 36 (9), Dec., 1998 van der Veen, J., and Lubin, P. (1993). Spotlight on the Sun, *The Physics Teacher*, May, 1993, 31 (5).

van der Veen, J., and Lubin, P. (1992) The Remote Access Astronomy Project at UCSB: An Example of a University/High School Cooperative Educational Effort; *Education & Computing: Proceedings Of The International Conference On Informatics In Education*, August, 1992, Elsevier, Inc.

van der Veen, J., and Lubin, P. (1991).The UCSB Remote Access Astronomy Project *Robotic Telescopes In The 90's,* Astronomical Society of the Pacific, Laramie, Wyoming, June, 1991

W. McCann, S. Nishenko, L. Sykes, and Krause, J. (1979). Seismic Gaps and Plate Tectonics: Seismic Potential for Major Plate Boundaries; *Pure And Applied Geophysics,* vol. 117,

Invited Colloquium

Symmetry and Aesthetics in Physics Education, October 27, 2006, Physics Department, Fresno State University, invited speaker

Invited Talks With Published Abstracts

Physicists and Firewalkers: The role of narratives in the co-construction of community identity. Amer. Assoc. for Adv. Science, June 19, 2006, San Diego.

Constraining Fundamental Cosmological Parameters by Understanding the Spectrum of Anisotropies in the Cosmic Microwave Background with P. Lubin and M. Seiffert, in THE ANNOUNCER, American Association of Physics Teachers, v. 24, no.4, January, 1998

The Remote Access Astronomy Project: A Research-Oriented Approach to Physics and Astronomy Teaching for Undergraduate and High School Students with P. Lubin in THE ANNOUNCER, American Association of Physics Teachers, v. 24, No.2, July, 1994

Community Service

Member, UCSB MIDDLE EAST ENSEMBLE Dance Troupe, 2000 - Present: Numerous free public performances for campus, local schools, and community events.

Professional Societies

American Association of Physics Teachers, 1989 – present.

Abstract

Symmetry and Aesthetics in Introductory Physics: An Experiment in Interdisciplinary Physics and Fine Arts Education

by

Janet (Jatila) Krause van der Veen

In a recent editorial in Physics Today (July, 2006, p. 10) the ability of physicists to “imagine new realities” was correlated with what have been traditionally considered non-scientific qualities of imagination and creativity, which are usually associated with fine arts. In view of the current developments in physics of the 21st Century, including the searches for cosmic dark energy and evidence from the Large Hadron Collider which, it is hoped, will verify or refute the proposals of String Theory, the importance of developing creativity and imagination through education is gaining recognition.

Two questions are addressed by this study: First, How can we bring the sense of aesthetics and creativity, which are important in the practice of physics, into the teaching and learning of physics at the introductory college level, without sacrificing the mathematical rigor which is necessary for proper understanding of physics? Second, How can we provide access to physics for a diverse population of students which includes physics majors, arts majors, and future teachers? An interdisciplinary curriculum which begins with teaching math as a language of nature, and utilizes arts to help visualize the connections between mathematics and the physical universe, may provide answers to these questions.

In this dissertation I describe in detail the case study of the eleven students - seven physics majors and four arts majors - who participated in an experimental course, Symmetry and Aesthetics in Introductory Physics, in Winter Quarter, 2007, at UCSB's College of Creative Studies. The very positive results of this experiment suggest that this model deserves further testing, and could provide an entry into the study of physics for physics majors, liberal arts majors, future teachers, and as a foundation for media arts and technology programs.

Preface

I began my doctoral studies in Physics Education with the intention of investigating why the gender imbalance in physics in the United States seems to be so robust, in spite of the parity that women have achieved in biological sciences in the U.S., as well as in physics in other countries, notably in Eastern Europe. According to the American Institute of physics, in the U.S., girls comprise forty-five percent of high school physics students, but less than twenty percent of bachelors in physics are awarded to women; approximately fifteen percent of Ph.D.'s go to women, and less than five percent of tenure-track physics faculty are women (Ivy and Ray, 2005). In spite of changes in delivery methods, the content and context of introductory physics has remained the same as it was thirty or forty years ago. I asked, Is it possible that the introductory college physics curriculum itself could be responsible for the apparent systematic gender bias against women in physics?

I left the physics community for a while, studying sociolinguistics and gender, cognitive development and "ethnomathematics." To borrow a phrase from anthropologist Sharon Traweek, I had to leave the physics community in order to "acquire strangeness" (Beamtimes and Lifetimes, 1988). In order to understand what makes physics so apparently intimidating, I had to gain the ability to see physics from the viewpoint of outsiders. I spent two years studying how the physics community, as a community of discourse, reproduces itself through communicative conduct in social interactions (Hymes, 1997). I analyzed the discourse of eight well known and highly respected professional physicists, recorded at physics conferences, interviewed college students at the University of California, Santa Barbara (UCSB), and second graders in a Santa Barbara elementary school, and looked at introductory textbooks from the standpoint of how the content is presented. I could not find any sense in which professional physicists exhibit overt gender bias through their communicative conduct, whether it be males discriminating against females, or females representing themselves as inferior through the way they speak. What I did find is a consistent gender bias in the way physics is taught, which is apparent in a range of discourse settings, from the narratives that serve to maintain the archetypes of the physics community (van der Veen, 2006a), to the way that textbooks often portray women as diminutive (Gosling, 2004), to the contexts in which introductory physics is presented - the "aggression and risk taking" contexts of high-impact sports and military applications – that are naturally more interesting to boys (van der Veen, 2006b).

I found examples of attempts to gender-balance introductory physics, for example by using "kitchen contexts" in the Force Concept Inventory, a widely used metric for determining beginning students' ability to apply Newtonian reasoning (McCullough, 2001). Such artificial applications ignore the fact that hockey pucks sliding on near-frictionless ice, and canon balls launched from a cliff, actually are more appropriate contexts in which to study Newtonian behavior of rigid bodies than babies sliding food off a horizontal tray (Gendered FCI, question 12, McCullough, 2001). To "feminize" Newtonian mechanics defeats the purpose of seeing the world through Newton's eyes. I believe there are other ways to make physics more appealing and "gender-neutral."

My foray into discourse analysis and my sojourn outside the physics community reinforced my suspicion that the introductory college physics curriculum itself may be contributing not only to the systematic gender bias against women in physics, but many others as well. If the physics community truly has a goal of increasing diversity, then we need a new paradigm for introductory physics education.

I asked: Why not START with Noether, and GET TO Newton? In other words, start with symmetry as the conceptual foundation of physics, and start with the approach of contemporary physics – the post-Einstein paradigm of dynamic spacetime – and later use symmetry as a lens through which to look back at Newtonian mechanics. Relativity is not conceptually too difficult for students, especially in the post-Star Trek generation.

I have also noticed that people who are not already in physics tend to avoid physics. College students normally take physics for one of two reasons: those few who come in already knowing they want to major in physics, and the majority for whom physics is a required course for some other major. Otherwise, students do not choose to take physics even though they may find it interesting; they avoid it because it is intimidating, and it has the potential to jeopardize their grade point average. At the same time, I began to notice a large number of people I met at recreational dance and music functions, who dance or play an instrument, also have jobs in physics, computer science, engineering, or mathematics-related fields – the same blend of physics and fine arts that I have had throughout my life. I asked: Is there some common ground between physics and math and fine arts that can be accessed to make physics more appealing and less intimidating? If people in physics like fine arts, why cannot we use fine arts to interest people in physics?

Thus I developed the idea for this dissertation project, Symmetry and Aesthetics in Introductory Physics. Symmetry – because it is the most fundamental conceptual principle from which to start, and because it is the fundamental principle which unifies all the seemingly-disparate topics in physics. Aesthetics – because by incorporating art, music, literature, dance, and history with physics and mathematics, we restore physics and mathematics to their rightful places as cultural endeavors, and we reduce the fear factor inherent in the introductory physics curriculum.

Before I embarked on this project, I asked: What are the points of intersection that are common to both physics and fine arts? What are the similarities in the way physicists and artists perceive, experience, and express beauty? I sent out a questionnaire to several ethnic dance mailing lists, asking subscribers who practice some form of dance or music, as well as some form of physics, engineering, or math, what they find common and satisfying about both. I received comments with keywords such as “symmetry,” “patterns,” “music is math in motion.” Then I read a copy of the book by Leon Lederman and Chris Hill of Femilab called “Symmetry and the Beautiful Universe,” and looking back at Lawrence Krauss’ book “Atom” I saw Rodin mentioned in the introduction. The more I looked, the more I found: physics, math, art, music – they just go together. Look beneath the surface of a practicing physicist, and you will find a person who dances, paints, plays an instrument – or is involved with the arts in another way, such as supporting the local symphony, - or is married to an artist or dancer.

Yet, in our mainstream education system the arts and sciences are completely separated. Moreover, according to Elliot Eisner of Stanford University, sciences are valued, and arts are not (Eisner, 2002). The original model of Aesthetic Education is attributed to the Swiss educator named Johann Heinrich Pestalozzi (1746-1827), who pre-dates American educator John Dewey. Pestalozzi advocated that education must be accomplished simultaneously along three braided strands of equal importance: visualization, numeration, and description. More recently, Maxine Greene of Teacher's College, Columbia University, has applied the term Aesthetic Education to refer to any study which begins with the contemplation of a work of art, and ends with a new creation, to give back to humanity. But – a work of art is not limited to a painting; it can be a piece of music, a dance performance, a sea shell, or an elegant equation. This is the theoretical model behind my experiment in Aesthetic Physics Education.

Finally, my research question became: Can introductory physics be taught in such a way so as to start with symmetry and contemporary physics, in the aesthetic context of the arts, so as to give students a unified hierarchical structure with which to understand the seemingly-disparate topics in physics, as well as make physics more appealing and less intimidating to a wider population? Can this be accomplished without losing the mathematical rigor which characterizes physics as a unique, pleasurable, elegant, and very human pursuit?

Mathematics is the language with which to understand physics, yet without first developing a sound conceptual understanding of the principles of physics, the math remains disconnected from the reality it is trying to describe. I believe, from my own experience as well as the comments of my students, that both math and art are different pathways to visualizing a reality that transcends direct personal experience. Much of physics also transcends personal experience. I am not equating physics and art, however I suggest that art and mathematics are perhaps similar pathways to visualizing concepts that lie outside our direct experience. Perhaps, in terms of how we arrive at our “gut-level understanding” of something, math and art are topologically similar.

I suggest that by utilizing multiple pathways of understanding, such as art, music, and dance, that are reducible to words but which also transcend words, interwoven with mathematics, students can begin to develop the necessary trust to allow math to take them to new levels of understanding - which also are reducible to words, yet which transcend them.

In order to begin to answer my research question, I designed an experiment in education, much as a physicist would design an experiment to answer a question about Nature. I designed a model curriculum with appropriate texts, lectures, group activities, homework assignments, and a final project, that I hoped would answer two main questions: 1. Can a symmetry-based curriculum provide a hierarchical conceptual framework to help students see physics as a coherent discipline instead of a series of disconnected topics? 2. Will an interdisciplinary curriculum of physics and fine arts, with symmetry as the linking principle, make physics more accessible and less intimidating, and thus begin to attract students who might otherwise avoid physics?

I then had to find a department which would agree to host an interdisciplinary physics and fine arts course for Winter Quarter, 2007. The course ultimately found an appropriate home in the College of Creative Studies, a small college within the greater University which especially caters to “gifted” students. Dean Bruce Tiffney welcomed the course under the category of General Studies – interdisciplinary electives which lie outside the College’s eight major programs – and the Geology Department graciously let me borrow one of their spacious classrooms.

Symmetry and Aesthetics in Introductory Physics was my experiment in interdisciplinary physics-and-fine-arts education. Like any single experiment, one learns about one small slice of the universe, and the best one can hope for is to place some limits on the validity of one’s model. A good fit of data to model encourages further testing. The very high evaluations given by the students, as well as their achievements, comments, and personal growth, suggest that further experimentation with this educational paradigm is most definitely warranted.

I hope that this study will provide a beginning for further investigation and collaboration between artists and physicists, teachers and teacher educators, and students who seek a broader educational experience.

Finally, this dissertation is not specifically about the gender bias in physics education; rather, the goal of this curriculum is universal access to physics, in the broadest sense, to the deepest beautiful secrets of nature. For those who wish to highlight the historic role of prejudice and misogyny in physics, the story of Emmy Noether, whose theorems are the foundation for the work of Newton, Einstein, and all new developments in theoretical physics, is a powerful heroine’s narrative. By placing Emmy Noether on equal footing with Isaac Newton and Albert Einstein in our physics narrative, we may begin to re-construct the identity of the physics community of the future. At the same time, by starting with principles of symmetry, and mathematics as a way of knowing – along with art, music, and dance - the study of physics can be made culturally relevant anywhere in the world. Thus, any teacher is free to use the art, music, dance, and natural environment which is most culturally relevant to his or her students. After all, the laws of physics are universal, so physics belongs to everyone – not just the western world from which Noether, Newton, and Einstein were born. Mathematics, too, is a universal human capability. For example, there is evidence that the mathematics that Copernicus, Kepler, and Galileo used in their astronomical calculations was smuggled into Europe from the Islamic nations (Bernal, 1987), and recent evidence indicates that Islamic architects discovered Penrose tilings five centuries before Penrose (Lu and Steinhardt, 2007). As a human construction, mathematics shares features with language; but mathematics also contains an element of discovery, which endows mathematics with science-like qualities.

Symmetry and Aesthetics in Introductory Physics represents a new paradigm in the teaching and learning of physics, the goal of which is access, in the broadest sense, to a deep understanding of physics.

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Chapter 1. A New Paradigm for Introductory College Physics

"For most men, save the scientific workers, science is a mystery in the hands of initiates, who have become adepts in virtue of following ritualistic ceremonies from which the profane herd is excluded". --- John Dewey, The Public and its Problems, 1927, page 164.

"The undergraduate physics major should be the liberal arts education of the twenty-first century! … Everything about the way we teach physics is useless for the purpose I have in mind. The methods, the textbooks, the language we use, all of it is designed more to get rid of the unworthy than to throw open the doors. What we need most of all is to change the mindset that says that real education takes people like we once were, and turns them into people just like us."
--David Goodstein, Provost of Caltech, "The Coming Revolution in Physics Education" American Institute of Physics, June, 2000

Since the early twentieth century, beginning with the contributions to physics of Albert Einstein and Emmy Noether, it has been recognized that symmetry principles ultimately motivate all of physics (Gross, 1996, and personal communication, 2007). The search for increasingly profound continuous symmetries, and broken symmetries, guides our developing understanding of the physical principles that govern the universe. The aesthetic appeal of symmetry, and the fascination with broken symmetry, seem to underlie our appreciation of art, music, and dance. Wondering about the universe also seems to be as fundamental to the human condition as are dancing, making art, and making music; why, then, should it be that physics, the business of which is to wonder about the universe, remains inaccessible to so many?

This dissertation is fundamentally about access to physics: access in the broadest sense, to a deep understanding of physics, motivated by the study of symmetry. I begin from the complaint about scientific workers by Dewey in 1927, and take up the challenge to physics educators uttered by Goodstein in 2000. This course, Symmetry and Aesthetics in Introductory Physics, is one possible path towards the goal of access to physics.

1.1. What is Aesthetic Education?

Dr. Maxine Greene, aesthetic education theorist and 'Philosopher-in-Residence' at New York City's Lincoln Center Institute, defines aesthetic education as

> …the intentional undertaking designed to nurture appreciative, reflective, cultural, participatory engagements with the arts by enabling learners to notice what there is to be noticed, and to lend works of art their lives in such a way that they can achieve them as variously meaningful. When this happens, new connections are made in experience; new patterns are formed, new vistas are opened. (Greene, 2001, quoted in Holzer, 2005).

Like any philosopher's advice, once it is given to us, the public, we are free to interpret the words in our own fashion; therefore, why cannot this same philosophy be applied to the study of physics? Greene's purpose is to bring the experience of art into all aspects of education. Because art is what she knows, she begins with observing a painting, however the goal of aesthetic education, as she stated, is to facilitate seeing new connections, new patterns, and new vistas in understanding. Is this not also the goal of physics education?

1.2. Why Do We Need Aesthetic Physics Education?

To answer the question of why physics remains inaccessible to so many people, I reach back to an editorial written by the famous experimental physicist Victor Weisskopf in the British journal *Physics Education* more than thirty years ago.

In this editorial entitled "Is Physics Human?" Weisskopf, one of the early director-generals of the Conseil Européen pour la Recherche Nucléaire (CERN), who came to the United States from pre-World War II Germany with colleagues Hans Bethe and Werner Heisenberg, asked, "Why is physics as a science considered 'inhuman' by so many people, including some of the students we teach?" (Weisskopf, 1976, p. 75). Weisskopf speculated that the perception of physics as inhuman arises because physics is too far removed from direct human experience, too abstract, and too mathematical (ibid.). The situation is apparently not much different today. One of my students, an art major, said,

> I was just actually talking with my parents about this yesterday, how bad it is that so many people are – in a way – conditioned – well, very Aldous Huxley, but – that children grow up learning that science is scary and – especially physics and math. Somehow, chemistry doesn't have that big of a stigma, but physics and math – it's like, Oooo, Scary. … I think there's just something that is DONE in the way that it is arranged or taught that makes people really AFRAID of it, and I think it is taught in a way that is kind of – seems very EXCLUSIVE. And I ALWAYS had that feeling about physics, I always had the feeling that scientists are exclusive… so, if there's some way to kind of …make it a little less… FRIGHTENING, I don't know how, though. ("Juno," post-course interview, April 17, 2007).

As anyone who has been a parent has observed, all children like to experiment with objects in their environment, particularly with applications of physics such as gravity and simple machines, yet somewhere between childish explorations and school science, the sense of wonder may have been lost. As physics educators, we must critically examine our role in this tragedy, and ask ourselves: What is it about the way physics is taught that makes people afraid of it, and gives the impression that physics is exclusive? My suggestion is that we begin by examining the introductory college curriculum.

Most introductory physics is taught as an engineering discipline (Tseitlin and Galili, 2005), heavily oriented towards solving engineering types of problems, however many students may not be ready or able to learn physics in the way the subject is usually taught (McDermott, 1993). Contemporary text books used in universities, colleges and high schools represent physics as a compendium of factual knowledge, delivered as a sequence of topics, and presented with well-structured mathematical formalism (Tseitlin and Galili, 2005), yet students have often been shown to exit their introductory college courses without understanding the connections between the topics in physics, or the connection between mathematics and physics (Redish, Saul, and Steinberg, 1996; McDermott, 2001).

More than forty years ago, Thomas Kuhn said of introductory science text books:

> …a concept of science drawn from them is no more likely to fit the enterprise that produced them than an image of a national culture drawn from a tourist brochure or a language text (Kuhn, 1962. p. 1).

In spite of the growing field of study of the Nature of Science, which addresses the issues of accessibility and negative public perceptions of science, most introductory physics text books appear to disregard such research (Guisasola, Almudi, and Furio, 2005). Introductory college physics has been criticized as being a gatekeeper, keeping the unworthy out of physics (Goodstein, 1999). To see if this criticism is warranted, I searched the Internet to get a sense of how physics is portrayed to beginning students as they enter college physics courses. The following excerpt from the website of one of the large introductory courses for non-physics majors at U.C. Santa Barbara summarizes the sentiments that are expressed by many of the introductory physics web pages that I found:

> Physics is very different from other subjects, so even if you get A's in other hard classes, you might be like a fish out of water with physics. Having done well in high school physics might not mean anything either…. (http://physics.ucsb.edu/~phys6C/s2007/)

Statements like this concern me. They seem more like a warning than a welcome. Is this really the message we want to convey about physics to beginning students? Students in these courses often corroborate the image of physics as a gatekeeper as well. When I served as a tutor in the Physics Study Center during the 2004-2005 school year, I overheard one biology major say, regarding this same physics course: "Physics is a weeding course for us. They want to see if we can do it before they let us into this program." Statements like these concern me, as they support the perception that physics is exclusive, and the image of introductory college physics as a gatekeeper, keeping out the unworthy. This is not the goal of physics education.

Professor Eric Mazur of Harvard University has also noted the dissatisfaction of students at Harvard towards traditional introductory physics, noting that for many students, their introductory physics experience leaves a "permanent sense of frustration" (Mazur, 1997, p. 3). He cautioned that, although one may be tempted to dismiss such comments as coming from non-physics majors, most of these students are not complaining about their other required courses outside their major fields (ibid.). His answer to this problem was to develop the Peer Instruction model of interactive teaching, which has improved the introductory physics experience for many students whose instructors utilize interactive practices (Mazur, 1997, 2007; Lorenzo, Crouch, and Mazur, 2006).

Although many improvements in classroom interactions have been made over the past two decades based on Mazur's original Peer Instruction model, such as Just in Time Teaching, Workshop Physics, and Modeling Instruction to name a few, the content and sequence of the introductory curriculum has remained largely unchanged. In addition, the persistent gender bias and lack of diversity in physics have begun to worry the physics community in the last decade or so, and are gaining attention in the American Physical Society (Ivy and Ray, 2005), at the national level (Nelson, 2005) and in the international physics community (Hersh, 2000; Sjøberg and Schreiner, 2007). If access to physics is the goal, and the introductory curriculum is the entry point, then perhaps it is time to critically examine the role of the introductory curriculum in granting or denying access to physics. The suggestion of this dissertation is along the lines of Thomas Kuhn's (1962) *Structure of Scientific Revolutions*, that perhaps it is time for a paradigm shift in the introductory physics curriculum. Such a paradigm shift might make physics appealing to a more diverse population, including female students, minority culture students, and future teachers, without sacrificing the mathematical rigor which is necessary to understand the logic, as well as the aesthetic appeal of physics. Aesthetic physics education takes up the goal of finding ways to increase access to physics.

Support for the need to critically examine the introductory curriculum is beginning to emerge from studies being conducted in Europe, under the auspices of the Relevance of Science Education (ROSE) consortium. After surveying 15-year-old pupils in thirty four countries in Europe, Africa, and the Pacific Islands about their attitudes towards science and technology, Schreiner and Sjøberg (2005) suggested that the perception of science as taught in schools may not be compatible with youth culture identity in contemporary western societies. They suggested that perhaps young people, especially girls, perceive the identity of an engineer or a physicist as "incongruent with their own" (ibid., p. 13). Their survey also suggested that boys prefer topics such as explosives and machines, which figure prominently in the introductory physics curriculum, while girls prefer topics relating to biology, health, ethical, aesthetic, and "New Age" concerns (Sjøberg and Schreiner, 2007). They also found that the favorite topics of both girls and boys, expressed equally, are curiosities of space science such as black holes, unsolved mysteries, and philosophical issues (ibid.). These results suggest that an introductory curriculum which begins with symmetry and relativity, incorporating art and emphasizing the aesthetic aspects of physics, may indeed broaden the access to physics for a more diverse population.

Professor Weisskopf concluded his 1976 article by suggesting that nonscientific aspects have a role to play in science:

> The beauty of a scientific insight is an example where nonscientific aspects play an important role even in science itself. Perhaps the recognition of the intrinsic human value of physics would be enhanced if there were more awareness of the fact that science is only one way - albeit a very important one- of establishing a relation between mankind and its natural and social environment (Weisskopf, 1976 p. 79).

In other words, Weisskopf – one of the leading experimental physicists of his time – suggested that the intrinsic value of physics could be enhanced by recognizing other ways of knowing, in addition to physics, as valuable. This is what I will dare to call the potential power of aesthetic physics education: that by recognizing, valuing, and incorporating into the study of physics, other ways of understanding the universe and our place in it - such as art, music, dance, poetry – the intrinsic value of physics will be enhanced. Professor Leon Lederman, Nobel Laureate and former director of the Fermi National Accelerator Laboratory, offered the same proposal in other words, nearly thirty years later:

> The dazzling beauty of Nature revealed by our developing understanding should be presented with enthusiasm. The sense of wonder at the simplicity of the laws of Nature and the mystery of how mathematics seems to be embedded in these laws are important to convey. Hence, the science teacher can find common ground with teachers of art, music, and literature (Lederman, 2003, p. 306).

1.3. Focusing In on the Issues

Three specific issues worry me, and motivate the present study: 1) The persistent perception that physics is "inhuman" or "exclusive," and only for 'smart people,' when physics is fascinating, everywhere, and belongs to everyone; 2) the persistent perception that physicists are inhuman and exclusive, when they (we) are very human, and just as fun-loving as anyone else; and 3) that unless something is done to open up access to the deep ideas that motivate contemporary physics <u>at the introductory level</u>, the knowledge gap between the practice of physics and the public perception of physics, even for those who have made it through an introductory course, is going to become increasingly wide, so as to reinforce the public perception that physicists are exclusive, and that physics is inhuman.

Finally, I ask: How can we bring the sense of wonder, aesthetics and creativity, which are important in the practice of physics, into the teaching and learning of physics at the introductory college level, without sacrificing the mathematical rigor which is necessary for proper understanding of the practice of physics? In other words, how can we humanize the teaching and learning of physics so as to make physics accessible, in the broadest sense? This is the goal of aesthetic physics education.

In this dissertation, I suggest a new "design concept" for the introductory college physics curriculum: Symmetry and Aesthetics in Introductory Physics. I propose that, in addition to interactive classroom techniques, a new design concept for introductory physics should incorporate three main design features: First, start with content of symmetry and the viewpoint of contemporary physics; second, utilize interdisciplinary strategies that integrate physics with fine arts as complementary ways of knowing and making sense of the world; and third, ground the curriculum in the ideology of aesthetic education.

To address the fear of physics, I propose teaching math as a language of nature, using the arts to help visualize the connections between mathematics and the physical universe; to make physics seem more 'human,' I propose that we give students literary works about physics written by theoretical physicists, instead of textbooks of encyclopedic proportions, so that students may get to know physicists as people and physics as an evolving way of understanding instead of a collection of facts; and to reduce the perception that physics is exclusive, I propose teaching students to value equally both the scientific and artistic ways of knowing.. These are the goals of aesthetic physics education. There is substantial justification for believing that art and creativity have a place in introductory physics education, and that symmetry is an appropriate entry point for physics education in the twenty-first century.

1.4. The Importance of Emphasizing Math as a Language of Nature

The orientation of the physics community is such that meaning is both taken from the physical universe, and given to the physical universe, via the language of mathematics. Thus, students who approach physics, regardless of their knowledge of mathematics content, are expected to orient to the idea of math a basis of communication about Nature. This math orientation feels so natural, that it is difficult to see how one could possibly take meaning out of the physical universe without the help of mathematics, yet many students have already developed a dislike of mathematics before they arrive at college. Thus, many students who might be interested in physics avoid it, due to their fear of math. I am not advocating a non-mathematical approach to physics; rather, I am suggesting that math is a powerful non-verbal language which helps us to visualize phenomena in the physical universe that we cannot experience directly. I suggest that mathematics and art are mutually supportive symbolic ways of extracting meaning from, and giving meaning to, phenomena in the physical universe. I suggest that by demonstrating the language-like features of math of describing, predicting, and creating analogies, and further demonstrating the wonder of math as it appears in nature – for example, Fibonacci series in pine combs and rabbit reproduction – that some of the fear of mathematics can be allayed. School mathematics is often presented as a set of disembodied equations and symbolic manipulations (Gellert, 2000; Carraher, Carraher, and Schleimer, 1985), thus I suggest that one goal of aesthetic physics education is to restore the wonder of the "unreasonable power of mathematics" (Livio, 2002, p. 237).

1.5. The Role of Art and Imagination in Physics

Arts and sciences have been separated in education and practice in western society, at least since the seventeenth century (Eisner, 2002). This separation was ingrained further in American public education in the late nineteenth century, as science gained in importance while the arts receded. According to Elliot Eisner of Stanford University,

> Science was considered dependable; the artistic process was not. Science was cognitive; the arts were emotional. Science was teachable; the arts required talent. Science was testable; the arts were matters of preference. Science was useful; the arts were ornamental. It was clear to many then, as it is to many today, which side of the coin mattered (Eisner, 2002, p. 6).

In spite of this separation of art and science in education and society, the fundamental connection between physics, mathematics, and imagery, particularly in discoveries that have shaped contemporary physics since the last quarter of the nineteenth century, is undeniable. Current models in theoretical physics suggest the presence of hidden extra dimensions (Randall, 2005), which cannot be understood without the ability to combine mathematics and imagery. Understanding the crucial interplay between mathematics and visual representations is necessary in order to interpret the results of experimental physics, which investigate phenomena that range from probing the Cosmic Microwave Background at fourteen billion light years to nanotechnology, which deals with scales of billionths of a meter. Bruno Latour's (1992) evaluation that science is not about making "words correspond to worlds" but about "building reference chains through a cascade of transformations from matter to form" (Latour, 1992, http://www.bruno-latour.fr/presentations/001-iconoclash.html, slide 15) is certainly applicable to the way physics is accomplished today. Thus the teaching and learning of physics requires not only a sophisticated understanding of mathematics as a language of nature, but must address the fact that most of the phenomena investigated by contemporary physics occur at scales beyond the limits of our direct sense experiences. Hence, art as a tool for visualization of the mathematical aspects of contemporary physics should be recognized as an important component of physics education.

A useful concept in teaching, which was first developed by nineteenth century Swiss educator Johann Heinrich Pestalozzi (1746 – 1827) is the *Anschauung*: mental imagery developed by abstraction from phenomena which have been directly experienced (Pestalozzi, 1805; Ashvin, 1981; Miller, 1989). According to Pestalozzi, understanding is built on making sense of the "sea of confused sense impressions, flowing one into the other," and it is the "business of instruction to remove the confusion of these sense impressions" (Pestalozzi,1805, translation by Bardeen, 1894, p. 85). In other words, knowledge evolves from confusion to definiteness, from definiteness to plainness, and from plainness to clarity (ibid). Pestalozzi advocated a three-fold system of interrogating the world: visualization, numeration, and description, or what he called form, number, and language. For successful education, these three aspects of making sense and creating meaning out of the physical world cannot be separated (ibid.). Einstein himself was trained in this method of *Anschauung* in high school at the Kantonsschule at Arrau, and visualization remained integral to his development of Einstein's Theory of Relativity in the twentieth century (Miller, 1989).

1.6. The Role of Creativity in Introductory Physics

In recent editorials in *Physics Today* (July, 2006, p. 10) the need for students to cultivate imagination and creativity, once considered non-scientific skills associated with fine arts, has been expressed by professional physicists as important to the future of physics. How can we foster creativity in the introductory physics curriculum?

Getzels and Jackson (1962) studied intelligence and creativity in adolescents in a mid-western city in the United States, and derived the following description of creative youth:

> to juggle elements into impossible juxtaposition, to shape wild hypotheses, to make the given problematic, …, to translate from one form to another, to transform into improbable equivalents. It is from this spontaneous toying and exploration that there arises the hunch, the creative seeing of life in a new and significant way… (Getzels and Jackson,1962, p. 53).

Their results implied that creativity is a quality which is inherent in an individual, and cannot be taught. In a later study, Wallace and Gruber (1989) suggested that the creative person should be thought of as an evolving system in an evolving milieu, which suggests that creativity can be nurtured. Csikszentmihalyi (1996) proposed two qualities of an environment which are conducive to the emergence of creativity: The first is that to achieve creativity in any domain, there must be a "surplus of attention" available; the second is that creativity is best nurtured at the intersection of different cultures, where beliefs, lifestyles, and knowledge structures permit the free exchange of ideas and points of view (Csikszentmihalyi, 1996; p. 9).

Nurturing creativity is generally not a concern in a traditional introductory physics course, which attempts to cover nine or ten chapters in one quarter. In an introductory physics course which attempts fewer topics, but in greater depth, it is possible to provide the necessary surplus of attention in which creative thinking about physics can be encouraged. In an interdisciplinary classroom, which brings together students from different disciplines of physics and fine arts, it is possible to encourage the free exchange of ideas, as students with different approaches to creating knowledge share their strengths.

1.7. Symmetry as the Conceptual Basis for Physics Education

One of the most robust problems in students' understanding of physics, which has been discussed extensively in the Physics Education Research literature, is students' failure to integrate the topics of physics into a coherent conceptual framework (McDermott, 1993, 2001; Redish, et al., 1996). Great emphasis is placed on solving problems in introductory physics, however physics education research has shown that learning physics primarily by solving problems does not necessarily promote holistic understanding of the concepts (Redish, Steinberg, and Saul, 1996). Professor Anthony Zee, theoretical physicist at the Kavli Institute for Theoretical Physics (KITP) at UCSB has said, regarding introductory physics:

> Many people are stumped by high school or college physics because they are presented with misshapen phenomenological equations having little to do with Nature's intrinsic essence, with Her beauty, Her symmetry, or Her fundamental simplicity (Zee, 1992, p. 824).

Professor Alan van Heuvelen (1999), in his Millikan lecture to the American Association of Physics Teachers, asked, in a similar vein:

> Traditionally, the goals for a one quarter or a one semester physics course have been to help students learn the physics concepts in 10 or 15 chapters of a book and to learn to solve the end-of-chapter problems. Are these the best goals? (van Heuvelen, 1999, p. 1139).

Physics Education Research suggests that these are not the best goals. In many cases, after a typical introductory college physics course, students' understanding of the relationship between mathematics and physics appears to deteriorate rather than improve (Redish, Saul, and Steinberg, 1998), and in fact, research has shown that traditional instruction often fails to impart a robust conceptual understanding of basic physics, even regarding students who have performed well on classroom examinations. Even physics courses which promote active engagement of students instead of traditional lecture methods, may fail to promote conceptual understanding of physics as a coherent whole (Elby, 2001).

I suggest that starting the introductory sequence from the viewpoint of contemporary physics, beginning with principles of symmetry as the conceptual and mathematical foundation, can provide a unifying conceptual hierarchy within which to organize the various topics in physics into a coherent whole. It is the goal of this dissertation, by discussing the very positive outcomes of the course Symmetry and Aesthetics in Introductory Physics, to present the case that such a model for introductory physics instruction deserves further development and testing.

1.8. Support for this Model from the Physics Community

Professors Leon Lederman and Christopher Hill of the Fermi National Accelerator Laboratory (Fermilab) have advocated curriculum reform in physics education, stating with symmetry, even down to the high school level, for more than a decade. Their book, *Symmetry and the Beautiful Universe* (2004) is intended to provide the foundation for a high school physics course starting with symmetry. I first heard a lecture on these ideas from Professor Hill as part of a summer institute on topics in modern physics at Fermilab, which I attended during the summer of 1995. The following electronic mail (email) communication from Professor Hill in the winter of 2006 supports the development of a symmetry-first model for introductory physics education:

> I have found the 27 years of lecturing in this format, emphasizing the great mathematician Emmy Noether (a woman), her tragic life at the hand of the Nazis (as a metaphor for modern times) and the synergy between abstract mathematics to have been quite successful…. I do believe that a new undergrad curriculum that is modern, as based upon the symmetry concepts which are 20th century ideas, is long overdue. Even the traditional Galilean physics is much illuminated via modern physics. (Hill, personal communication, 02/17/2006).

Support for this approach of starting with symmetry also came from Professor David Gross of the Kavli Institute for Theoretical Physics (KITP), from personal discussions and a lecture he gave for the class (March 9, 2007). According to Professor Gross,

> Without regularities embodied in the laws of physics we would be unable to make sense of physical events; without regularities in the laws of nature we would be unable to discover the laws themselves. Today we realize that symmetry principles are even more powerful- they dictate the form of the laws of nature (Gross, 1996).

This statement is visualized in the diagram shown in Figure 1.1, and represents the underlying motivation for the physics content of the course, Symmetry and Aesthetics in Introductory Physics.

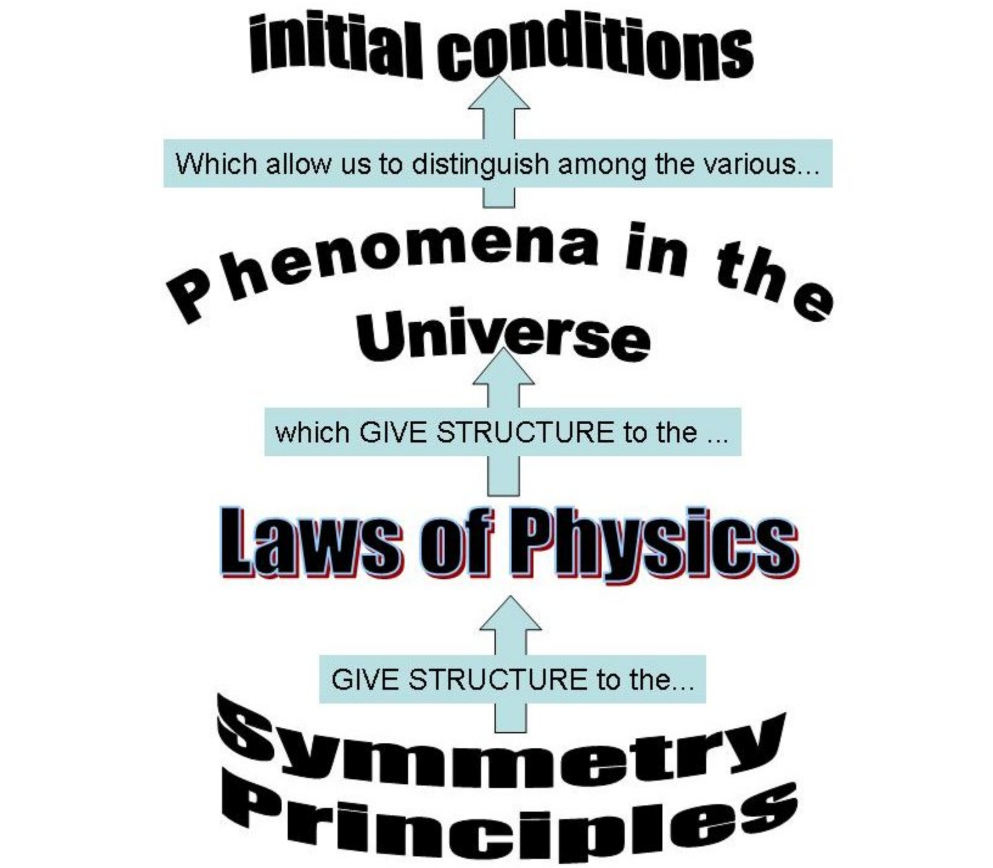

Figure 1.1. Symmetry as the foundation of physics, after Professor David Gross.

In Chapter Four I will give a detailed description of the curriculum and the rationale behind the various curricular choices I made regarding scope, sequence, and assignments.

1.9. Allaying Concerns that Starting with Contemporary Physics may be Too Difficult

The concern that starting with symmetry may be too difficult for introductory students has not been substantiated. Levrini (2002, 2006) has suggested that on the contrary, the oversimplification of introductory texts contributes to students' misconceptions as well as their difficulty in seeing the coherence of physics as a unified discipline. She has proposed that "the more instruction gets simple, the less students get involved in understanding" (Levrini, 2006, p. 2). Further, she suggested that by starting with at least a conceptual introduction to General Relativity and contemporary views of spacetime, much can be done to overcome the conceptual inconsistencies imposed by the traditional historically motivated approach. Moreover, her research on teaching contemporary physics to college students in Italy suggests that not only students already interested in physics, but students who were more attracted to humanities, enjoyed the approach of starting with contemporary physics as well.

There is also the question of the scientific literacy of an educated citizenry: although the basic ideas of contemporary physics, now a century old, have introduced radical modifications in human thought, they have not influenced the general outlook of educated citizens (Levrini, 2002). Hartle (2006) suggested that a conceptual understanding of General Relativity (GR) should be part of what is considered scientific literacy for the simple reason that a number of technological devices that are now in common use, such as global positioning systems, use it. Concepts which are fundamentally interesting to students, such as black holes and the expanding universe, require at least a conceptual understanding of GR.

Levrini (1999) also suggested that starting with Relativity is a potentially viable means of attracting art students to the study of physics because of the parallel interests in art and contemporary physics with problems of space and time. I found this to be true for the art students in my course, as they expressed in their post-course interviews. In addition, the historical coincidences of the lives of Einstein and

Picasso, and the mutual influences in the early twentieth century between contemporary physics, contemporary art and music, and modernism / post modernism are also interesting for students.

1.10. Summary: Symmetry, Aesthetics, and Contemporary Physics

The focus of this research is on the curriculum that was developed, and how it was implemented with a class of arts and physics majors, in the College of Creative Studies at the University of California, Santa Barbara. The very real cultural boundaries between artists and scientists, which were immediately apparent and had to be overcome, may also be useful in understanding ways of overcoming the persistent gender bias and lack of diversity in physics. In developing this course, I started with three main premises: First, that math is a language of nature; second, that introductory physics should start with symmetry and contemporary views of space and time as the motivation for the study of physics, rather than starting with the Newtonian paradigm; and third, that physics is an aesthetic, human endeavor, the purpose of which is to try to understand and represent the universe and our place in it. As such, physics shares common goals and ideals with art, music, and dance, even if the methods and claims differ, thus we can utilize the parallel pathways of mathematics, art, music, and movement to enhance the teaching and learning of physics.

In this dissertation, I weave together the development of my model for symmetry and aesthetics in introductory physics education with the ethnographic study of the eleven students - seven physics majors and four arts majors - who enrolled in the course, and saw it through to the end. I will describe my model curriculum and how it was implemented in the College of Creative Studies (CCS) at the University of California, Santa Barbara (UCSB). The very positive results of the students, as represented in their writing, their final projects, the results of the Maryland Physics Expectations survey (MPEX), and their comments, interviews, and evaluations, suggest that this model deserves further development and testing. I suggest that this model can be potentially adapted to suit the needs of physics majors, students from other sciences who must study physics, non-science students who would like to learn some physics, and can be especially beneficial for students who will become future teachers. My initial visualization of the possible applications of this model to introductory physics instruction is represented in Figure 1.2, and I will return to this in Chapter Eight.

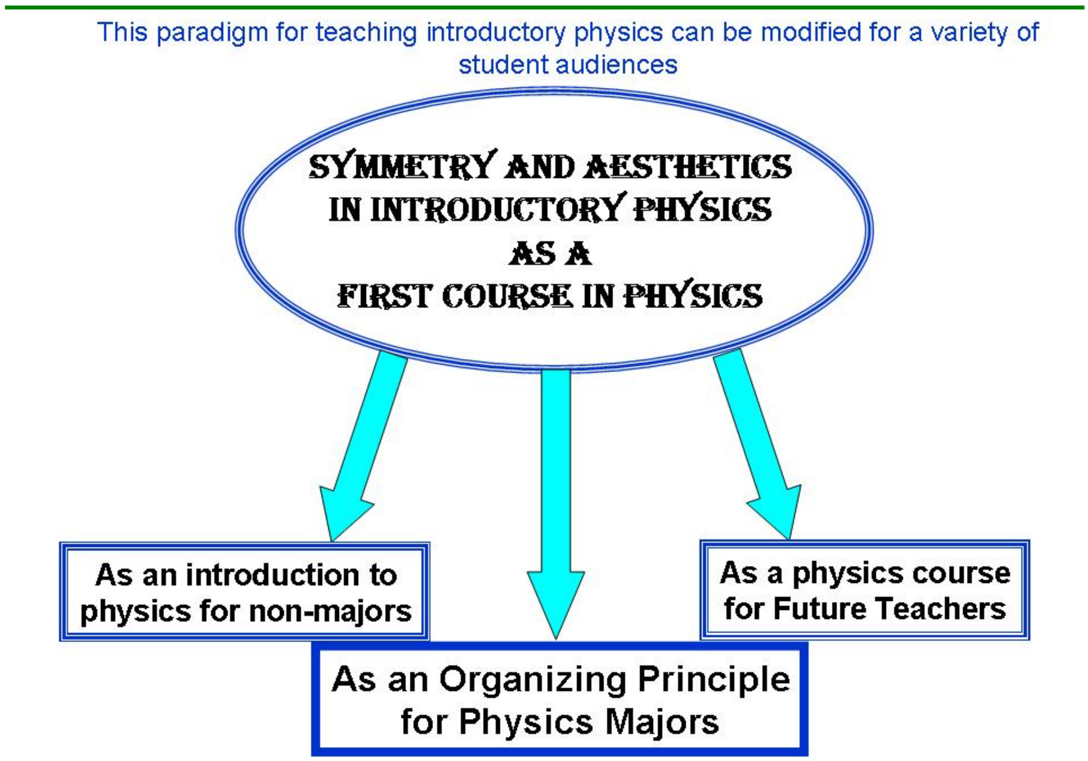

Figure 1.2. Potential audiences who would benefit from this model.

1.11. Brief Summary of Topics, by Chapter

In Chapter Two, I will discuss some of the literature which informed this study. Chapter Three summarizes previous studies of the integration of arts and sciences. Chapter Four is a description of the curriculum and organization of the course, and Chapter Five is an analysis of the implementation of the curriculum through ethnographic field notes, students' comments, my teaching journal, and individual post-course interviews. In Chapter Six I present and discuss examples of students' written work, and Chapter Seven provides a window into the classroom, by way of a video that was taken by the Instructional Development Group on campus, early in the course. In Chapter Eight I discuss general conclusions and recommendations, and the Appendices provide some of the details of the course, such as lecture slides, homework assignments, the syllabus, and extra notes.

Chapter 2: A Brief Review of Supporting Literature

" It is essential that the student acquire an understanding of and lively feeling for values. He must acquire a vivid sense of the beautiful and of the morally good. Otherwise he – with his specialized knowledge – more closely resembles a well-trained dog than a harmoniously developed person."

- Albert Einstein, editorial for the New York Times, 1952

"In this century, as we have seen in the cases of General Relativity and the electroweak theory, the consensus in favor of physical theories has often been reached on the basis of aesthetic judgments before the experimental evidence fore these theories became really compelling. I see in this the remarkable power of the physicist's sense of beauty acting in conjunction with and sometimes even in opposition to the weight of experimental evidence."

– Steven Weinberg, *Dreams of a Final Theory* (Pantheon Books, NY, 1992), p. 130.

Physics Education Research (PER) has revealed many difficulties with teaching and learning of classical physics, and with teaching modern physics after students have been ingrained in the paradigm of classical physics. Reform efforts which have concentrated on the methods of teaching, keeping the content fixed, have shown in general that interactive methods are superior to lecture-based instruction, however three main 'complaints' still prevail in the PER literature: that students do not understand the relationship between mathematics and physics (Redish, Saul, and Steinberg, 1998; De Lozano and Cardenas, 2002), that students who have become competent problem solvers may not be able to explain basic concepts (McDermott, 1993, 2001; Mazur,1997, 2007), and that there is still a dearth of women and minority students who major in physics (Ivy and Ray, 2005; Nelson, 2005; Zohar, 2006). The Relevance of Science Education (ROSE) study in Europe is beginning to reveal that there are indeed gender-related differences in contextual preferences, which, in the current curricular paradigm of physics with its emphasis on classical mechanics, favor males over females (Sjøberg and Schreiner, 2007). Simply putting females into mechanics problems – what Zuga (1999) called the 'add women and stir' approach - does not suffice to make physics appealing to girls (Zuga, 1999).

The content and organization of the current sequence of the introductory physics curriculum is traced to the 1957 launch of the Soviet satellite Sputnik, which sparked several physics education reform movements in the United States at the time (Brekke, 1995). In 2007, even though instructional methods have changed in many institutions from traditional lecture to interactive methods, the content and sequence of the introductory physics curriculum has remained constant over the past fifty years, and the population of physicists and physics majors has also been slow to change (Ivy and Stowe, 2003; Ivy and Ray, 2005; Nelson, 2005). One of the goals of this project is to ask whether changing the content and sequence to start with contemporary physics, and broadening the curriculum to include examples from art, music, and dance, can encourage diversity in physics, as well as make physics – with mathematics – more accessible to a wider population.

In this chapter I will first give a brief review of physics pedagogical reform efforts which began in the last two decades of the twentieth century, which have addressed teaching methods, but have not addressed the curriculum proper. I will then highlight several studies in Europe which indicate that curriculum reform which includes more contemporary physics and interdisciplinary approaches may be one way to redress the gender and cultural imbalances in physics, as well as modernize the curriculum. In section two I will touch on the discourse of physics as a way of maintaining a community identity which gives physics the appearance of being exclusive and perhaps intimidating, and in section three I will provide a brief background on one perspective of the need to provide opportunities for creativity in introductory physics.

2.1. A Quarter of a Century of Physics Education Reform

The university physics curriculum has its origins in the first medieval academies of Western Europe in the twelfth century, when scholars studied seven subjects: the trivium, consisting of grammar, rhetoric and dialectic, and the quadrivium which consisted of geometry, astronomy, arithmetic and music (Stuver, 2001).Physics became a separate topic in the undergraduate curriculum towards the end of the nineteenth century (ibid). The present curriculum, which starts with Newtonian mechanics, followed by electricity and magnetism, optics and sound, thermodynamics, and lastly (time permitting!) a few topics from "modern" physics, was established shortly after the 1957 Soviet launch of the Sputnik satellite (Stuver, 2001; Brekke, 1995). This curriculum is covered in one year for students who major in biological sciences, or two years for students who major in physical sciences or engineering. Physics majors, after the introductory sequence, study each topic in more depth; for other students, this introductory sequence may be their only opportunity to study physics. It is of interest to note that the topics which are called "modern" physics include the discoveries of Special Relativity, Quantum Mechanics, and Heisenberg's Uncertainty Principle, all of which are now from seventy five to more than one hundred years old, and most introductory undergraduate courses omit any discussion of the Standard Model of Particles and Interactions, modern cosmology, or General Relativity.

The standard introductory curriculum has not changed in fifty years, however sometime in the 1980's, physics professors in a number of universities in the United States began to notice that their students did not understand the basic concepts, even if they could perform the calculations (Halloun and Hestenes, 1985; Van Heuvelen, 2001; Hake, 1998), and that this failure was independent of the professors' reputations. A reform movement in physics education in the United States began at that time, starting with the development of the Mechanics Diagnostic Test (MDT) by Ibrahim Halloun and David Hestenes at Arizona State University, which was published in 1985. Halloun and Hestenes studied undergraduates' "common sense" beliefs about the behaviors of simple mechanical systems, based on their direct experiences. They found that students' common sense beliefs, which are generally not correct in terms of classical Newtonian understanding, share features with older historically held beliefs of Aristotle and the medieval impetus theory. After Halloun and Hestenes released their diagnostic test in 1985, a number of educators began administering it, realizing that students could learn to solve problems in mechanics without understanding the concepts behind the formulas (Hestenes, 1987; Mazur, 1997; Savinainan and Scott, 2002).

Malcolm Wells, a high school physics teacher working with Hestenes at the time the MDT was published, was the first documented high school educator to administer this test to his students and, working with Halloun and Hestenes at Arizona State University, developed the pedagogical method called Modeling Instruction (MI). The goal of MI was to address the confusion of students by teaching them to mathematically model physical systems using sound Newtonian reasoning.

Instead of lecturing to students and teaching them to solve problems, MI advocated helping students develop their scientific intuition by developing working models, and learning how to use equations to model physical systems (Wells, Hestenes, and Schwackhamer, 1995).

In 1992 Hestenes, Wells, and Schwackhamer published the Force Concept Inventory (FCI), a revised version of the original MDT of Halloun and Hestenes, in *The Physics Teacher*, the monthly magazine of the American Association of Physics Teachers. Since it was first published, the FCI has undergone several revisions, and has become the most widely used metric of classical physics instruction, having been translated into nine languages besides English, taken by tens of thousands of students, and is now available on the Internet from http://modeling.asu.edu/R&E/Research.html.

The results of giving the FCI as a pre- and post-course diagnostic have consistently shown that before instruction, most students hold naive beliefs about motion and interactions which are not compatible with a correct Newtonian analysis, and that traditional lecture methods do little to change such beliefs (Hestenes, 1996, 1998; Mazur, 1997, 2007; Van Heuvelen, 2001; McDermott, 2001; Hake, 1998, 2007). The FCI has been used to test graduate students' and faculty members' understanding of Newtonian concepts, and in a number of surveys, it has been found that often even graduate students and faculty score in the sixtieth to seventieth percentiles (Pride, Vokos, and McDermott, 1998). The general conclusions of the physics education community have been that traditional physics instruction does not guarantee correct Newtonian reasoning, but correct understanding of motion and forces according to the Newtonian paradigm is a predictor of success in physics (Hestenes, 1995, 1996). Interactive instructional methods, including the use of Socratic dialogue, which engage students as active participants during class, as opposed to traditional lecture methods, have been shown to cause significant improvement in Newtonian reasoning, as tested by the FCI (Hestenes, 1996,1998; Hake, 2007; Laws, 1991, 1997; Mazur, 1997, 2007).

Edward Redish, Jeffrey Saul, and Richard Steinberg published their Maryland Physics Expectations test (MPEX) in 1996, which was designed to be a companion metric to be used with the FCI. Whereas the FCI was designed to test concept development, the MPEX was designed to test whether students' attitudes towards the process of doing physics improved over the course of instruction. Their research, administering their test to over 1500 college students enrolled in introductory physics courses at six different universities, revealed that attitudes towards physics actually declined after instruction, regardless of the method used (Redish, Saul, and Steinberg, 1998).

The FCI and the MPEX have become the standard metrics in the United States for measuring the success of introductory physics courses, and are still widely used as diagnostics against which any new pedagogical methods are tested. One of the first teaching physicists to turn the FCI on his own students was Eric Mazur, of Harvard University. He described his shock at seeing the poor results of his students, which led him to develop the interactive method he called Peer Instruction (PI). PI emphasizes the Socratic method, whereby the instructor poses conceptual questions to the class at regular intervals during the lecture, which the students discuss first in small groups and then together as a class, instead of students passively listening to a lecture (Mazur, 1997, 2007). PI has been shown not only to improve conceptual learning via the FCI (Crouch, Watkins, Fagen, and Mazur, 2007), but also to eliminate the gender gap in introductory college physics, as measured by the FCI (Crouch, Oster, and Mazur, 2001; Lorenzo, Crouch, and Mazur, 2006).

The poor results on the MDT and FCI prompted a number of other instructional innovations in the 1990's, most of which include elements of interactive engagement from Peer Instruction as well as concept building from Modeling Instruction. The most widely recognized instructional innovations over the past decade or so have been Workshop Physics, developed by Priscilla Laws at Dickenson College, Physics by Inquiry, developed by Lillian McDermott at Washington University, and Learning Cycles, developed by Dean Zollman at Kansas State University. All three of these instructional methods emphasize the use of manipulatives, peer interactions, and discussions, and de-emphasize the role of lecture in physics instruction.

Workshop Physics is similar to the Modeling Instruction approach in that it seeks to help students develop mathematical models, but different in that these models all start with a physical experience. Every concept is first illustrated by an experiment or other practical activity, which is followed by the instructor guiding a mathematical derivation. This is followed by an “equation-verification experiment” (Laws, 1997).

Physics by Inquiry, developed by the Physics Education Group at the University of Washington, under the direction of Lillian McDermott, has been described as learning physics by guided inquiry (McDermott, 2001). McDermott's approach is similar to Laws' Workshop Physics in that each new concept is motivated by a short investigation, which could be an actual experiment or a thought experiment, but there is less emphasis on developing equations to model phenomena, and more effort spent on concept development. Physics by Inquiry also relies heavily on peer interactions, as all the experiments are done in cooperative groups, and the instructor poses questions for discussion rather than lecturing.

Zollman's Learning Cycles method incorporates elements of Physics by Inquiry and Peer Instruction, but utilizes a cyclic approach to learning concepts in physics (Zollman, 1996). Two inquiries are performed by students, at their own pace, outside of the regular class period: an exploratory investigation on Monday, followed by a more in-depth application on Wednesday. On Friday the class discusses the results, and the professor summarizes the week before beginning a new cycle the following Monday (Zollman, 1996).

"Just in Time Teaching" (JiTT) was developed by Evelyn Patterson (US Air Force Academy), Gregor Novak and Andrew Garvin (Indiana University – Purdue University), and Wolfgang Christian (Davidson College). JiTT emphasizes the use of the World Wide Web for near-real-time adjustments of an instructor's lesson plans to the current state of understanding of the class as a whole. The technique that is stressed is to have students read the text and answer questions via the Internet before class; the instructor reads their answers prior to class, and adjusts the lesson for the day accordingly. JiTT methodology makes extensive use of computers for modeling physical systems using simplified graphics called *"Physlets,"* which were first developed by Wolfgang Christian in the early 1990's.

Physlets - Java applications ("applets") which can be run over the Internet in the Java programming language, are useful with Modeling Instruction techniques, in that they allow students to change initial and boundary conditions in a simple system, make predictions, and test their predictions against the outcomes. Physlets are designed to be media-focused problems, as opposed to a passive, media-enhanced demonstrations of a system or process (Christian and Belloni, 2001). An extensive library of Physlets is now available on the internet (http://webphysics.davidson.edu /physletprob/) and instructions for how to code one's own Physlets are available in book form (Christian and Belloni, 2001).

More recently, Eugenia Etkina of Rutgers University has found that high gains in conceptual understanding, as measured by the FCI, are related to students' personal epistemologies - beliefs or views about how knowledge is constructed and evaluated. (May and Etkina, 2002). Students whose personal epistemologies are more appropriate to the methods of physics tend to show higher conceptual gains than others, even though they have all been taught using the techniques of Modeling Instruction and Peer Instruction (May and Etkina, 2002). Thus, in addition to promoting active learning, the next goal of physics education they recommend is to interrogate students' epistemologies – how they understand the process of acquiring knowledge and making sense of observations – and design strategies to help students learn the process of creating meaning from physical observations (ibid).

Etkina's work, and the research on student epistemologies of Hammer and Elby (2002), and diSessa (1993), while important, all center on understanding how students understand Newtonian physics, however Jonathan Osborne of King's College in London suggested that, although Newton's contributions were certainly revolutionary for his time, they represent a world view which is "relentlessly deterministic, linear and remote from human action or influence" (Osborne, 1990). Osborne suggested that the content of physics should be thought of in three basic realms of understanding: classical physics, from Newton to the end of the nineteenth century; modern physics, which includes discoveries of Relativity and Quantum Mechanics that occupied the first third of the twentieth century; and contemporary physics, which covers the recent advances in fundamental physics. Osborne suggested that the complete over-representation of Newtonian physics at the expense of contemporary physics presents a distorted view of the world, which fails to address what should be the goals of physics education: what do we know (ontology), and how do we know it (epistemology).

Thus physics education research in the United States in the past twenty years or so has shown that interactive methods are more effective than the traditional lecture method in promoting conceptual understanding in introductory physics. However, the content and sequence of the introductory curriculum has remained constant for the last fifty years, with an over emphasis on the deterministic Newtonian paradigm, so that the questions which motivate the practice of physics in the contemporary world are not being addressed in introductory physics.

2.2. Diversity and Equity Issues in Physics Education

At the same time as efforts to reform instructional methods in undergraduate introductory physics have been undertaken in the United States, women and minorities remain under represented in physics (Wertheim, 1996; Zuga, 1999; Fox-Keller, 2001, Tobias, 2003; Ivy and Ray, 2005). Blickenstaff (2005) examined thirty years of research on the gender imbalance in physics, and concluded that the very nature of science may be the largest contributor to what has been called the "leaky pipeline" whereby women have greater attrition rates than men, particularly in physics. A few studies in the United States have attempted to recontextualize Newtonian mechanics in terms of female scenarios, but with no conclusive evidence that such changes had any effect on increasing the numbers of girls in physics, nor improving their Newtonian reasoning (McCullough, 2001; Whitten, Foster, and Duncombe, 2003).

In Europe, the Relevance of Science Education (ROSE) project has revealed that girls and boys in high school do indeed have different interests regarding content and orientation in physics. In a study of high school students in thirty four countries Sjøberg and Schreiner (2007) found that boys report interests in electrical, mechanical, spectacular and violent phenomena, while girls' interests are more directed toward biology, health, caring, ethical, aesthetic, philosophical issues. On the other hand, they found that both girls and boys reported similarly high interests in topics from contemporary physics, including black holes, supernovas and other spectacular objects in outer space, stars, planets and the universe, unsolved mysteries in outer space, and phenomena that scientists still cannot explain (Sjøberg and

Schreiner, 2007). Angell, Guttersrund, and Henriksen (2004) interviewed Norwegian high school students in physics in grades twelve and thirteen, and found that both boys and girls reported much greater interest in topics such as relativity and quantum mechanics than classical physics. Interestingly, these same students also reported that the topics from contemporary physics were much more connected to their every-day experiences than topics from classical physics, because these were often topics of conversation among their friends.

Kessels, Rau, and Hannover (2006) studied negative attitudes toward physics of high school students and undergraduates in Germany. When they tested the high school students using an implicit association test, they found that high school students associate physics with difficulty, masculinity, heteronomy (lack of opportunity for self expression), and unpleasantness. They then compared a control group of undergraduates who were given a passage to read from a traditional physics text book with a treatment group who were given a passage by Thomas Kuhn that emphasized the importance of discourse and creativity in physics. They found that the negative associations with physics of the treatment group were significantly reduced compared to the control group (Kessels, et al., 2006). They found that the avoidance of physics as unpleasant, although more pronounced in high school girls, was also present in boys. They recommended that educational strategies which seek to overthrow stereotypes of physics can be effective in reducing the perceived barriers to studying physics (ibid.). This recommendation supports the findings of the present study, in which art students with initially negative impressions of physics and physicists reversed their attitudes as a result of this course.

Zohar (2006) compared connected knowing, which was originally described as "women's ways of knowing" (Belenky, Clinchy, Goldberger, and Tarule, 1986), with feminist epistemology of science, which is characterized as an interconnected knowledge system. She defined four ways in which interconnected thinkers are characterized: seeing connections between phenomena to be understood and the contexts in which they occur; seeing connections between the phenomena to be understood and themselves; connecting their mental representations of knowledge with their emotions, bodies, and actions; and seeing knowledge as a collaborative construction among people. It is interesting to note that the attributes of connected knowing, ascribed to feminist epistemology by Zohar, are essentially not different from the practices of contemporary physics, in the following ways: In contemporary physics, it is understood that an observer cannot observe a system without influencing its behavior (phenomena connected with contexts in which they occur), which is the opposite of the Newtonian paradigm which divorces the observer from the observed. Experimental physics research is becoming increasingly connected with other disciplines, for example: biophysics, nanoscience, and media arts technology (phenomena connected with different 'selves'). All branches of physics encourage and require collaboration (phenomena connected with people), from theoretical physics to international experiments in particle physics and space science. Lastly, although in traditional physics instruction, understanding physics has not been associated with emotions and physical sensations, one has only to read personal accounts of Einstein and other famous scientists to understand the role of emotions, images, and intuition in their accomplishments (Wallace and Gruber, 1989; Miller, 1989; John-Steiner, 1997). Thus, I would like to suggest that instead of labeling connected ways of knowing as "feminist epistemology," that we instead look at them as "humanist epistemology," and consider the possibility that starting the introductory physics sequence with contemporary physics, especially with contextual applications from nature and fine arts, may have a positive effect in attracting a more diverse student population.

Conventional science instruction, Zohar concluded, is based on the dualistic conceptions of science that grew out of the Enlightenment of Western Europe, in which reason and objectivity were identified with science and masculinity, and emotion and subjectivity were identified with art and femininity. Other scholars of the history of science have also associated science, especially Newtonian physics, with objectivity, which has come to be associated with conventional masculinity (Wertheim, 1996; Zuga, 1999; Traweek, 1988). Zohar recommends that the goal of science education should be to challenge the conventional dualistic mode of thinking by developing ways of interconnected knowing (Zohar, 2006).

Symmetry and Aesthetics in Introductory Physics combines features of each of the above recommendations for improving introductory university physics: starting with contemporary physics rather than Newtonian mechanics as more interesting and meaningful for both male and female students; utilizing connections with art and nature to illustrate concepts from math and physics; utilizing alternate learning strategies of drawing and visualization to enhance mathematical and logical understanding; encouraging discussion, collaboration, and self reflection; reading literary works by theoretical physicists instead of a standard text book; and a final project connecting physics with an art form of personal relevance to each student, thus allowing for freedom of expression (the opposite of heteronomy) within the correctness of the discipline.

2.3 How Discourse Shapes the Physics Community

The discourse of physics sets physicists and physics students apart from other discipline-based communities, thus any reasonable attempt to understand the lack of diversity in the physics community should include an investigation of the role of the discourse of physics in maintaining the boundaries and borders of that community. A male English major from the College of Creative Studies, who was enrolled in an astronomy course for which I was a teaching assistant in 2004, after attending a meeting of the Society of Physics Students at UCSB said to me, "They TALK different from most of the rest of us.” This language difference between the physics and art students was apparent in the course Symmetry and Aesthetics in Introductory Physics (CCS-120) in the present study, in the way they spoke, wrote, communicated, and represented themselves.

Traweek (1988) described the culture of physics as "an extreme culture of objectivity; a culture of no culture, a world outside human space and time," and the knowledge represented by physics as “a certain kind of privileged knowledge, a way of knowing that is profoundly gendered and cultural” (Traweek, 1988). Bazerman (2000) described the discourse of physics in the following way:

> Unfamiliar words signify objects and phenomena from the microscopic and macroscopic limits of the universe, objects distinguished from each other and classified with a precision and

> taxonomic care having little to do with our everyday fuzzy naming of the objects of domestic life *(*Bazerman, 2000, p. 293*).*

He further said that these practices give physics discourse "special status separate from the turbulent, murky, and illusion ridden language of the rest of the human world" (Bazerman, 2000, p. 296). This obscurity of language, he says, often leads to a general mistrust of physicists. The art students in CCS-120 expressed similar resentment towards this usurping of familiar terms from everyday parlance into physics usage, as will be discussed in Chapter Five.

Sociolinguistics scholar John Gumperz' (1968) definition of a speech community provides a more objective definition which can be applied to the community of physicists:

> any human aggregate characterized by regular and frequent interaction by means of a shared body of verbal signs and set off from similar aggregates by significant differences in language usage (Gumperz, 1968. p.381).

Dell Hymes (1997) defined a socially constituted linguistics as one which has both social as well as referential meaning. Thus, even setting aside Bazerman's rather emotionally charged condemnation of the discourse of physics, it is conceivable that the specialized language of physics is a socially constituted linguistics in that it has referential meaning, and also serves to identify members of the physics community as separate from others. The language of physics and mathematics did present a boundary between the art and physics students, which had to be overcome, even in this group of students who were otherwise culturally homogeneous. Thus, if we are to increase the diversity in physics, one important aspect to consider, which is suggested by the present study, is to find ways to make the language of physics and mathematics more accessible to a wider population.

2.4. Discourse of Physics as a Barrier to Minority Culture Students

The problems of accessibility with the discourse of physics and language of mathematics are magnified for minority students in the United States (Aikenhead, 1999; Aikenhead and Jegede, 1999; Lee, 2003). According to the Multiple Worlds Theory of Phelan, Davidson, and Yu (1993), students from minority culture home worlds must make a transition to the dominant culture of the school world. The theoretical framework of border crossings between multiple worlds has been applied to understand the combined difficulty of minority-culture students both with the dominant white culture of school itself, and with the additional difficulty imposed by the culture of western science, particularly physics. Not being part of the dominant culture language group, learning the language of physics is even more problematic for minority culture students (Lee, 1998, 2003; Aikenhead, 2002, 2003). Not surprisingly, recent studies by the American Physical Society (Ivy and Ray, 2005; Ong, 2007) reveal the persistent lack of people of color in physics. Thus the physics education reforms cited above, which address pedagogical strategies for introductory physics, but do not consider the role of the discourse of physics and mathematics in maintaining the unseen boundaries around the community of physics, do not automatically benefit minority culture students who may be reluctant to enter a physics course at all. The problem of under-represented groups in physics continues to be both monolithic and implacable (Burciaga, 2007), and the physics education community has been slow to address issues such as discourse, which fall outside the arena of mainstream physics education research.

The rationale for a paradigm change in the introductory physics curriculum as being necessary for a change in the physics community can be found in Thomas Kuhn's *The Structure of Scientific Revolutions* (1962, 1970, 1996). To change the structure of the physics community requires a change in the way we educate our students, which necessitates the acceptance of a new paradigm – which, it seems, the physics community is reluctant to do. Why is it so important to the community identity that everyone be trained first to conceptualize the phenomenological world in terms of strict Newtonian determinism, when the axioms of the Newtonian paradigm, absolute space and universal time, are not those of the contemporary world view? Perhaps, according to Kuhn, we maintain this paradigm because it is a cultural outgrowth of western Europe. Thus it unconsciously acts as a barrier which prevents cultural diversity: unless a student is prepared to first adopt the Newtonian world view prescribed by the introductory curriculum, he or she cannot progress to the higher level, where the contemporary issues and technologies are taught. Thus the system of physics education, which begins with a strict adherence to Newtonian mechanics may function as a tacit filter, which is so culturally embedded as to be invisible to mainstream Physics Education Research, yet which acts to prevent cultural diversity from changing the face of the physics community.

In a recent editorial in *Physics Today*, “Rethinking the Content of Physics Courses” (February, 2006), Diane Grayson of the University of Pretoria, South Africa, recommended changes in the scope, sequence, and content of the introductory physics curriculum, based on proposals from an international conference on physics education that took place in Durban, South Africa, in July, 2004.

A physics curriculum for the 21st century should include the human dimensions of what is a very human activity, the generation of knowledge about the physical world. That knowledge generation does not take place in a vacuum; it is always embedded in a time and place, influenced by history and culture, passion and prejudice. Students should come away from their physics courses with an increased sense of wonder and excitement at the marvels of the physical world and the ingenious ways in which human beings have tried and continue to try to understand them. (Grayson, Physics Today, Feb., 2006)

The curriculum, teaching strategies, and goals of Symmetry and Aesthetics in Introductory Physics support and are supported by the proposal of the international conference on physics education summarized by Grayson. This interdisciplinary introductory physics and fine arts curriculum takes into account the research in mainstream physics education, incorporating elements of Peer Instruction and Modeling Instruction; addresses students' epistemologies by interrogating students' beliefs about the role of mathematics in understanding the physical universe; reframes the curricular paradigm from Newtonian determinism to a contemporary, post-Einstein world view; and attempts to make physics accessible to a more divese population by including ways of knowing that are connected to nature, art, and music. The results of the present study suggest that including art as a way of understanding concepts in physics may provide a way to open up access to the discourse of physics and mathematics to a wider population, thus ameliorating the negative perceptions of physics described by Bazerman.

An additional goal of this curriculum is to foster creativity while maintaining mathematical rigor and developing sound physics reasoning by exploring the connections between art and physics, through the common principle of symmetry.

2.5. Creativity theories and Interdisciplinary Curriculum

In a recent editorial in *Physics Today* (July, 2006, p. 10) the ability of physicists to "imagine new realities" was correlated with what are traditionally considered non-scientific skills, including imagination and creativity, qualities which are usually associated with fine arts. Sheila Tobias (Research Corporation, Tucson, Arizona) commented in another editorial in *Physics Today* that the physics education community needs to seek alternate ways of teaching physics to overcome "America's lagging production of physics majors" so as to recognize a talent for physics that is "differently packaged from the norm" (August, 2006, p. 10). The present study is addresses the need for an introductory physics curriculum which promotes the ability to imagine the new realities as revealed by contemporary physics, and encourages students who may be differently packaged from the norm to excel in physics via the similarities between physics and the arts. Research on intelligence, creativity, education theory, and the nature of physics as it is practiced, supports the rationale for such an interdisciplinary curricular paradigm for introductory college physics.

2.5.1. Creativity and Intelligence

What is creativity? Creativity theorists, such as Mihaly Csikszentmihalyi, Howard Gruber, and Vera John-Steiner, have shown that creativity is defined by a product and a process, often a very long process, which is defined within a socio-cultural system, of which the individual is one component. Creativity does not occur in a single insightful moment, nor is it possible without being situated within a cultural system. Csikszentmihalyi interviewed famous people who are considered creative, who came from a wide variety of disciplines, ages, and cultures, including physics, literature, art, music, and dance, as well as hundreds of college students, in a multi-year study. Based on his findings, he defined a systems approach to creativity:

> Creativity occurs when a person, using the symbols of a given domain such as music, engineering, business, or mathematics, has a new idea or sees a new pattern, and when this novelty is selected by the appropriate field for inclusion into the relevant domain. (Csikszentmihalyi, 1996).

Thus we can understand from this definition that creativity requires training in one or more domains. What about intelligence? As Gruber (1989), Csikszentmihalyi (1996) and John-Steiner (1997) have shown that there are many different ways in which creativity is expressed, Howard Gardner (1985) has shown that there are several different ways in which intelligence is expressed. Gardner (1985) identified five main types of intelligences that involve cognitive skills: linguistic / verbal intelligence; musical intelligence; logical/mathematical intelligence; spatial intelligence; and bodily/kinesthetic intelligence. Moreover, Gardner showed that people express intelligence in more than one mode simultaneously (logical, kinesthetic, musical, e.g.). Gardner founded "Project Zero" at Harvard University to study the cognitive aspects of the arts, or *artistic intelligence* (Gardner, 1983). Artistic intelligence, Gardner proposed, involves the production and recognition of symbols (ibid).

Since Gardner's Multiple Intelligence model was published, several programs have explored the incorporation of arts in science education in universities (Walton, 1998; Korey, 2000; Nikitina, 2003; Hertzberg and Sweetman, 2004),which have shown that people simultaneously express themselves intellectually as well as creatively in more than one realm, for example: engineering and dance, engineering and photography, or math and art. These studies will be discussed in Chapter Three.

The implications for education are clear: the intelligences defined by Gardner are avenues by which creativity can be expressed, and people naturally express both intelligence as well as creativity in more than one area simultaneously. It is the suggestion of the present study that symbolic representations, whether in visual arts, mathematical symbols, movement arts, or musical notation, share the common feature that they communicate ideas via representations that tap into concepts more efficiently than words, although they are ultimately reducible to verbal description. Thus, it may be possible to utilize, for example, a cubist painting to communicate the idea of what the world might look like to a traveler undergoing a Lorentz boost, movements from dance to communicate concepts from dynamics, or – as one of the art students in CCS-120 expressed, translational symmetry as wallpaper.

> The passage about Morris (p.21-22 in reader), which some may consider an irrelevant tangent made me instantly get what translational

> symmetry is – a concept I have been struggling to see before my mental eye thus far. Wallpaper - of course! It makes complete sense!

Elliot Eisner of Stanford University has discussed the separation of arts and sciences in education as having originated in the Enlightenment of western Europe (Eisner, 2002a, 2002b). Natural science - which later became known as physics – represented the epitome of knowledge as being rational, objective, deterministic, universal, and reducible to mathematical relationships. Episteme, or true knowledge, was independent of beliefs and values (ibid.); such is the basis for the Newtonian *weltanschauung*. The viewpoint of practicing physicists, on the other hand, is that while acknowledging the ultimate universality of the laws of physics as constant under translation, rotation, or Lorentz boosts, for example, physics is ultimately a creative and cultural endeavor, which shares experiential features with arts and literature. Quoting theoretical physicist Lawrence Krauss (*Fear of Physics),* physics is a creative endeavor.

> I want to stress that physics is a human creative intellectual activity, like art and music. Physics has helped forge our cultural experience. … it is a grave mistake to ignore the cultural aspect of our scientific tradition. … And the chief virtue of a cultural activity – be it art, music, literature, or science – is the way it enriches our lives. Through it we can experience joy, excitement, beauty, mystery, adventure (Krauss, 1993, p. xi).

Eisner (2002b) proposed that the choice of symbolic forms of representation influences not only what one is able to say, but also what one is able to see. "We seek what we are able to find" (Eisner, 2002b, p. 380). Just as narrative is a form of discourse in which the way in which something is told conveys a deeper meaning behind that which is being said, images make it possible to "apprehend that which we wish to comprehend” (ibid., p. 380). Thus it is logical to conceive of bringing art and other forms of symbolic representation into physics education. These two statements, one from a theoretical physicist and the other from an education theorist, if understood together, lend support the model of interdisciplinary arts and physics education, at least at the introductory level, before specialization in the more advanced courses narrows a student's focus. The reactions of both physics and art students in CCS-120 support this view as well.

Csikszentmihalyi proposed that creativity is best nurtured at the intersection of different cultures, where beliefs, lifestyles, and knowledge structures permit the free exchange of ideas and points of view. *“Creativity is more likely in places where new ideas require less effort to be perceived”* (Csikszentmihalyi, 1996; p. 9). The interdisciplinary course, Symmetry and Aesthetics in Introductory Physics, which combined arts and physics was certainly an environment which encouraged the exchange of ideas and points of view, in a classroom culture that was neither uniform nor rigid.

Further support for the idea of interdisciplinary arts and sciences education can be found in the work of Vera John-Steiner (1997), who studied the cognitive aspects of creative thinking. She investigated the similarities, across cultures and across disciplines, in the way people who are publicly recognized as highly creative think about what they do. She proposed that between the external object and the internalized conception of the object, there is the translation through some set of symbolic representations. She called these representations *languages of the mind* – how people think in images, music, patterns, words, numbers, algebraic symbols, mnemonic techniques, and spatial relationships. Her interviews revealed a wide variety of symbolic representations that people use to translate from the external world to their understanding of it, via their own internal symbol systems, and in turn, how they communicate their internal understanding with the outside world through creative processes of literature, music, dance, science, and mathematics. She found, for example, that physicists and mathematicians often think in images, as in the following quote from Einstein:

> The words or the language, as they are written or spoken, do not seem to play any role in my mechanisms of thought. The physical entities which seem to serve as elements in thought are certain signs and more or less clear mages which can be voluntarily reproduced or combined (John-Steiner, 1997, p. 4).

Combining the research of Gardner on multiple intelligences, Csikszentmihalyi on the nature of creativity, and John-Steiner on the creative process, it is logical to consider that perhaps intelligence is the ability to understand sensory input from the outside world, and creativity is the ability to express one's understanding in one or more symbolic forms so as to stimulate new ways of understanding in others. Thus, we can see how physics and mathematics embody creativity, and arts express intellect. Combining these ideas leads us to try new paradigms in undergraduate education, such as the interdisciplinary course, Symmetry and Aesthetics in Introductory Physics of the present study.

2.5.2. Optimizing the Educational Experience

One final element that is missing from traditional introductory physics courses, which was cited by John-Steiner as being important to the creative people she studied, has been cited as important by scientists and artists, and was cited as important to the students in CCS-120, is *passion.* John-Steiner reported that the creative people she interviewed had the common experience of school as being "sparse and lifeless" (1997, p. 45), while both art and physics students in CCS-120 reported that it was the passion of the other students and the instructor which made the class important to them, and inspired them to attend. Csikszentmihalyi developed a *theory of optimal experience,* based on people's personal accounts of what it felt like to be doing what they most enjoyed (Csikszentmihalyi, 1990). He defined the *"flow*" experience as "the state in which people are so involved in an activity that nothing else seems to matter" (ibid., p. 4). Qualities of the flow experience include the loss of a sense of time as measured by a clock, and the loss of the sense of self, yet the self concept emerges stronger as a result. There is the sense that the task can be completed, there are clear objectives and the opportunity to concentrate, and there is a sense that the task is worth while for its own sake. Several experiences with the interdisciplinary course CCS-120 had qualities that embodied those of the flow experience, particularly the final project, which students said did not feel like an assignment at all, and the class discussions, which often went on for an hour or more after class. Thus, the suggestion of incorporating arts into physics, and of starting introductory physics with contemporary physics instead of Newtonian mechanics, should be taken seriously by the physics community as a way of improving the introductory physics experience for all students.

2.5.3. Emerging Support for Symmetry –based Curriculum

Finally, to become accepted as a creative contribution, a new idea must be accepted by those in power who function as gatekeepers of a discipline (Csikszentmihalyi, 1996). Evidence that the combination of arts and physics is gaining acceptance by some of the gatekeepers of physics is apparent in the support for this curricular model by Professor David Gross, the director of the Kavli Institute for Theoretical Physics (KITP) and 2004 Nobel Laureate, who gave a guest lecture for the class (Gross, personal communication, March 9, 2007). The KITP has supported Dr. Jean-Pierre Hebert as Artist in Residence for several years, and maintains two informal art galleries within the KITP itself. The School of Engineering at UCSB began a graduate program in Media Arts Technology several years ago, which encourages interdisciplinary research in art, music, and computer technology.

Outside of UCSB, support for a symmetry-based integrated physics and fine arts curriculum comes from Dr. Leon Lederman, 1998 Nobel Laureate and former director of the Fermi National Accelerator Laboratory in Illinois, who has designed a high school based on these principles (the Illinois Math and Science Academy).

2.6. Summary of Supporting Research

In summary, research in physics education in the past twenty years has shown that interactive methods are superior to straight lecture in promoting understanding of physics concepts. At the same time, while the methodology has changed from traditional lecture to interactive classroom environments, the prevailing view that Newtonian mechanics should dominate the introductory curriculum has been very slow to change. The physics community continues to be characterized by a lack of diversity, with both women and minority cultures being under-represented. Research in Europe is beginning to show that the gender bias may be maintained by the introductory curriculum due to its over emphasis on Newtonian mechanics and contexts which address the specialized interests of traditional masculinity. The perspective of contemporary physics is more aligned with what has been called feminist epistemology, or connected ways of knowing, which suggests that reframing the introductory physics curriculum so as to begin with contemporary physics may have a positive effect, at least on redressing the persistent gender bias.

From a sociolinguistic viewpoint, the specialized discourse of physics serves to create and maintain the boundaries of the physics community, which set physics students apart from others even in otherwise culturally-homogeneous groups. The discourse of physics as a marker of physics identity is even more problematic for minority culture students. Most of the mainstream physics education research in the United States still focuses on improving students' understanding of Newtonian mechanics, yet the effectiveness of this approach at increasing diversity of the physics community has not been demonstrated. The number of women graduating with PhD's in physics is still under 20%; for minority culture students this figure is much lower.

At the same time, practicing physicists are calling for the undergraduate curriculum to encourage greater creativity in the next generation of physicists. Theoretical support for the combination of creativity and multiple intelligences from the work of psychologists Howard Gardner, Howard Gruber, Mihaly Csikszentmihalyi, and anthropologist Vera John-Steiner can be used to help design interdisciplinary curricula which can encourage the development of creativity in physics. Education theorist Elliot Eisner of Stanford University has advocated for greater emphasis on the arts in education.

The goal of this project, then, was to design a new curriculum for introductory physics, which starts with symmetry and math as a language of nature, and utilizes symmetry as the natural connection between physics and fine arts, and to test whether such a curriculum could make physics appealing and accessible to a wider population of undergraduates, without sacrificing the mathematical way of knowing which is the foundation of physics. The enthusiasm of the students and their progress in learning concepts in physics are testaments to the success of this model with these students, and suggests that this model deserves further development and testing with a wider population.

In the next chapter I will present the results of several interdisciplinary arts and sciences courses at other universities which support the idea that such curricular paradigms can make physics accessible to a wider student population, without sacrificing mathematical rigor. I will also present the results of a survey I conducted in 2006 of recreational folk dancers who have jobs in physics or math-related fields.

The reports by these people, from the United States and Europe, demonstrate that indeed connections do exist for many people in their approach to dance and physics.

Chapter 3: Connections between Physics and Fine Arts: Case Studies

> "What we need is imagination, but imagination in a terrible straightjacket. We have to find a new view of the world that has to agree with everything that is known, but disagree in its predictions somewhere, otherwise it is not interesting. And in that disagreement, it must agree with nature. . A new idea is extremely difficult to think of. It takes a fantastic imagination."
>
> \- Richard Feynman

In Chapter Two I presented evidence from physics education research, sociolinguistics, and the psychology of creativity and intelligence as theoretical support for the design of the course Symmetry and Aesthetics in Introductory Physics. In this chapter I will discuss the results of other studies which promote interdisciplinary science, math, and arts education at the college level, and interrogate the connections between arts and sciences in people's professional and personal lives. These studies lend further support and justification for the curricular paradigm represented by my course, Symmetry and Aesthetics in Introductory Physics.

3.1. Physics and Dance Connections

The notion that there is a connection between bodily/kinesthetic intelligence and physics/math reasoning is not new. According to psychologist Howard Gardner (1985), bodily intelligence contains a trio of object-related intelligences: logical/ mathematical intelligence, which grows out of patterning and sequencing; spatial intelligence, which depends on the ability to comprehend transformations in one's surroundings; and bodily/kinesthetic intelligence, which entails both the ability to focus inward on one's own body and skill development, as well as the ability to focus outward to interact with and manipulate objects in one's environment. If logical/mathematical intelligence is psychologically and cognitively associated with a bodily intelligence, which is related to patterning and sequencing, then it is reasonable to pursue the question of whether dance, which is based on patterns and sequences in space and time set to music, is somehow related to mathematics. If so, then perhaps dance and music can be used to help students learn mathematics and physics.

Physics professor Kenneth Laws (2002) has taught the physics of ballet to dancers for approximately twenty years, and has written about the eagerness with which ballet students embrace concepts from Newtonian mechanics, which then help them improve their ballet performance. He said of ballet students,

> It is also often astonishing to see dancers sense, in some deep analytical part of their minds, how to accommodate to near-impossible challenges. And if dancers have not yet learned to fear science, they are open to the benefits and joys of this analytical level of understanding (Laws, 2002, p. viii).

The last sentence is perhaps the most pertinent for this study: *if dancers have not yet learned to fear science*, by which he means, of course, if they have not yet learned to fear *physics*. This is part of the question that motivated this study: can the arts be integrated with physics so as to reduce the fear of physics?

The following studies of adults and college students who work in, or study, physics, math, and engineering fields, and are also involved in recreational and performance-oriented dance and music indicate that there is a connection. Reviews of a number of extant interdisciplinary arts-and-sciences programs demonstrate that integrating arts into physics, math, and engineering can indeed reduce fear of these subjects for many students.

3.1.1. Physics and Folk Dance Connection

In 1985 Canadian teacher, researcher, and dance ethnologist Yves Moreau conducted a mail survey of recreational folk dancers and musicians, mostly residing in the United States and Canada, as well as Balkan musicians residing in twelve other countries. The purpose of Moreau's survey was attempt to understand the interest in Bulgarian music and dance that has been steadily growing outside of the Balkans since the middle of the twentieth century (Moreau, 1990). Over three hundred people responded to his survey, and of that population, 36% reported that their professions were in the scientific domain of engineering, mathematics, physics, or computer science. Moreau reported that 51% of the respondents were female, but he did not report on the distribution of women in scientific professions.

Melissa Miller, an American scholar in Balkan and Middle Eastern music and dance, who is also a clinical psychologist in Mountain View, California, did a similar survey at the Mendocino Woodlands Balkan Music and Dance Camp in July, 1994, and published the results in a paper entitled, "Who are These People, and Why do they Dance?" (Miller, 1994). Balkan Camp has been in existence for more than thirty years, and draws participants from all over the United States. A number of professional musicians from Balkan countries of Bulgaria, Macedonia, and Turkey attend the camp as well, some as teachers, others seeking professional connections with musicians in the United States. In the summer of 1994, 200 people attended this camp, and 121 answered Miller's survey. Twice as many women as men responded to the survey (80 women, 41 men), mainly between the ages of 25 and 55. Although virtually every one who attends this camp participates in the Balkan folk dancing during the evening parties, 85% of the men and 66% of the women said they were there primarily to study music, with more women specializing in vocals and more men concentrating on instrumental music.

Miller found 60% of the men and 23.3% of the women in her survey identified themselves as having professions in science or engineering, and 6.7% of the men and 16.3% of the women identified themselves as being in medical professions. She also found a large number of campers in education fields (11 men and 43 women), but of these educators, 25% (14 people) identified as science teachers at the secondary or higher levels. Combining men and women, in all science-related professions (science, engineering, medicine, and science education), 60% (73 out of 121) of the adult campers in Miller's survey identified as working in a science-related field in 1994.

During the spring of 2006, I sent an email survey to three international mailing lists of folk dancers and musicians, requesting members to respond to a Dance and Physics questionnaire. Forty five people responded to the detailed questionnaire. Two-thirds were living in the United States, near moderate to large urban centers, the remaining third were distributed between Europe (18%) and Turkey (6%); 60% were male and 40% female; 76% were over 46 years of age, and only one of the respondents who was under 36 years of age was American. 61% of the respondents in my survey reported that they work in physics, chemistry, engineering, math, or computer science, which is similar to Miller's (1994) results. This figure includes those who said they are currently retired, those who are currently students, and those who had multiple fields, such as science and business (i.e., engineers who ran their own businesses). Although my questionnaire inquired about dance and physics, a number of people commented that they also considered themselves to be Balkan musicians, and suggested that I should have included the connections between physics and music in my questions.

Two styles of recreational folk dance were represented in my survey: Balkan dance, primarily from the countries of Bulgaria, Macedonia, Serbia, Croatia, Greece, and Turkey, and contra dance, which is an American derivative of English country dance and French *contredance*. Both of these dance forms are very pattern-oriented, and intimately related to the musical structure, and both are very community-oriented. I will first give a brief description and comparison of the two dance and music styles before reporting on the χ^2 statistic and some individual comments of respondents.

Balkan dances are done in a long curving line of people holding hands (*horo*). It is common for the musicians to play one piece for ten minutes or more, so that the repetition may become almost meditative. The music is characterized by complex asymmetric rhythmic patterns, such as 11/16, 7/8, 5/8, 9/8, and 12/8. The traditions behind the dances are centuries old, and the origins of the dances are obscure. There are fascinating stories behind many of the tunes and choreographies, which trace themes from Balkan history. The melodic lines in the older tunes are based heavily on Ottoman *makam* tuning, which utilizes half tones and quarter tones, quite unlike western European folk tunes or western classical music. Some musicians play modern instruments such as accordion, however the traditional instruments which are most often used in Balkan music include zurla, kaval, duduk, and gaida (wind), and tambura, oud, cumbus, and gadulka (string). Percussion is also quite important in Balkan music, the most common drums being the large tupan and Arabic darabuka.

Contra dance, one of the few American folk dance styles, is based on very simple, symmetric rhythmic structure in which the meter is always 4/4. There are sixty four bars of music in every tune, usually a primary melody ("A") and a variation on this melody ("B"), so that every contra dance predictably follows a musical structure of "A-A-B-B." The musical style is predominantly based on folk tunes from Celtic, Irish, Appalachian, or Blue Grass traditions, and the instrumentation is familiar to western ears (typically some combination of guitar, banjo, fiddle, bass, and keyboards). There is always a caller, so there is no need for participants to memorize choreography. Although the music is simple, the choreographic structure relies heavily on the accomplishment of intricate spatial patterns, performed by men and women in two opposing lines, which repeat every sixty four measures, shifted by one or two places along the line (translational symmetry). Many of the choreographic elements are similar to Scottish country dances, which are also done in sets with even numbers of men and women.

Thus, both Balkan dance and American contra dance rely on patterns in space and time. Music and dance in the Balkans relate more to asymmetry in time and simplicity in space, while contra dance, with very simple musical and rhythmic structures, relies on complex symmetric patterns woven in space by the movement of bodies. Both styles apparently have a high degree of appeal to people who also are attracted to logical / mathematical thinking. This was suggested by Gardner (1985), who correlated logical / mathematical and spatial / kinesthetic aspects of bodily intelligences.

I investigated this apparent correlation by calculating a χ^2 statistic for my survey data, using the 2000 United States Census Bureau figures as the standard comparison group. According to the 2000 census, among people who reported themselves as professionals, 27% held jobs in science, engineering, or related fields, and 73% held non-science-related jobs, while in my sample of forty five recreational folk dancers, 61% held jobs in science, engineering, or related fields and 39% held jobs in other fields. Assuming a null hypothesis that there is no correlation between recreational folk dance (Balkan or contra) and physics-related work, the proportions of folk dancers who hold physics-related jobs *should be* similar to a comparison group of working professionals of similar socioeconomic status. The χ^2 of 29.2, (degrees of freedom = 1, $\alpha = .001$, with the probability of $\chi^2 = 29.2$ for $df = 1$ being less than 10^{-6}) indicates that there is less than .001% chance that the null hypothesis is correct, meaning that it is *very unlikely* that there is *no* correlation between people who enjoy folk dancing and work in a physics or math-related field.

When asked the question, “Are there similarities in the way you experience dance and physics or math?” the respondents most frequently cited an appreciation of symmetry and patterns, a satisfaction which is similar to solving a math problem, complexities of Balkan rhythms, and the sense of losing track of time which they felt in dance and in math. Some of the individual comments are excerpted below. (Full report currently available at http://www.physics.ucsb.edu/~jatila/symmetry.html.)

> I find patterns and structures truly fascinating. Both physics and dancing (and music making) have plenty of that.
>
> For Balkan folk dancing, it is the complex dance sequences and odd beats that are challenging to me as math /physics problems are.
>
> It has the same feel of solving a problem. It is about spatial relationships, which is the essence of math. It may be why folk dancing is has a high proportion of math/science types.
>
> Concentration and creative problem solving is what they have in common for me.
>
> There is a kind of magic that happens when you put it all together with the music that is similar to a research problem. You break it down into pieces and then the flash of insight comes when you identify new relationships
>
> There is beautiful symmetry in music, math, physics, and dance. Dance and music in the Balkans is the abstract brought to life, the spirit of the subtle nature of complex rhythms and musical themes manifested in an audio form that gives us an opportunity to move with it and experience it directly. Applied physics in a way.
>
> Symmetry in physics is one property which is very important, and in dancing it has a super importance also.
>
> In Balkan folk dance it is the complex dance sequences and odd beats that are challenging as math/physics problems are.

The results of these three surveys suggest that there is a correlation between an affinity for math/physics and music/dance, as suggested by Howard Gardner (1985), and thus it may be possible to utilize these natural correlations to reduce the public perception that math and physics are to be feared and avoided.

3.1.2. The Math of the Waltz: Engineering & Dance at Stanford University

At Stanford University there is a large dance program that includes ballet as well as folk styles from several countries, including the American folk and social dance forms known as *Vintage Dance.* A decade ago, one of the dance instructors (Joan Walton) noticed that there was an unusually high percentage of students in the social and vintage dance classes who were engineering majors, to the extent that the university newspaper was printing cartoons about these students (Walton, 1998). She observed dance and engineering classes, and interviewed eight students in depth, and concluded that, in the group of students she studied, there were definite correlations between bodily/kinesthetic perceptions, spatial awareness, and logical/mathematical thinking. She also noted that the director of the social dance program at Stanford, who also directs the performing ensemble in Vintage Dance, is himself a graduate of the Stanford School of Engineering (Richard Powers). Walton reported that 23% of the student body at Stanford was enrolled in the School of Engineering, while 52% of the students in the Social Dance II class were engineering majors. The percentage of engineering majors per dance class increased in the upper division dance classes, up to a maximum of 60% engineering or science-related majors who were members of the performing ensemble in Vintage Dance (Walton, 1998). These figures are similar to the percentages I found in my study (van der Veen-Davis, 2006).

Walton interviewed a number of her dance students who were engineering majors and found two prevalent themes in their reported feelings about dancing: (1) they related to the musical and spatial patterns through their understanding of mathematics; and (2) they valued and cherished the balance in their lives that dance, particularly social dance, provided. Walton reported that the students she interviewed displayed a high degree of spatial, musical, and bodily/kinesthetic, as well as mathematical/logical intelligence, and a preference for learning by analogy. She quoted some of her student-informants:

> One Aeronautics & Astronautics major puts it very neatly: "Music and math are one. Music is humanized math, basically."
>
> A Computer Systems major more concretely says, "I think mathematically for the Lindy. I use numbers. I hear a downbeat and know I have seven more beats to do something before the rock step comes back."
>
> One Mathematics major wrote about "The Math of the Waltz." She says: "Waltz is by far the most logical dance and the most geometrically designed as well. It resembles a sine and cosine wave proceeding together <…> I bring up this analogy because a cosine wave is a sine wave shifted half a Pi in time, and so is Waltz, if we view the man as the sine wave and the woman as a cosine wave. The beauty of it comes from the fact that unless the partners understand that it must be completely symmetrical, it does not work." (Walton, 1998).

The study by Walton at Stanford was prompted by her taking notice of the unusually high percentage of engineering majors in the social dance classes. She did not make specific recommendations for education based on these findings, choosing instead to simply report on two main observations: some of the students in her study reported that dance helped them balance their lives, since the social experience and classroom interactions in their engineering classes and dance classes were completely different; and all of the students in her study reported correlations between dance/music/kinesthetic/spatial reasoning and mathematical / logical reasoning which made this dance form appealing to them.

If we combine the affinity for logical / mathematical reasoning and dance observed by Walton (1998) among engineering students at Stanford, and the similar observations by Moreau (1990), Miller (1994), and myself (2006) among professional adults who work in physics-related fields, with the recommendations by education theorists such as Eliot Eisner (2002) who advocate for the blending of arts and sciences in education, then it seems appropriate to ask whether we can use the general human affinity for dance, music, and art to teach subjects like mathematics and physics. When I began to investigate the question of interdisciplinary science and arts education, I found examples of programs which combine one or more of the fine arts with science, math, or engineering which have been in existence for fifteen years or more.

3.2. Aesthetic Principles and Interdisciplinary Arts and Sciences Education

Before discussing interdisciplinary arts and sciences programs, or the research on the organization of successful interdisciplinary programs, let me refer back to the title of this project: Symmetry and *Aesthetics* in Introductory Physics. Aesthetics is most often associated with arts, but it need not be, and although interdisciplinary education is likely to be aesthetic, it need not espouse the philosophy of aesthetic education. Paraphrasing the definition of aesthetic education of Maxine Greene, which I quoted in Chapter One, aesthetic education is

> the intentional undertaking designed to nurture appreciative, reflective, cultural, participatory engagements with the arts … such that … new connections are made in experience; new patterns are formed, new vistas are opened. (Maxine Greene, *Variations on a Blue Guitar*, 2001).

Thus, for an interdisciplinary program to be aesthetic, these outcomes must somehow be embodied in the program, whether explicitly stated, or implicit in the results for the students and faculty involved. But – how can we recognize an aesthetic interdicsiplinary program? One additional point from my Dance and Physics Survey is worth mentioning in the context of recognizing the effects of an education which is <u>not</u> aesthetic.

In response to the questions, “Who first inspired you to dance? Who first inspired in you an interest in science?” 54% of the respondents said they were first inspired to dance by a family member or friend, and 33% by an inspirational teacher. Regarding science, 48% said their interest came from a natural childhood interest in math and science, 15% said they were inspired to pursue science by family members who were scientists or engineers, such as fathers, uncles, and in one case an aunt, 15% said it was the practicality of earning a living that led them to science or engineering, but *only 8.7% cited an inspiring teacher*. One male folk dancer, who works as a software engineer, added the following comment:

> Time, and the enigma of an infinity of infinities started to fascinate me by age 14, but the brutal way math was taught at my school left me with no understanding.

This comment is similar in feeling to sentiments that were echoed by some of the art students who took my course, during their post-course interviews, and are the kinds of experiences that aesthetic education seeks to eliminate.

3.2.1. Organizational Strategies of Successful Interdisciplinary Programs

Project Zero was founded in 1967 at Harvard University's Graduate School of Education, to study and promote the incorporation of arts into all areas of education, and to advocate that arts learning should be treated as a serious cognitive activity, equal to any other academic discipline (http://www.pz.harvard.edu accessed August 24, 2007). Since 2000, researchers at Project Zero have been studying successful interdisciplinary programs at the secondary and college levels. Their focus is not on aesthetic education, but is built on the cognitive model of Howard Gardner's Multiple Intelligences Theory (Gardner, 1985).

Svetlana Nikitina of Harvard University's Project Zero identified three organizational strategies of successful interdisciplinary curricula, based on their different pedagogical approaches: contextualizing, conceptualizing, and problem solving (Nikitina, 2002). Contextualizing, or context building, she said is the humanist approach, a method of embedding disciplinary material in a fabric of time, social context, or personal experience, such as the history of science, epistemology, or metaphysical philosophy. Contextualizing is the approach taken when the goal is to humanize knowledge, engaging in a humanities-based inquiry, such as is commonly used in history, philosophy, and literature (ibid.). She cited a course at San Francisco State University in which the scientific theory of the development of the atomic bomb was taught in the context of the exodus of scientists from Nazi Germany during World War II as an example of an interdisciplinary program where the goal was to humanize science by contextualizing it in history.

Another type of contextualizing, according to Nikitina, is epistemology, in which students are encouraged to question how knowledge is produced. She cited examples of Theory of Knowledge courses which were created by the International Baccalaureate (IB) Association, which are being taught in high schools in the United States which have adopted the IB program.

Conceptualizing, she said, involves identifying core concepts that are central to two or more disciplines, and establishing rigorous, quantifiable connections between them, such as evolution, periodicity, or linearity in biological, geological, astronomical, and chemical systems. Students exposed to interdisciplinary classes in which the theme is conceptualizing become adept at abstracting concepts from data and seeing the underlying patterns and processes that are common to different systems (ibid.). Conceptualizing is the method most often used to create connections between the sciences and mathematics, exposing the underlying similar patterns.

Whereas contextualizing aims to understand the commonality of human experience, conceptualizing aims to understand the commonality of physical laws, mathematical at their core, which underlie the phenomena we observe. Teachers whom Nikitina interviewed who use contextualizing interdisciplinary strategies stressed the need to make the connections explicit for students, not assuming that they automatically understand the underlying concepts.

The third strategy, problem solving, links strategies and ways of knowing from different disciplines to solve an open-ended problem, often aimed at improving some aspect of the human condition, such as stopping the spread of AIDS or global warming (ibid.). Problem solving as an interdisciplinary strategy seeks a tangible outcome by linking several disciplines, with a pragmatic orientation, utilizing applied science and technology, sometimes with the incorporation of arts-based disciplines, to solve a problem or develop a new product. Whereas the goals of contextualizing and conceptualizing are to advance fundamental knowledge, the goal of problem solving is to draw upon a range of disciplines to attack a common problem. Nikitina cited the Toy Symphony project of MIT's Multimedia Lab as an example of a problem solving interdisciplinary approach, in which musicians, composers, computer programmers, engineers, and graphic artists come together to create computerized toys and software for children to learn music.

Nikitina's analysis of interdisciplinary strategies is useful as a kind of taxonomy for designing interdisciplinary programs, and she recommended that instructors combine strategies for a maximally effective interdisciplinary course. After reviewing interdisciplinary strategies and Maxine Greene's definition of aesthetic education as exclusively art-based, I have come to understand that the most effective courses should combine elements of both interdisciplinary and aesthetic education.

3.2.2. Interdisciplinary Aesthetic Education

Once I started investigating, I found a number of examples of interdisciplinary programs in high schools, colleges and universities, many of which also embody the principles of aesthetic education, according to Greene's definition, even if they did not state their goals explicitly as aesthetic. I also found an example of a program that utilizes organizational strategies of interdisciplinary education, and embodies the principles of aesthetic education by making new connections, although remaining within the subject domain of physics. I will discuss (briefly) two high schools, one college course, two undergraduate programs, and one large graduate program which embody aspects of interdisciplinary as well as aesthetic education, and one middle school in Los Angeles where two teachers are collaborating with each other to bridge the gap between arts and sciences.

3.2.2.1. Illinois Math and Science Academy: Focus on Interdisciplinary

At the Illinois Math and Science Institute (IMSA), founded in 1985 by Nobel Laureate Leon Lederman (former director of the Fermi National Accelerator Laboratory), the focus is on interdisciplinary education, with science, math, and technology as the axis about which the rest of the school revolves. The interdisciplinary organizational strategy of the school as a whole, as presented on the website (www.imsa.edu), is Problem Based Learning (PBL), which is defined as

> …an educational approach that organizes curriculum and instruction around carefully crafted ill-structured problems. Students gather and apply knowledge from multiple disciplines in their quest for solutions.

The goals of the academy are explicitly science-oriented:

> The internationally recognized Illinois Mathematics and Science Academy® (IMSA) develops creative, ethical leaders in science, technology, engineering and mathematics. *(*www.imsa.edu, *accessed on August 26, 2007).*

Although there is an established arts program at IMSA, it appears to complement, rather than be integrated with, the overall science mission of the school. The principles of creativity, aesthetics, culture, and appreciation which are described under the arts program, make no direct mention of incorporation of art into science, according to the publicity information available on the IMSA website (ibid.). On the other hand, the stated goals of the program are sufficiently broad so as to allow for individual teachers to collaborate, and integrative learning experiences are encouraged. The claim on the IMSA website declares, *" Our students become leaders who understand that knowledge crosses disciplines and has real world applications*" (www.imsa.org). Fine arts courses, however, are listed as electives, and do not count towards fulfilling the minimum number of required units each semester.

Nikitina (2002) observed and reported on one of the interdisciplinary courses at IMSA, the Perspectives Seminar, in which the instructor took a historical approach (contextualizing), presenting the emergence of western scientific thinking in the late Renaissance by incorporating elements from astronomy, astrology, geometry, metallurgy, painting, geography, and shipbuilding from that time. Other topics reported by Nikitina which form core contexts for other IMSA Perspectives Seminars include seminal questions such as, "Why is it necessary to understand St. Augustine to understand Isaac Newton?" (ibid.). Two courses listed on the website of the IMSA history department appear to be interdisciplinary, although no information was available as to the specific content of each: *Mind and Cosmos: A Cultural History of Astronomy*, and *Genesis Rewritten: A Cultural History of Biology and Natural Science*, both taught by Dr. Rob Keily (http://staff.imsa.edu/socsci/).

In conclusion, the Illinois Math and Science Academy is a private, honors academy for grades ten through twelve, which revolves around the development of sound scientific and mathematical skills, with attention to how science is a cultural endeavor, embedded in society. The program is interdisciplinary in its goals, outwardly focusing on problem solving (according to the information distributed on its website), though certain courses use interdisciplinary strategies of contextualizing, as described by Nikitina (2002), who visited the school. There appears to be a robust arts program which operates independently of the science mission of the school, although its prominent web presence gives the impression that the arts at IMSA, though separate, are highly visible. It is somewhat disappointing to read that arts courses do not count towards the minimum requirements each semester.

3.2.2.2. High School for Art, Imagination, and Inquiry: Focus on Aesthetics

The Lincoln Center Institute (LCI) is an independent arts-in-education advocacy organization that was founded in 1975 to promote arts across the curriculum in all levels of education. Situated within New York City's Lincoln Center for the Performing Arts complex, LCI is based on the philosophy of Maxine Greene and John Dewey (www.lcinstitute.org). In more than three decades of operation, LCI has given numerous workshops, training classroom teachers on the goals and methods of aesthetic, arts-based education, and training artists to work in public schools with teachers and students. Maxine Greene is the "Philosopher-in-Residence" of the LCI.

New York City's High School for Arts, Imagination, and Inquiry (HSAII) was founded in 2005 by the members of the LCI, including Maxine Greene, and is located across the street from the Juilliard Music Academy, within the Lincoln Center for the Performing Arts complex. Currently located in the basement of a building that it shares with other groups, as of Fall, 2007 HSAII has an enrollment of 200 students in grades nine and ten (http://schools.nyc.gov/SchoolPortals/03/M299/default.htm). Entering its third year of operation in Fall, 2007, it does not yet have a physics program (personal communication from HSAII program coordinator Sarah Feeley, November 7, 2006), although the goals are eventually to incorporate arts as a focus of all areas of academics, including math and science (Holzer, 2005).

Art, music, and dance form the axis about which the rest of the academic program revolves. Based on the philosophy of its parent organization LCI, the educational focus at HSAII aims to uphold the practice of aesthetic education through "*art-making explorations in dance, music, theater, and visual arts, to encourage students to integrate their prior experiences and perceptions to create new understandings, and ask further questions that might reshape their world* " (ibid., p. 1). Rather than learning 'art for art's sake' or subordinating art as a vehicle for teaching other subjects, this approach is intended to incorporate elements of both (ibid.).

To facilitate curriculum development at the new arts-based high school, a planning committee which included Maxine Greene designed a set of criteria to serve as points of reference for teachers and students as they co-create a new arts-based learning environment. These criteria are called the Capacities for Aesthetic Learning, as opposed to a term such as "skills" or "knowledge," to indicate that what can be learned from studying works of art is not finite. These Capacities for Aesthetic Learning are: Noticing Deeply, Embodying, Questioning, Identifying patterns, Making connections, Exhibiting empathy, Creating meaning, Taking action, and Reflecting/Assessing which, rather than the endpoint, is meant to be the beginning of another inquiry (Holzer, 2005). Although originally intended as guidelines for the development of arts-based curricula, these Capacities could serve as points of reference for designing a program of aesthetic education in any subject.

Next, I will examine four college and university programs which embody aspects of interdisciplinary as well as aesthetic education.

3.2.2.3. Lies and Damn Lies: The Art of Approximation in Science

Professor Sanjoy Mahajan, formerly a member of the Physics Department at the University of Cambridge but currently (as of Fall, 2007) at MIT, has developed a thematic physics course, in which he teaches introductory physics in the context of political science, with the goal of raising issues of social justice. His course "Lies and Damn Lies: The Art of Approximation in Science" (http://www.inference.phy.cam.ac.uk/sanjoy/mit/ ; accessed on August 23, 2007) utilizes Nikitina's interdisciplinary strategies of contextualization and conceptualization: approximation and scaling laws are the unifying concepts, and the context is the political impact of physics. Mahajan's premise is that the physics community is responsible for much of the war machinery that exists in the world, and if educators can eliminate fear of physics, it would help reverse the inequities of a hegemonious society (Mahajan, 2004). His goal in contextualizing physics in terms of social justice is to teach students that they should not be afraid of math and physics because it is their way to fight back, so to speak (ibid.). In his course "Lies and Damn Lies," each of the topics of approximation, scaling laws, dimensional analysis, fluid drag, mechanical properties, thermal properties, waves, and weather is contextualized in terms of issues such as the environment, wasteful uses of oil, and nuclear weapons proliferation. Thus, Mahajan's approach is interdisciplinary according to Nikitina's organizing principles in that he uses conceptualizing (approximation and scaling laws) and contextualizing (social justice). His approach is not aesthetic according to a strict interpretation of Greene's definition, as he does not specifically incorporate art, however it qualifies as aesthetic under a liberal interpretation of Greene's definition, because of the connections and realizations which he hopes his students can apply to the rest of their experience. Interestingly, he has entitled his approach "*The Art of Approximation*."

Mahajan's approach is useful for students who already have some facility with mathematics, but may not be attractive for students who would otherwise not enroll in a physics course, as it assumes a level of familiarity with the language of math. Rather, his intention is to alert physics students to the potential consequences of irresponsible choices by scientists, and how to become socially responsible scientists themselves.

Although he did not include art specifically, Mahajan's approach lends itself to incorporation with arts, and his style invites imagination and open-ended questioning. His approach to approximation helps students develop a *feeling* for math as a way of knowing, which would make an excellent sequel for the introduction to numbers in nature with which I began my course. To emphasize trusting one's feelings and intuition with math, he enjoins his students, *"Talk to your gut"* (Mahajan, 1998).

Students' comments indicate that they appreciate the conceptual approach, as it unified ideas in physics for them, and is applicable to other areas of their lives. Many found it a playful way to approach physics, as exemplified by the following comment:

> learning how our problem solving methods applied to varied aspects of life made me feel like a child discovering the intricacy of the natural for the first time, and I was thoroughly engaged.
>
> (http://web.mit.edu/sanjoy/www/6.084-F2006/8.298-comments.html, accessed August 27, 2007*)*

3.2.2.4.Dartmouth College: Math Across the Curriculum

In 1995 Dartmouth received a National Science Foundation grant to pilot a series of interdisciplinary courses in which topics in mathematics were combined with topics from art, music, literature, and philosophy, which they called "*Math Across the Curriculum"* (MATC). The program had the following primary goals: to make math more relevant to students' lives; to increase students' confidence in mathematics; to enhance students' critical and analytical skills; to attract a larger and more diverse student population to study math; and to make interdisciplinary mathematics courses a permanent part of the Dartmouth College curriculum (Korey, 2000). During the first five year trial period, four hundred and forty students and fifteen faculty (eight from mathematics and seven from humanities and arts) participated. The interdisciplinary format attracted a range of students, from those who reported themselves to be "mathematically timid" to those who self-reported as being confident in mathematics, and were concurrently enrolled in upper division math classes.

The interdisciplinary courses in Dartmouth's MATC program were organized around the themes of contextualizing and conceptualizing, as defined by Nikitina (2002), and although the term aesthetic education was not explicitly mentioned, the program embodied the ideals of aesthetic education as defined by Greene (2001). The courses offered during this five-year trial period were: *Late Renaissance Thought and the New Universe*, which focused on the discoveries of planetary motion in the sixteenth and early seventeenth centuries, and the interactions between mathematical, scientific, political, philosophical, artistic and magical fields of discourse in the early modern period; *Pattern*, which explored the connections between symmetry, group theory, and art; *Geometry in Art and Architecture*, which explored the multiplicity of connections between mathematics and art; *Mathematics and Music*, including Fourier analysis; *How Many Angels?* which explored the mathematics and philosophy of infinity; *Chaos; A Matter of Time*, which used mathematics, literature, and the arts to explore time as a key concept and reality in the development of Western culture; *Mathematics and Science Fiction*; and *Renaissance Math in Fiction and Drama.*

The study team found that these courses attracted a more diverse population than their standard math courses, drawing students from a broad range of disciplines. In addition, they found that the interdisciplinary classes had greater female participation than the traditional math courses, which was particularly noticeable in the Patterns and Music courses. The first time the Patterns class was offered in Spring of 1996, 100% of the class was female; the second time it was offered, in Spring of 1998, the enrollment was 58% female and 42% male. Math and Music attracted an enrollment of 67% females and 33% males. The other courses were either balanced (Kepler, Time, Geometry in Art), or more heavily male (Chaos, Infinity, and Science Fiction).

The evaluation team reported that, based on the results of both surveys and individual interviews, these courses were largely successful in expanding students' understanding, awareness, and appreciation for mathematics (Korey, 2000, p. 11). Some of the most successful outcomes that were reported included the changes in students' outlook on mathematics in their daily lives, and seeing the world from multiple perspectives. A few quotes from the student interviews reported in the evaluation summary illustrate the positive effects of these courses:

> how to think more broadly, and look at things in a less than mainstream way, kind of off the beaten path, and just took a different approach to ordinary things.
>
> being able to look at whatever I do from different angles now,generally not seeing math for just being math but seeing its

> effects on humankind andconversely seeing the effects of literature on math, and how it's interpreted.
>
> Before, my concept of art was that the artist has the idea in his mind, and he creates his work on paper. But it was really incredible to me to see how very mathematical some of these painters thought, and how they created their work based on something other than imagination. It was very mathematical. I could see that they had thought very analytically about their painting, and that blew me away. I was like, wow, you know, math really is applicable to things other than just equations.
>
> I found ultimately was that the math component of music is what ties it to us as humans. The fact that it's regular, that we don't understand things that are completely random. And that we need to connect it to earth, we need to have some type of pattern
>
> The world is not divided into little groups. It's all very interrelated. So to have an education system that draws clear distinctions between math and sciencand English, it's very unrealistic. I don't think that that's the way for the majority of people to learn. I think the reason a lot of people shy away from math or science is because it's not like a tangible subject that you can relate to different aspects of your life. Which is very false.

One of the main goals of these courses, as reported by the faculty involved, was to explore the connections between two disciplines and to demonstrate the modes of thinking that facilitate the connections (ibid., p. 25). An important realization reported by the Dartmouth faculty was that, although some students were timid about math in the beginning, they wanted to improve their competence in mathematics, and it was this interdisciplinary environment which facilitated their feeling more confident about their math abilities. *"Few students like feeling handicapped in math, and they seek the opportunity to demonstrate that they can learn new math"* (ibid., p. 27). This outcome is similar to the comments that I received from the art majors in my course, namely that they had either not liked or been afraid of math and physics before, but now wished to learn more math and physics *in such an integrated environment*.

The conclusion of the Dartmouth study was that students perceived that mathematics can illuminate humanistic subjects, that math is a creative endeavor which is useful in all fields, and that students in the program gained an increased confidence in their ability to do math, and a new openness to mathematical thinking (ibid., p. 27). These remarks are similar to those of the art students in my course, regarding their attitudes to both physics and mathematics.

Another interesting and serendipitous similarity between the Dartmouth study and my course is that both attracted similar bimodal populations students: the Dartmouth courses in the Math across the Curriculum program attracted math majors and arts/humanities majors, and my course, Symmetry and Aesthetics in Introductory Physics attracted physics majors and arts/literature majors. Both the Dartmouth courses and my course utilized a combination of reading, writing, problem solving, art explorations, and interactive classroom strategies.

The MATC program at Dartmouth has ended, although the information can be found at the website http://www.math.dartmouth.edu/~matc/. The interdisciplinary curricula from the original courses at Dartmouth, as well as links to interdisciplinary courses at other universities, are now available for direct access via the Internet through Dartmouth's "*Electronic Bookshelf*," which can be found at the website http://www.math.dartmouth.edu/~matc/eBookshelf/index.html. The original MATC pilot study has been replaced by a larger program, the Center for Mathematics and Quantitative Education at Dartmouth, which distributes the MATC curriculum materials via the Internet, and is dedicated to improving math literacy at the K-16 levels. This program can be found at the website http://www.math.dartmouth.edu/~mqed/index.html. Thus, this interdisciplinary math-and-humanities program at Dartmouth can be considered to have been successful in that it has now been expanded beyond its original scope, and the materia

3.2.2.5. Interdisciplinary Center for Arts and Technology at Connecticut College

The Ammerman Center for Arts and Technology at Connecticut College was founded in 1984 for the purposes of bringing together faculty and students to explore the connections between technology and the arts (http://cat.conncoll.edu/aboutus.html). In creating the center, faculty wanted to give undergraduates the opportunity to do interdisciplinary research, which is usually reserved for graduate students. A quote from the Center's website summarizes the philosophy of this program:

> Through interdisciplinary collaborations and individual work, students and faculty not only promote proficiency in working with technology, but also deepen the understanding of the meaning and role of technology within the larger context of the liberal arts. (From http://cat.conncoll.edu/mission.html, accessed Aug. 24, 2007).

The role of the Center is to act as an interdisciplinary hub for disciplines such as computer science, visual arts, music, mathematics, theater, dance and physics (Izimrli and Baird, 2002). According to Nikitina's classification, the interdisciplinary program is built around the theme of problem solving, as the goal is the completion of a technology-based work of art, which comprises the senior project. The Center is also promoting Greene's model of aesthetic education in that its stated goal is to promote the forming of new connections. Although the words aesthetic education are not specifically used, the goals are both interdisciplinary as well as aesthetic.

The center offers a certificate program, in which students can enroll in addition to their major programs of study. Most students in the certificate program have majors in either arts or computer science, although a few come from other disciplines such as economics, languages, or literature (ibid.). Students in the certificate program are required to take a core curriculum of arts, computer science, and the history of art and technology courses, as well as complete a senior project. Examples of projects created by students include computers and music, film and animations, choreography and computer-generated music, computer-generated sculpture, and sound-sensitive sculpture. All students place their projects and results on web pages, some of which can be found at the website http://cat.conncoll.edu/projects.html, (last accessed August 24, 2007).

The faculty have noticed an interesting beneficial outcome: students who enter the Connecticut College program with more experience in arts and are initially uncomfortable in a science-based environment, after taking courses in computer science, express their surprise at their newly-discovered abilities in technology-based fields. Many of these students change their major to computer science as a result. The Connecticut faculty find that this process works in reverse as well, in that students who enter the program from computer science find they have an affinity for music and a sense of aesthetics of which they were previously not aware (although they do not report that these students switch their majors from computer science to an arts major). The faculty who teach in the Center work to dispel stereotyped images of "insensitive geeks" or "illogical artists" (ibid., p. 105). Similarly, in my course, the art majors expressed surprise at their newfound abilities in physics, where they had been uncomfortable with physics in the past, and the physics majors found new avenues to explore in aesthetics. Both groups came to these realizations on their own, as a result of working together, which dispelled previously-held stereotypes of the other. Both these findings are similar to the results reported by the Dartmouth faculty, in which humanities students previously uncomfortable with math grew more confident in math as a result of their interdisciplinary, aesthetic math courses.

3.2.2.6. The Toy Symphony and Other Projects at MIT's Media Lab

The Media Lab at the Massachusetts Institute of Technology (MIT) was first conceived of in 1980 by Professor Nicholas Negroponte and former MIT President and Science Advisor to President John F. Kennedy, Jerome Wiesner, and first opened its doors to students in 1985 (http://www.media.mit.edu/?page_id=16). The Media Lab is a large research and teaching program with over forty full-time faculty, as well as faculty who hold joint appointments in other departments, 135 graduate students (masters and doctoral), and 150 undergraduates who work in the lab for research credit towards their majors.

The Media Lab brings together the disciplines of computer science, music, art, kinesiology, human cognition, health, and psychology which revolve around the common axis of finding new ways to utilize computers and artificial intelligence to create a better society. Using Nikitina's taxonomy of organizational principles for interdisciplinary programs, MIT's Media Lab *assumes* the conceptual and contextual connections between technology and every phase of life, and actively focuses on interdisciplinary problem solving. Although there is nowhere on the website, or in the publications of the lab which I found, in which the term aesthetic education is ever used, the results of the collaborations all embody Greene's criteria for aesthetic education.

According to the Media Lab website, in its first decade the concentration was on innovative research in the computer-human interface, ranging from cognition and learning, to electronic music, to holography. In its second decade, the concentration was on wearable computing, wireless communications, machines with common sense, new forms of artistic expression, and innovative approaches to how children learn. In its third decade, the focus of the lab is on human adaptability, using computers to understand and treat conditions such as Alzheimer's disease and depression, designing sociable robots that can monitor the health of children or the elderly, and the development of smart prostheses that can mimic–or even exceed–the capabilities of biological limbs. The Media Lab website describes their interdisciplinary program as "*Media Arts and Sciences*" as follows:

> Media Arts and Sciences signifies the study, invention and creative use of enabling technologies for understanding and expression by

people and machines. The field is rooted in modern communication, computer and human sciences (http://www.media.mit.edu/?page_id=32; August 24, 2007).

Although currently the Media Arts and Sciences (MAS) program offers only graduate degrees, undergraduates who wish to participate in the program may do so as early as their freshman year. They attend regular classes in the core freshman subjects, but attend separate recitation sections in chemistry and physics taught by MAS instructors, which emphasize the connections between the subjects of physics and chemistry and current Media Laboratory research. Students in the MAS program also take two focused courses, a design-oriented seminar and a seminar on carrying out research and documenting results, in addition to their regular major programs. Undergraduates have the opportunity to participate with graduate students and faculty on their research projects, through the university's Undergraduate Research Opportunities Program

The current research projects at the MIT Media Lab range from developing a prosthetic foot with the complete articulation of a human ankle, developing new performance technologies for music and opera, using computers to quantify the human experience of the enjoyment of music, using computer interfaces to understand how people learn movement, and using computers to understand and alleviate symptoms of depression, Alzheimer's disease, and autism spectrum disorders. Two projects in particular that I will describe focus on using computers to develop or enhance children's creativity, demonstrating how computer and engineering technologies can be natural components of children's creative experiences. These are the interactive toys "*Robo*" and "*Topobo*," and the Toy Symphony project.

The Robo and Topobo project is built around the idea that technology and engineering should become natural components of children's creative and play processes. Topobo is a Lego-like creature which possesses artificial intelligence. A user (child) puts it together, and then "teaches" it to move in certain ways by moving its body and appendages, and recording the motions using Robo, a small hand-held computer which acts like a remote control device. Robo is capable of storing up to four independent movement schema, which the child can play back in sequence, changing the direction, frequency, and amplitude of Topobo's movements. The goal of this project is to allow children to explore performance and storytelling by constructing a Topobo creature, programming it with the Robo device, and then utilizing it to enact a story, resembling a robotic puppet theater performance. With the combination of Robo and Topobo, the designers hope to emphasize the organic and emotionally engaging aspects of robotic design, making engineering lessons implicit in a child's creative process (Raffle, Yip, and Ishi, 2006). A video of a Robo and Topobo in use by a child is available at the website http://www.rafelandia.com/topobo/robo (accessed August 24, 2007).

The Toy Symphony is an international music education project, led by composer and inventor Tod Machover at the MIT Media Lab, which is designed to bring children and professional performers together to create a symphony performance. At the heart of the project are robotic, computer-based instruments, which respond to gesture and movement called "Beatbugs" and "Shapers" (http://www.toysymphony.net/), and a graphic interface software tool for composing music, called "Hyperscore" (Harmony Line, Inc.). Beatbugs are hand-held devices that resemble computer "mice," which can be used alone or networked to create percussive sounds by moving the devices through space. When networked, Beatbugs can be used to create dynamic and collaborative percussion compositions. Shapers are soft, deformable, objects made of colorful material with conducting embroidery. Children can move, squeeze, and stroke the Shapers to create musical sounds. Shapers allow children to explore parameters such as pitch and timbre, and create interactive musical compositions. Shapers and Beatbugs together permit children to collaboratively and interactively create musical compositions which combine the elements of melody and rhythm.

Machover and his graduate students have given workshops in the United States, Europe, and Japan, in which they have taught children to use Beatbugs and Shapers. Each workshop, which consists of several hours per week for one to three months, culminates with a performance of the children with a professional orchestra, such as the New York Philharmonic, which gives the children the experience of performing music in the authentic environment of a concert hall. Machover stated that one of his primary goals in creating this type of performance was to bring together “disparate and improbable collaborators” of children, symphony orchestras, and virtuoso soloists, to create a pleasing performance experience for performers and audience (Machover, 2004).

Machover and his graduate students have also used their Hyperscore software to benefit patients suffering from mental disorders such as Alzheimer's disease, autism spectrum disorders, and depression in hospitals who, after several months of training sessions in a computer lab learning to use Hyperscore to compose short pieces, showed signs of medical improvement (Machover, 2004).

The Toy Symphony and Robo and Topobo are only two of many interdisciplinary projects at the MIT Media Lab which combine arts with technology. I have chosen to focus on these two projects because they demonstrate the potential benefits of combining arts and engineering with children, who have not yet learned to be afraid of math and physics. The results of the Media Lab projects relate back to the statement by physics professor Kenneth Laws, quoted earlier in this chapter, in which he said, "if dancers have not yet learned to fear science, they are open to the benefits and joys of this analytical level of understanding" (Laws, 2002, p. viii). Laws' statement can be re-interpreted in the context of the Media Lab studies to indicate that the incorporation of arts with math, science, and engineering has the potential to prevent children from growing up to fear math and science, if the intervention sufficiently early. The studies at Dartmouth and Connecticut College and, as I will demonstrate, my own study with students at UCSB, indicate that even for college students who have learned to fear math and physics, intervention with arts can reverse their fears.

I began this chapter by discussing the correlations between physics and folk dance that have been observed in adults and college students at Stanford University; I will conclude with a discussion of my site visit to Millikan Junior High in Los Angeles, where a folk dance teacher and a physical science teacher are collaborating to create connections between dance physics in the minds of their young students.

Constrained by the requirements of their public school system, each of these two teachers strives to build mental connections between dance and physics by incorporating discourse from each other's way of knowing into his own teaching practice.

3.3. A Day of Dance and Physics at Millikan Middle School, Los Angeles

The Millikan Performing Arts Magnet is a program of approximately 400 students, contained within Millikan Middle School, a public middle school in Los Angeles. A magnet program in California public schools is identified as one which offers a specialized program that is not available elsewhere in a particular school district, but which is open to all students by petition. Students from from outside the district can attend, also by petitioning. The demographics of the Millikan Performing Arts Magnet for the 2006-2007 school year, according to the public information available from the website of the Los Angeles Unified School District indicate that of the 389 students in the program, 40.6% were white, 39.1% were Hispanic, 12.1% were African American, and 8.2% identified as Asian, Native American, or Filipino (http://search.lausd.k12.ca.us/cgi-bin/fccgi.exe?w3exec=school.profile.content&which=8238). These numbers have been fairly stable over the past five years. The total attendance was listed as 94.69%, with no expulsions.

The demographics of Millikan Middle School for the 2006-2007 school year, of which the performing arts magnet is a part, indicate a total enrollment of 1611, with 50.5% white, 33.0% Hispanic, 10.2% African American, and 6.4% Native American Asian, and Filipino. Thus, compared to the general school, it appears that the magnet program attracts a larger portion of non-white students. Attendance is high in the general school, at 94%, and there were only three expulsions last year.

Within Millikan Middle School there are four academies: performing arts, sixth grade science, seventh and eighth grade science, and civic arts. The performing arts academy exists within the performing arts magnet, and students are accepted by audition only. Academy students specialize in dance, drama, or music. Qualified students may participate in more than one academy, such as performing arts and sciences.

In 2007 the Millikan Middle School received the prestigious California Distinguished Schools Award, thus the school in general is one of the better public middle schools in California.

On Monday, Oct. 23, 2006, I visited the ethnic dance classes of Mr. William "Billy" Burke at Millikan Performing Arts Magnet School in Los Angeles. The following data are based on my observations, and conversations with Mr. Burke and the physical science teacher, Mr. Beraru.

Mr. Burke's classroom is a large dance studio, with a raised wooden floor and mirrors on one wall, cabinets on one wall, and bleachers on the other. There are dressing rooms for the girls and boys on the side of the studio opposite the mirrors, which is also the side where the door and the teacher's desk and cabinets are located. On the wall outside the girls' dressing room are two racks of black skirts hanging on hooks; one rack has plain circular skirts for daily practice, the other has ruffles for practicing Mexican folkloric dance. The rows of practice skirts on the wall are reminiscent of aprons hanging in a science lab.

On the walls are a number of posters made by students depicting "The Physics of Dance" – two show the physics of the grande jete (big leap) and one shows the physics of a pirouette (rotation). As I talked with Mr. Burke before class, I learned that 'performing arts' is now a "Category f" requirement, designated as such by the Regents of the University of California as a U.C. entrance requirement. There are now content standards for dance in the California Education Frameworks, but there is, as yet, no credential for dance; dance teachers who wish to teach in public school must obtain a Physical Education credential. I also learned that Mr. Burke received a grant from the State of California to develop interdisciplinary lessons for middle school, combining dance, music, science, and history.

I observed all of Mr. Burke's classes for the entire day, which all followed a similar format: students "dress out" in the required uniform of white shirt and black pants for the boys, white shirt and one of the black skirts over black stretch pants for the girls. After attendance, the students go through a series of warm up exercises before practicing their choreographies or learning new dances. In between, the teacher discusses principles of performance, history, and physics with the students, who respond with questions, comments, and answers to his questions. The students talked about what it was like to perform: one girl stated that she noticed that "*kids 'put out' in performance more than they do in class*;" one boy stated that when he heard his group being announced when the students performed at a recent street fair, "*something snapped inside his head*;" another girl talked about what it was like for her to make eye contact with people in the audience. As a veteran performer myself, I could not help but be impressed with the natural wisdom expressed by these young students, ages twelve to thirteen.

The students also discussed correlations between dance and history, and how their science teacher talked about ligaments providing the forces for moving the body. In each class Mr. Burke reminded them of about centrifugal and centripetal forces, friction, inertia, and gravity in dance, and how walking is like "controlled falling."

In periods three and four (eighth grade) I was pressed into service to teach the girls some movements from North African and Egyptian dance which included body undulations and hip movements, which they were going to need for a choreography from Tunisia that was to be taught the following week. Being mostly unfamiliar with these ways of moving, the students expressed themselves by laughing quite a bit during this portion of the lesson!

In each dance class, although the choreographies being taught were different for the different levels, the format was the same: the students' dance practice was interspersed with the teacher's explanations and constant connections between dance, physics, history, and performing experience. At the end of the last class Mr. Burke discussed an upcoming open-notes test, which would include both dance and science terms that relate to dance.

After spending the day with Mr. Burke's dance students, I visited the physical science classroom of Mr. Beraru. I learned that he has a background in musical theater, taught elementary school for six years, then picked up some additional courses to teach physical science at the middle school level. In his classes he teaches a bit of chemistry, astronomy, and physics, and is a member of the local astronomy club. He assigns his students to make posters on "*the physics of whatever they like,*" whether dance, basket ball, baseball, surfing, or skate boarding.

Mr. Beraru also shared with me that he incorporates a great deal of the physics of ballet in his lessons, commenting that "*kids do a whole lot better when physics is related in this way."* We also discussed the practice of teaching math as a language. He expressed his concern that the math teacher "puts too many equations up all the time, and it scares kids off." He said that his approach is to “sneak” the algebra into the concepts, and then applaud the students. He said he tells them, “*See – you’re doing algebra and you did not even know it!*”

I was very impressed with the way each teacher has made an effort to learn terms from the other’s discipline and incorporate these terms into his own teaching, and each felt that the this interdisciplinary approach benefited the students. After my site visit, I sent them a copy of Kenneth Laws' book, *Physics and the Art of Dance* as a thank you gift, to assist them with further applications of physics and dance.

3.4. Reflecting and Assessing

I have come to believe that aesthetic education is interdisciplinary education in which the focus is on bringing together arts, math, language, and science as complementary and overlapping ways of knowing, for the purposes of opening up new realizations, patterns, and connections and ways of understanding - for students as well as teachers. Thus, aesthetic *physics* education should teach physics and the arts as overlapping and complimentary ways of knowing about the world, using the language of mathematics as a way of knowing about nature, rather than as a set of disembodied equations and problems to be solved. This should be the introductory experience, not reserved only for graduate school, or for students who are already enrolled in college as physics majors. Aesthetic physics education is the appropriate introductory course for the twenty-first century. In the next four chapters I will describe my course, and analyze the students' reactions, and samples of students' work, interviews, and video transcripts.

Chapter 4. An Experiment in Aesthetic Physics Education

> " I believe with Schopenhauer that one of the strongest motives that leads men to art and science is escape from everyday life with its painful cruelty and hopeless dreariness, from the fetters of one's own ever shifting desires. … This is what the painter, the poet, the speculative philosopher, and the natural scientist do, each in his own fashion. Each makes this cosmos and its construction the pivot of his emotional life…"
> (Albert Einstein, 1918, on the occasion of Max Planck's 60th birthday. First published in 1934; reprinted in English in 1954).

Symmetry and Aesthetics in Introductory Physics was designed to combine all three strategies of interdisciplinary education - contextualizing, conceptualizing, and problem solving - defined by Nikitina (2002), as well as the elements of aesthetic education, in the fullest interpretation of Greene's (2001) definition. As will be demonstrated in the next three chapters, new connections and realizations were opened up for the students by the teaching of art and physics together, and the creation of a major work of art (and smaller drawings along the way) facilitated seeing connections in math and physics in new ways. In this chapter I explain the organization of the curriculum, rationale for my decisions, and teaching methods.

4.1. Organization and Instructional Methods

The experimental course, Symmetry and Aesthetics in Introductory Physics (CCS-120), consisted of ten seminars of three hours each, and one official final exam period, which was used for final presentations. The class met every Friday afternoon from 1:00 to 4:00 PM, during Winter Quarter, 2007, at UCSB. Eleven students participated: seven science majors and four humanities majors. The students are listed by pseudonym, major, year, and college, in Table 4.1.

Student	Major	Year	College
Al	Physics	4th year	CCS
AT	Physics	1st year	CCS
Beatrice	Painting	3rd year	CCS
Charlie	Physics	4th year	CCS
Frank	Physics	1st year	CCS
Juno	Sculpture	3rd year	CCS
Manny	Physics	1st year	CCS
MKS	Literature	1st year	CCS
Sam	Geophysics/ East Asian Studies	4th year	L&S
SS	Physics	1st year	CCS
Victor Eremita	Book Arts	3rd year	CCS

Table 4.1. Students in CCS-120

4.1.1. Organizing Principles of the Course.

The organizing principles around which I based the course were two: starting with symmetry and contemporary physics instead of classical physics; and integrating physics with fine arts. As has been discussed in Chapter 1, contemporary physics is not only intrinsically interesting as a starting place for the study of physics, but considerations of symmetry, and investigations of spacetime which are important in contemporary physics, are also fundamentally important in art, and thus provide a natural connection between physics and the arts. This connection was also motivating to students, as they said in post-course interviews:

> **Beatrice:** In art, the three main subjects you talk about are time, space, and memory, And … in physics you have… time and space, as such a

> major component, … there are so many relationships that can be drawn between the two.
>
> **SS:** When I chose to do physics it was-- because it's like an appreciation that goes deeper than just interest in the subject...and like...kind of a similar thing that I feel when I play music which is an aesthetic thing, and I felt the same way about some aspects of physics.
>
> **Sam:** The incorporation of art, of humanities into physics.… it's the reason why I signed up for [this course] and it's the aspect that I liked the most.
>
> **Manny:** It's a lovely mixture between physics, math, and art…and symmetry. There's not much you'd want to miss. It's…pretty perfect in every way.
>
> **Juno**: I think – the beautiful thing about this class was that I felt it was NOT necessarily a – "this is physics, this is art" keep them apart and don't – but rather, an all inclusive thing where music and art and physics are OFCOURSE what we talk about and it's – of COURSE it belongs together… and so it's a very different way of seeing, rather than just combining categories, which I expected it to be. And this is why I was so blown away ultimately, because I realized it was a whole different way to look at the world.

Thus, the idea of organizing an introductory physics course around the teaching of contemporary physics before classical physics, and incorporating art, music, and dance proved to be attractive to students. That the principle of integrated arts and science education is motivating for students is further evidenced in the following email statement of Dr. Bruce Tiffney, Dean of the College of Creative Studies:

> Hi, Jatila: … One of your students was praising the class to me today and asked for more like it! I will look with delight to the possibility of a repeat or a higher level variant next year (received May 31, 2007).

Having established that a certain level of interest and support for the idea of teaching an integrated arts-sciences curriculum is present in the UCSB community, I will describe the general organization of my course, and my rationale behind the curriculum design.

4.1.2. Design and Organization Strategies

The two organizing principles, Symmetry and Aesthetics, shaped the design of the intellectual content (cognitive aspects) and the interactive climate (affective aspects) that I hoped to achieve in the course. Table 4.2 represents an organizational chart for the structure of the course in terms of activities and general goals.

4.1.2.1. Creating a Climate of Trust.

In order to facilitate the kind of intellectual climate that I wanted to develop in the class, there first needed to be established a climate of trust between the physics and arts majors, in which they could learn from each other. The strategies I used for creating trust were the use of mixed-major collaborative groups and open class discussions. The idea of mixed-major collaborative groups is an extension of the model of Peer Instruction (Mazur, 1997; Mazur and others, 2006, 2007) which is applied in regular introductory physics classes. It is based on Vygotsky's idea of the Zone of Proximal Development, which states that learning takes place most effectively in a social context rather than alone, and that novices can accomplish a great deal more in the presence of experts than they can on their own. The class discussions were always constructed around open questions for which there was no single correct answer, prefaced by “What do you think?” or “Why do you think this is so?” The goal of such discussion was the exploration of the question itself, not the arrival at a particular conclusion. I also encouraged students to ask their own questions, and propose tangents for the class to explore. That this type of open ended discussion contributed to the climate of trust was apparent from the students’ comments. As one art student said on one of the weekly exit cards, “…this seems sort of a “safe environment” where it is good thinking that counts…” .An excerpt from my post-course interview with Beatrice and Juno illustrates how important the class discussions were for them in creating a welcoming environment. Particularly significant is their statement that they felt at home in a physics class.

	Cognitive Domain	Affective Domain
General Problem being addressed :	**Conceptual Coherence in Physics, Mathematics as the Language of Nature**	**Fear of Physics**
Organizing Principle:	**SYMMETRY**	**AESTHETICS**
General Topics:	Math Orientation Math-Physics Connection via Symmetry Relativity	1. Numbers in Nature 2. Symmetry in art and music 3. Explorations of spacetime in art
Implementation strategies:	**Creating an Intellectually Stimulating Climate** 1. Learn from Masters Read scholarly works by theoretical physicists and popular literary works about physics by theorists, as they are the most interesting and accessible – no big expensive text books 2. Involve Guest Speakers Scholars in the fields of theoretical physics, algorithmic art, algorithmic music, inspire students and show them possibilities beyond the classroom 3. Involve writing and drawing before problem solving for homework Writing about physics creates a scholarly interaction between reader and physicist-author, and facilitates learning the language of physics for both arts and physics students 4. Final project, no final exam Students appreciate and validate each other in collegial atmosphere	Creating a Climate of Trust 1. Peer Instruction: Mixed-major collaborative groups 2. Class Discussions: No right or wrong answer, emphasis on "good thinking" 3. Integrate Arts & Sciences Class activities rely on strengths of both physics and arts 4. In first quarter, keep problem sets for in class only Use Vygotsky ZPD in class for problem sets; optional hw in first quarter; require for hw later.

Table 4.2. Organizational strategy

> **Beatrice:** For me the class became SO important because of the passion … that the other students had in the class, and their willingness to discuss, and explore, and question, and this is the same that I feel the artists do <…>, and it made me very dedicated to the class, because –
>
> **Juno:** <jumps in> - It was HOME <little laugh> -
>
> **Beatrice**: - Yah, it made me feel at home…<…> And I felt like HERE I was FINALLY in a WHOLE room of people that were SO enthusiastic and so passionate about what they were doing, and they were ALL QUESTIONING and INVESTIGATING and asking each other things, and it was just such an amazing atmosphere to be in.

The integration of physics and fine arts brought together students who had each achieved a certain level of mastery in their chosen fields, and each could learn from the others. Had the learning been unidirectional, namely that of the art students learning about math from the physics students, without giving back in return, the climate of trust may not have been achieved. The fact that the physics students valued the superior knowledge of the art students in their fields, created a sense that each recognized and valued the contributions to the class that were made by the others. Several of the physics majors commented on how they appreciated learning from the artists in the class. The following quote from my post-course interview with Frank, first year physics major, is representative of the opinions of the physics majors whom I interviewed.

> **Frank:** For me, I think, the number one thing was the input we would get every week from the two visual arts majors in the class, because … they were… so assertive … in, um, the way they understand things,

> and whenever they don't understand things, they would never hesitate right away to come out and question things, and ask why, and, that led to a lot of really good discussion and…um, they say that when you… teach other people something you're helping yourself learn it even better at the same time, and I think that, for at least myself, trying to explain some of the more difficult ideas in physics to them, helped to…ingrain it into myself even further. … But, um…but it went both ways, because some of the things that they were saying about aesthetics and visual arts were also very compelling to me. … and, um…basically, every week that they were there was guaranteed to bring a lot of controversy and arguments, and that was great because that's a lot of fun.

4.1.2.2. Creating an Intellectually Stimulating Climate.

To foster the kind of climate that would encourage questioning and exploration, I chose four strategies, which depart from traditional introductory physics courses. First, instead of a single text book, I assigned readings on physics content and physics in context from books and articles written by theoretical physicists for general and introductory audiences. Second, I enlisted the assistance of guest speakers, experts in the fields of art, music, and symmetry.[1] Third, I assigned writing and drawing as ways of analyzing articles, whereas in most introductory physics classes, at least at UCSB, students primarily solve problems without critically evaluating the texts they are asked to read. Fourth, instead of a final exam, I assigned a final project.

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[1] We were extremely fortunate to have as one of the guest lecturers, Professor David Gross, Nobel Laureate and director of the Kavli Institute for Theoretical Physics at UCSB.

The project I assigned was to create a physics work of art in any medium in which they chose to work, and then write a critical paper of five pages minimum length, discussing the principles of physics illustrated by their work. This project represented the third aspect of Nikitina's taxonomy of interdisciplinary teaching strategies, in that it presented the students with an open ended problem to solve – the creation of a product by means of which they could demonstrate their knowledge of those aspects of physics and mathematics from the course that were most important to them, while expressing their personal sense of aesthetics. In Greene's terminology, it was an art-making exploration by which students integrated their prior experiences with the perceptions they learned from this course to create new understandings and ask further questions. In Chapter Six I will present some examples of their work, as well as their reactions, demonstrating that this assignment achieved what I (and the students!) had hoped.

4.1.2.2.1. Learning from the Masters.

Instead of a single, univocal text book, I assigned readings from multiple authors. I chose one popular physics book, *Fear of Physics* by theoretical physicist Lawrence Krauss, as the main text. In addition, I compiled a course reader, composed of fifteen articles from professional journals, as well as chapters and portions of chapters from texts by theoretical physicists Richard Feynman and Mario Livio. The journal articles consisted of selections about theoretical physics, written by theorists at an introductory level, mostly without math, as well as articles about physics in context with art, history, philosophy, and mathematics. The reader table of contents is listed in Appendix A.

Two or three articles were assigned each week, and for homework the students were asked to write their reactions to each article. The choice of readings had the positive effect of making physics seem more personal, presenting physics more as an evolving creative process, rather than a static body of knowledge. The following quote from the post-course interview with SS, first year physics major, indicates how the readings helped change her attitude towards physics:

> **Jatila**: So, do you think that your attitude towards the process of doing physics has changed as a result of doing this course?
>
> **SS**: I think it HAS, just because of reading the accounts of physicists, like realizing new things and discovering their new ideas. Like, I think I appreciate physics as more of a creative endeavor now, than I did before…<…> I guess there's more of a personal aspect to it. Like you kind of have to think outside the box instead of just going along with your math until you arrive at something.

As the students interacted with the physicist-authors through their literary works, they got to see them as people and, as in any community of individuals, some are more personally appealing to us than others. Beatrice, one of the art majors, wrote the following about Nobel Laureate Steven Weinberg, in her commentary on his article about physics and history:

> Weinberg then assesses that "Einstein's theory is nothing but an approximation valid at long distances." I think from his writing that Weinberg is grumpy…<…>. He has a demeaning tone in his writing but I also strongly agree with him on several points.

Another important value of using multiple authors instead of a single text book is that students have an opportunity to access the same content from different viewpoints. Regarding the reading assignments on symmetry, it turned out that a majority of the physics students preferred the style of presentation by Lawrence Krauss, while the majority of the art students preferred the style of theoretical astrophysicist Mario Livio. For example, Juno, sculpture major, compared authors Krauss and Livio in one of her homework reflections:

> Having just read Krauss, and reading Livio this weekend, I began comparing the way they argue and present reasoning to their readers. Both present essentially physics-related ideas and aim that presentation at essentially non-physicists. I as a non physicist, find Livio a lot easier and more engaging to read. He uses many examples from daily life experience to illustrate what he means, and often gets a point across with slightly goofy metaphors for 'serious' matters.

MKS, literature major, wrote the following comment after reading one of the selections by Mario Livio:

> I loved this article because it is clearly the work of a man with great insight into many different dimensions of the problem he is addressing.

All the students were excited about reading articles by Einstein himself. I included two: one article on physics and philosophy in the reader, and one appendix to his popular book on Relativity, which I distributed later. In all, the students had the opportunity to read scholarly works by eight different theoretical physicists, four of them Nobel Laureates. The interaction of the students with physicist authors through the readings will be discussed further in Chapters Five and Six.

Another aspect of 'learning from the masters' was the involvement of guest speakers. The opportunity to hear from professionals who are creating knowledge in their fields was one of the highlights of the course for each student, and although different students had individual preferences, they appreciated the contributions from each one. To talk about art and physics, we had Dr. Jean-Pierre Hebert, Artist in Residence at the KITP. To talk about physics and music, we had Professor Stephen Travis Pope of the Media Arts Technology program, who is a composer of algorithmic music. To talk to the class about symmetry, we were fortunate to have Professor David Gross, 2004 Nobel Laureate and director of the KITP at UCSB.

4.1.2.2.2. The Use of Drawing in Analyzing Physics Texts

As has been discussed in Chapter One, the use of the *Anschauung*, or visualization, was an important part of the developments in theoretical physics since the latter part of the nineteenth century. This type of visualization goes beyond the construction of Newtonian force diagrams which are required in introductory physics. While force diagrams are seen as a visual aid in solving mathematical problems in introductory physics, the *Anschauung* refers to a visualization which is part of the concept itself. Although no longer commonly referred to using this older terminology, the use of visualizations is a seminal component of understanding theoretical physics at higher levels. Two examples are Faraday’s lines of force depicting the divergence of a field, and Feynman diagrams in quantum mechanics. Besides using numerous visual aids in my presentations of physics and art, I asked students to draw their interpretation of homework articles from time to time. When I asked them if this assignment was a "*totally weird thing to be asked to do*," they said no; on the contrary, it was quite natural.

> **AT:** It was quite natural.
>
> **Sam**: Art has been absolutely vital to my current comprehension of any and all areas of science.
>
> **SS**: Doing the visual representation felt very natural to me. I tend to visualize concepts in my mind as part of the process of understanding and thinking about them.

I will discuss the drawing projects in greater detail in Chapter Six, including drawing the "world lines" of authors to analyze an article.

4.1.2.2.3. Final Projects, Not a Final Exam

The most direct way to test the learning gains in a course such as this was to assign a final project in which the students would have to demonstrate their gains in knowledge, comprehension, analysis, synthesis, application, and evaluation of both physics and art. A final exam would have been a completely inappropriate metric for a seminar such as this. The final class period was devoted to each member of the class presenting his or her final project, without time limit, for the review and appreciation of the peer group of scholars. The class ended close to 6 PM, yet no one left early (with one exception of a student who had to be at his job). Each person explained his or her project, fielding questions, and each physics work of art was received by the group with applause and admiration. Thus, the scholarly and intellectual climate of questioning, exploring, and evaluating that had been cultivated during the course, ended appropriately with each member submitting his or her scholarly/ artistic creation to the review and approbation of his or her peers. In addition, it was an assignment that they all enjoyed, because it was self directed. As Frank, physics major said in his post-course interview:

> It hardly felt like an assignment at all, it was just something that I was doing that I enjoyed, and that I wanted to show to other people. … and that I hoped they would enjoy, too. … So…I got to learn something about math and physics and aesthetics and art all at once, and create something that I really liked, so I thought that was educational, and also purely fun, and good.

The final projects will be discussed in detail in Chapter Six, but at this point it is interesting to note that one testament to the success of the final physics works of art is that several of the students' projects involving algorithmic music and interactive art are being considered for choreography in the 2007-08 season by dance majors in the UCSB Dance Department.

4.1.3. Organization of the Topics: Designing the Syllabus

I organized the progression of the course approximately into three phases:

1. Math orientation
2. Symmetry
3. Relativity and its applications

Of the ten class sessions, three were dedicated to math orientation and development of symmetry and Noether's Theorem; four were intended to be dedicated to the development of Special and General Relativity and applications, and three were intended for special guest speakers. One of the classes (the eighth) ended up being dedicated entirely to catching up on the discussions of the readings, as we had fallen behind. The sequence of topics is listed in Table 4.3.

The original intention for each class was to divide the three hours approximately into three sections: a lecture/presentation; group activity; and discussion of readings and homework. After the third class, however, this general pattern was not maintained. As the topics became more challenging, students asked more questions and there was a greater need for more discussions; thus, the format for each class became more fluid. At the end of each class, the students wrote comments on index cards (*exit cards*), and I used their comments to make adjustments to the course as I went along, in response to their requests.

Date	Topics
January 12	Introduction to math as a language of nature
January 19	Introducing the ideas of symmetry Special Guest Speaker : **Dr. Jean-Pierre Hebert,** Artist in Residence at the KITP
January 26	More about Symmetry and Groups as applied to physics
February 2	Conservation Laws; Dimensions and Natural Units
February 9	An introduction to Special Relativity and explorations of spacetime in art
February 16	Einstein's derivation of what we call the Lorentz Contraction
February 23	More on Special Relativity and intro to General
March 2	Discussion and analysis of the last five articles World Lines of Authors
March 9	Symmetry Breaking Special Guest Speaker: **Professor David Gross** Director of the KITP and 2004 Nobel Laureate
March 16	Special Guest Speaker: **Professor Stephen Travis Pope,** will talk about algorithmic composition of music
March 23	Final Presentations and Celebration

Table 4.3. Sequence of Topics from course web page

After each class I read and transcribed their comments, and reflected on the class in my teaching journal. I also wrote journal entries after each session of office hours or outside tutoring that I conducted with individuals or small groups. The exit card comments and my teaching journal will be discussed in Chapter 5.

In the remainder of this section, I will describe each of the three general themes of math orientation, symmetry, and relativity. I will discuss the rationale behind some of the specific points I wanted to present, the reasons for the examples I chose and the order in which I chose to present them, and where useful, I will report some of the students' comments.

4.1.4 The Problem of Language in Introductory Physics

The problem of orienting to math is intertwined with the problem of language in physics, which makes the teaching of introductory physics difficult on two fundamental levels. The first is the problem of students' orienting to the way physicists use terms from every-day language to represent very specific concepts in physics. The second is that in order to build the mental models which are necessary to understand physics, students must be able to orient their thinking so as to be able to experience the world through the symbolic language of mathematics.

The problem of the language of physics for introductory students has been addressed in previous studies. Hestenes (1998) cited managing the quality of classroom discourse as one of the most important factors in teaching and learning of physics. Bazerman (2000) has shown how the ways in which physicists imbue certain linguistic terms with precise mathematical definitions makes the language of physics quite foreign to the uninitiated. Besides the redefinition of common words to signify new meanings in physics, DiSessa (1993) has shown that students arrive in physics class with pre-existing beliefs about the way the world works, based on bodily sensations built up from prior experiences, and this further complicates the problem of assigning meaning to terms in physics. May and Etkina (2005) studied the ways in which professional physicists use language in quantum mechanics and thermodynamics to inform their understanding of physics. He suggested that in order to understand physics, students must first learn to use language in the way physicists do. In the introduction to *Fear of Physics* Krauss explains:

> The way physicists approach problems, and the language they use, is also removed from the mainstream of modern-day activity for most people (Krauss, 1993, p. ix).

The problem of math as a language of physics has also been addressed extensively. McDermott (1993) demonstrated, through a series of clinical interviews with students in both calculus-based and algebra-based introductory physics, that students commonly failed to see the cause and effect relationships in physics equations, such as the work-energy and impulse-momentum equations. Failure to correctly apply these equations to physical situations was a result of students' considering the equals sign to indicate simply mathematical equality, rather than causality.

Hickman and Huckstep (2003) have compared the learning of mathematics to the learning of language, in the sense that students must make sense of mathematics and they must originate mathematical assertions of their own that have not been directly taught. Students are expected to arrive at college having mastered the ability to understand and apply mathematics as a necessary language for the symbolic formalization of concepts, particularly in physics (De Lozano and Cardenas, 2002). De Lozano and Cardenas have shown that even students who have had a great deal of prior math exposure often have difficulty extrapolating the meaning of certain terms, such as the equality sign, or operations such as addition and multiplication, from abstract mathematics to the syntactic and symbolic meanings in physics. De Lozano and Cardenas cited examples of their own university students' work which illustrates how, without a correct understanding of the physical meanings behind the terms of an equation such as Newton's Second Law ($\mathbf{F} = m\mathbf{a}$), students may logically arrive at a meaningless answer if they view such a relationship as a simple arithmetic equality. The persistent failure of introductory students to see the connections between mathematics and the physical world, and the failure of introductory physics courses to alleviate this problem, has been a dominant theme in much of Physics Education Research literature (Redish, Saul, and Steinberg, 1998; McDermott, 2001; among many others).

Among the art majors in CCS-120, the dual problems of the language of math and the language of physics were cited in their post-course interviews as having been significant areas of difficulty for them in the beginning

> **Beatrice:** I just didn't have – I didn't have the background to understand what we were discussing or what we were looking at. I didn't understand the words we were using, the language that we were using, was such a issue for me, because …. I just didn't have the foundation to be able to…to come to terms with what we were

> discussing. And so that kind of threw me off a bit, as to…what we were looking at, and what WAS physics…
>
> **Juno:** I actually remember feeling SO lost in the beginning, it felt so…completely overwhelming, and I thought – it made me feel very really stupid, because I wasn't a physics major…
>
> **Victor Eremita**: That was the greatest challenge in the class, was that despite having all the things related to art and to …um… y' know, making it understandable…I still had a very hard time grasping a lot of the concepts. It took me a lot longer to process than…I noticed a lot of the physics majors did.

Beatrice in particular expressed her frustration with the use of terms from her experience as an artist, and redefining them mathematically, and then using the same words in physics contexts, such as symmetry and curvature, to mean something different from the way she was accustomed to using them. Some excerpts from one of her homework reflections explains her viewpoint:

> In trying to understand Richard Feynman's article specifically in regard to curved space, I am struck with my difficulty to understand "exceptions" of this idea. … My first reaction is to say that the definition that Feynman gave in the beginning must be wrong because a cylinder is obviously curved to an outside perspective. … This concept agitated me so much I spoke with Jatila regarding the thought and I came to the conclusion that math is a language which one must accept a general convention to with hold an idea and express a reality.

I will discuss this idea further in Chapter Five, as I wrote extensively in my teaching journal about her seeming resentment of what she perceived as physicists' usurping of language for their own purposes. In this class, Beatrice was quite vocal, however the difficulty she expressed with the language of physics is consistent with prior research cited above. This raises the question of how many beginning students may have the same difficulties, yet do not voice them. Therefore it should be important to build into any curriculum ways to address these difficulties with the language of physics and math.

A study by Finkelstein (2005) of teaching and learning of electricity, in which he suggested that the context in which physics is taught is central to students' development of understanding, may have particular bearing on the intentions of the present study. Context, he suggested, is not merely a backdrop to students' learning, it is intrinsic and not separable from the conten; moreover, certain features of a given context may promote or inhibit content understanding (Finkelstein, 2005).

In the present study, the contexts of art and music did appear to be helpful in conveying the concepts of physics, particularly for the non-physics majors, as they commented in their post-course interviews:

> **Beatrice**: When I read the articles, it made complete sense, what the articles were saying t' me, like, ah, kind of viewing this relationship between art and physics, and physics being the investigation of our physical world, and of our, of our understanding of our physical world.

Regarding the problem of the language of physics, the informal classroom atmosphere in which physics and art majors were mixed was also beneficial in helping the art students gain familiarity with the terminology of physics. Again, quoting Beatrice:

> **Beatrice:** I felt really comfortable and really SAFE to ask questions, and they were so willing to explain things to me, and have discussions with me – and I give a lot of credit to them as well because they helped me to learn . <…> And I understood a lot of what we were discussing from them.

I will return to these themes in the next several chapters; I have introduced students' comments here as supporting evidence from my class that is in agreement with published studies that language of physics and language of math are problems for novice students, and that context – both subject matter and classroom climate – can play a role in mediating the difficulties with language in introductory physics.

4.1.5. Math Orientation

Traditionally, introductory physics classes (and text books) begin with an orientation to the mathematical techniques that will be necessary for the course. In most cases, the mathematical introduction includes some mention of units and dimensions, powers of ten notation, and vectors. My concept of an orientation to the way I wanted students to view math in my course was to start with examples of math as a language of nature, and how art that attempts to reflect nature has utilized these same mathematical concepts, such as "φ," the Golden Ratio. My idea of introducing dimensions was to explain how and why length and time are really interdependent in the contemporary world view, and how the dimensions of mass, length, and time are related. Regarding units and estimation, these are discussed quite adequately in Chapter Two of my chosen text book, *Fear of Physics* (Krauss, 1993).

In the introductory lecture, I explained the features of this course which, in addition to the incorporation of arts, would make this course different from a regular physics class: Instead of starting with solving problems, we were first going to talk about math as a language. Instead of assuming the Newtonian paradigm of static space and universal time, then learning about Relativity and having to revise our paradigm, we were going to assume the post-Einstein paradigm of dynamic spacetime and later look at how and why the Newtonian paradigm is a limiting case of the more general view. We were going to adopt the initial position that symmetry is the theoretical basis for investigating the mathematical aspects of the physical universe, as it is the most fundamental.

In the first class, before discussing numbers which appear in nature, I presented the diagram shown in Figure 4.1, illustrating the inter-dependence of the object in nature, the symbolic representation of the object, and the meaning it has in the human realm. My intention was to inspire the students to consider that the way we symbolically represent nature influences the way we conceptualize about it. I believe this is an important basis for establishing dialog between arts and sciences, in the sense that neither is superior, but each is suited to a different purpose.

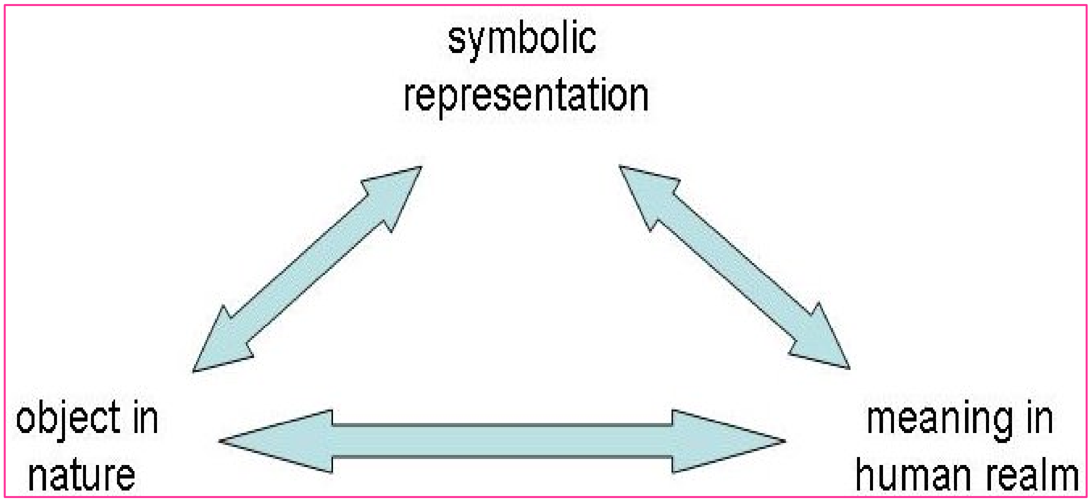

Figure 4.1. Physics as a semiotic system.

Thus, by presenting math and art as different semiotic systems, each with its own ways of symbolically representing nature, my intention was to establish the tone for the class that if our goal is to understand the physical universe, then we can do so most effectively by utilizing both means of perception.

This is a theme to which I repeatedly returned throughout the course, for example: I compared the view of spacetime which twentieth century cubist painters attempted to capture with the view a traveler at high speeds would see, due to rotation of spacetime axes (Lorentz boosts); I compared the view of distant galaxies through gravitational lenses caused by intervening dark matter to some of Escher's drawings of objects reflected in spherical mirrors. These kinds of discussions proved to be highly motivating to students, as was evidenced by their questions and comments.

After establishing my premise of the interdependence between nature, symbolic representation, and human understanding, I proposed to the class my model that math as a language helps us understand the physical universe by its properties of description, prediction, and analogy (Figure 4.2).

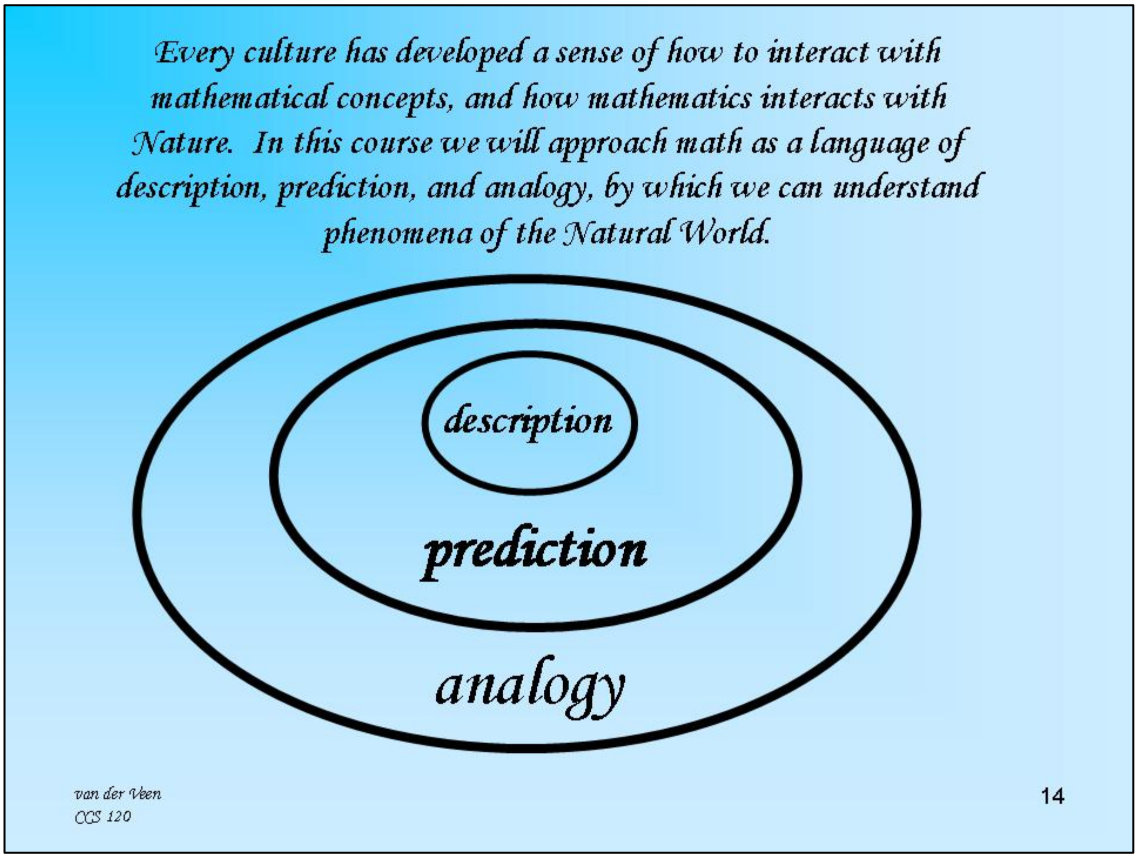

Figure 4.2. Math as a language of description, prediction, and analogy.

Numbers describe specific relationships, corresponding to the innermost circle. Equations which describe the laws of physics allow us to make general predictions, but end with specific relationships; thus equations are both predictive as well as descriptive, and belong in the second circle, encompassing the descriptive properties of pure numbers. Symmetry is the principle which facilitates understanding of the deeper connections in nature, as does analogy in spoken language. Symmetry is represented by the outer circle, and contains the other two.

The topic of mathematics as a language, and the question of whether mathematics is a human invention like spoken languages, invented to describe nature, or whether math is the language of nature, there to be discovered by humans – or some combination – was one that we were to return to throughout the course. This discussion topic was particularly motivating for the physics majors:

> **Frank:** … what I especially liked … was, it got me thinking about a lot of really big, deep questions in physics like, Does the math that we use really have any genuine connection to the physical world? Or, why are the equations that we state without proof such as, You can rotate things and it's still the same, why should those things be true? And, like, all the things that we just take for granted when we're working through problems really should be thought about a little bit, because they're not easy questions at all

> **Manny**: There was a lot in this class that…that we studied … that elucidated a lot of other things that before just seemed as rules to many, so I think that's a good way to approach the subject. … I also think that…the students in the class might not – or, the ones who don't know physics as well as- as a physics major, for example, I think it really helps THEM to see more clearly what physics is all about. Like the art majors in the class. … I think that's GOOD.

> **Charlie**: I feel that I could spend hours discussing our view of the universe through math, as this topic is so fundamental, and many people can be passionate about philosophy.

Comments from the arts majors indicated that the discussions helped them to feel more comfortable with mathematics, and that perhaps I should have encouraged even more discussion in the beginning of the course.

> **Juno:** I actually remember feeling SO lost in the beginning. It felt so completely overwhelming, and I thought – it made me feel really stupid, because I wasn't a physics major… then eventually I started gaining so MUCH from that experience of just being in discussion with everyone in the class. I'm really glad I didn't drop the class, because I was scared.
>
> **Beatrice:** I think that because I hadn't done math or science for so long, that I was completely -- I was a little confused when we started, but as we were continuing our discussions, I became much more aware of what we were investigating.
>
> **Juno:** I feel that, if, maybe we would have started with MORE discussion …or…well, if this kind of class were to start with MORE discussion about what people THINK about physics, or how they FEEL about physics, and then immediately start kind of having people compare their experiences or something, it might create a less afraid notion the first couple weeks.

Thus, talking about mathematics as a language, and the connections between math and nature, proved to be interesting and motivating for both physics as well as arts majors, and such discussions appeared to be effective in reducing fear of math. I will discuss the implications of this approach for other educational settings, such as compulsory introductory physics courses and teacher education, in Chapter Eight.

After my philosophical introduction about math, I decided to start from the inner circle of my model of math as a language (description), and discuss specific examples of numbers in nature. I took the ideas for my presentation of numbers in nature mainly from the book *The Golden Ratio* (Mario Livio, 2003), in which the author uses the appearance of the irrational number "φ" (pronounced *phee*) in a wide variety of seemingly-unrelated physical phenomena, as an illustration of what he calls the *unreasonable power of mathematics*. There are many such abstract numbers which were discovered, and later found to have wide-ranging applications in nature (such as π and *e)*, but φ is arguably the most ubiquitous as well as the most tangible, appearing in nature and art, from the shapes of sea shells, spiral galaxies, the growth patterns of plants, in the reproductive sequences of bees and rabbits, and in the pentagram, which was thought to have mystical powers. (Even its name, the Golden Ratio, is intriguing.) It even has applications in fractal geometry and geometric tilings. It is perhaps the best-known example of how a concept which originated purely in mathematics was found to have applications in the physical world. My presentation of φ and the Fibonacci Series in the first two lectures was designed to prepare the students for the idea that the mathematics of groups and symmetry actually have predictive capabilities which are manifest in the physical world. This theme – that a concept which originated purely in mathematics was later found to have a real manifestation in the physical universe – is what makes math tangible for students, and more interesting and motivating.

Next, I wanted to emphasize the difference between abstract, dimensionless numbers, which were discovered first by pure mathematics and later found to describe relationships in nature, and the fundamental constants of nature, which were predicted on the basis of observations, and later measured. The fundamental constants of nature, such as *c*, the speed of light, *G*, the gravitational constant, *h*, Planck's constant, appear to define the properties of the physical universe, and express certain underlying symmetries. They have been measured with high precision, and it is understood that if they differed even slightly from their measured values, the universe would not be as we know it. Fundamental constants of nature have dimensions which are reducible to the fundamental dimensions of mass, length, and time, and express relationships between these fundamental dimensions of nature. I believe that foregrounding such appearances of particular numbers in nature can help reduce the perception that physics is intimidating and exclusive. I will discuss this further in Chapter 8. That this topic of math in nature aroused interest in the students is evident because five out of the eleven students based their final projects on the Golden Ratio, Fibonacci numbers, or fractal applications.

4.1.6. Symmetry and Relativity.

After introducing math as a language of description, I began the main portion of the course, to introduce the idea of symmetry and the algebra of groups, leading into the topic of Relativity. My reason for introducing symmetry and group theory at this point in the course was because symmetry is the mathematical formalism which is at the heart of contemporary physics (Gross, 1996). The line of reasoning I wanted to present, which would lead to the physics content of Relativity, was as follows:

First, I established the mathematical definition of symmetry as an operation, which, when applied to a system, leaves the system unchanged. I used the example of the equilateral triangle to define symmetry operations and closure of a group under symmetry transformation, as suggested by Professor Christopher Hill of the Fermi National Accelerator Laboratory (Hill, personal communication, 17.02.2006). I also used examples from music to illustrate discrete symmetry operations of translation and reflection. The students worked in mixed major collaborative groups to derive the symmetry operations of the equilateral triangle and demonstrate that the group "equilateral triangle" is closed under the operations of reflection and rotation. This activity worked quite well, and will be discussed in detail in Chapter Seven.

The next step was to establish that the laws of physics are invariant to rotations, which I did by deriving the coordinates of a line segment which has been rotated in the x-y plane, demonstrating that the length of the line remains constant under a change of coordinates or a rotation of axes. This strategy was also suggested by Professor Hill (ibid.) as being foundational to the conceptual development of Special Relativity. I intended this activity to have been done again in groups, as had been done with the development of the rotation group of the equilateral triangle the previous week. I handed out the following diagram (Figure 4.3), and asked students to break into mixed major groups, as they had done the previous week. I was hoping that, as with the previous group exercise, with a bit of instruction from me, the physics majors would be able to take the lead and help the art majors through the proportional reasoning, as this type of trigonometric argumentation, I thought, is part of a physics major's vocabulary. This idea of mine did not work well; although the two senior physics majors in the class were concurrently enrolled in graduate-level physics courses, perhaps this exercise was not appealing to them. It appeared to me, as I walked around the room, that everyone was stuck.

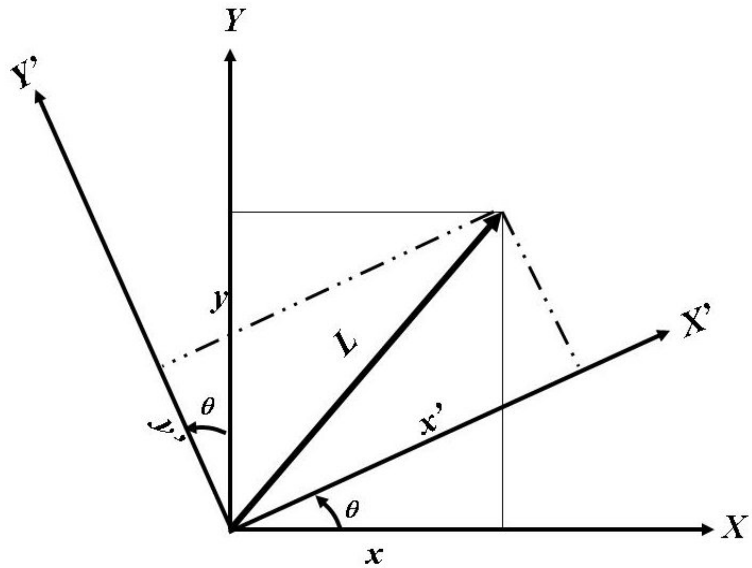

Figure 4.3. Handout intended for rotated reference frame activity

I perceived that to insist upon the independent completion of this activity would be too tedious, even in mixed major groups; thus I developed it on the overhead projector, with the groups following along and drawing in the components on the rotated axes, ending up with the following completed diagram (Figure 4.4).

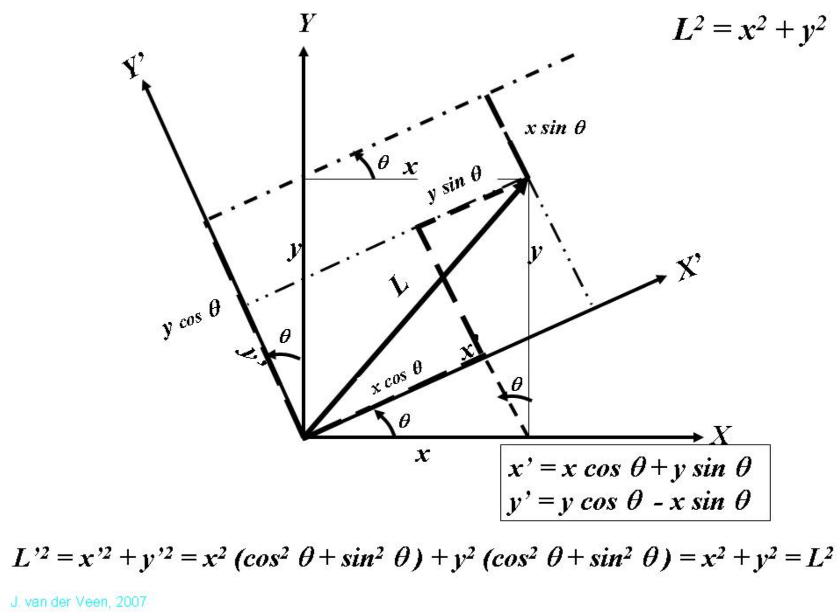

Figure 4.4. Completed activity, rotated reference frames.

Even though this particular activity was not enthusiastically received at that time, never the less, I felt it important to demonstrate the principle of "mixing" coordinate axes in space, where x' and y' each contain contributions from both x and y, in proportion to the rotation angle. I was planning to build on this concept in the development of Special Relativity, as when moving at speeds approaching light speed, time takes on space-like qualities and space takes on time-like qualities.

Next I demonstrated, without actual proof, that continuous symmetries in nature imply the conservation laws of physics. To demonstrate this, I followed the qualitative reasoning of Lederman and Hill (2003), as the full proof of Noether's Theorems would be much more advanced and require the definition of the concept of the *action*, which I had not yet discussed. However, establishing the relationship between continuous symmetries and conservation laws is the conceptual foundation of contemporary physics. In addition, I felt was important to introduce the biographical information of Emmy Noether, as her situation pertains to the historic discrimination against women in physics.

At this point I introduced Special Relativity with a lecture-presentation entitled “Investigations of Spacetime in Physics and Art,” in which I first developed the idea of time dilation from the thought experiment of the light clock in the moving train (Figure 4.5). I then discussed the view that an observer moving at very high speeds would have, and compared this to the representations of spacetime by various artists of the Cubist movement. In the next class, we also discussed the problem of simultaneity developed by Einstein in conjunction with the attempts by the Cubists, notably Picasso, to represent multiple viewpoints simultaneously on one canvas. This was a turning point in the course: having laid the philosophical and mathematical foundations for the physics concepts, we could begin to discuss physics and art in a unified way. Up to that point, giving examples of fractals and the Golden Ratio in art and nature was interesting to the physics students, but appeared to be somewhat confusing to the art students, however as soon as I began tying together the concepts of Relativity in physics with art, the interest level visibly rose.

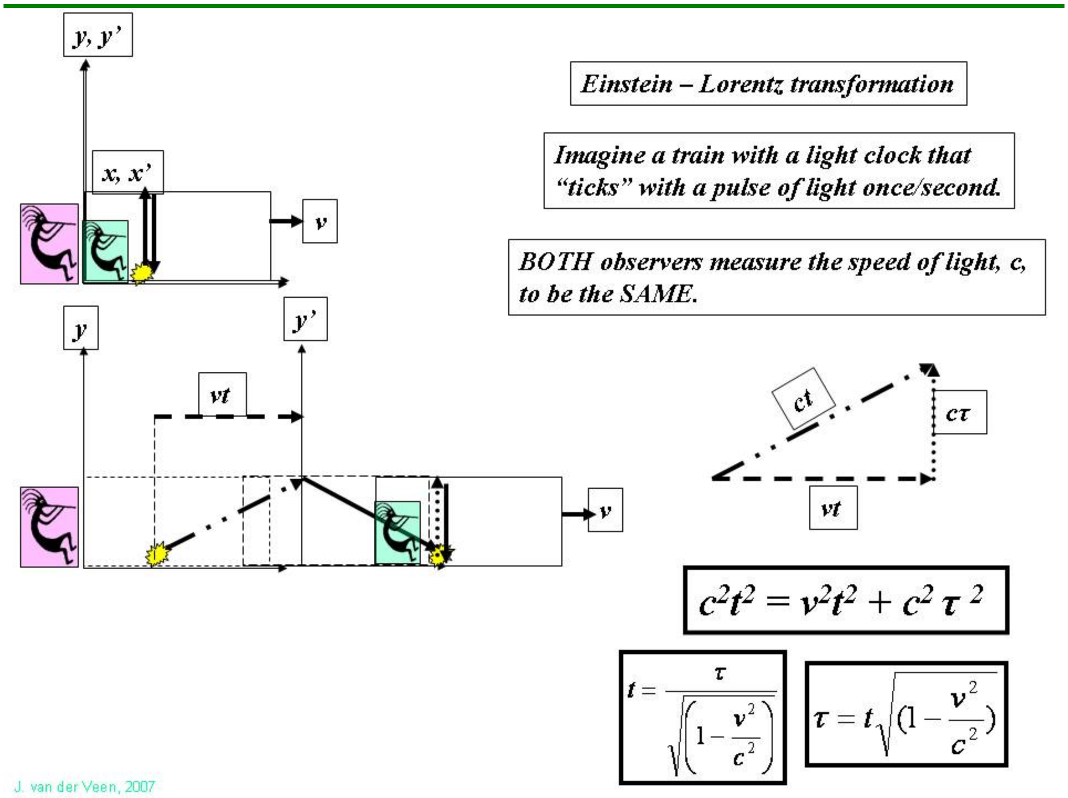

Figure 4.5. Visual derivation of the concept of time dilation in Special Relativity.

Some of the comments of the art majors in their post-course interviews illustrate their enthusiasm for learning about Relativity:

> **Juno:** As soon as we started talking about relativity I was totally on board, I just was – yah, I think actually the first time that we started talking about, um, the time frames - And…really, about relativity - That's when I really started understanding what we were talking about. And before, I was just kind of try – holding on with my fingernails, and kind of pulling myself along just because it was fun to have these discussions, and I appreciated the discussions we had before, but I didn't really understand any of the physics- related things we were talking about. But, um, once we started with relativity, I

> really started UNDERSTANDING what we were talking about. And so that…sort of added another level of appreciation for the class.
>
> **Beatrice**: That was for me as well. That was definitely for me as well. And also then… so I started to gain the understanding, so that when David Gross came to speak, I also- like, that sort of cemented it in the contemporary parts of physics.

In the next class, I presented Einstein's original derivation of the Lorentz Transformation, using his own published notes. Originally I had not intended to spend so much class time on one derivation, however I changed my approach after I read the following exit comment, written after class on February 9:

> I wish we would go into more detail about the mathematical aspects. (Please.) Relativity is worth deriving

I decided that the best way in which to respond to this request would be to present Einstein's original derivation, using an English translation of his own words, as this would be a chance to glimpse the mental process of the master craftsman who created the theory. Although it was a tedious process, in retrospect I feel that this was one of the most important presentations of the course for the art majors. It made an impression on them as revealing a creative process in physics which they understood as artists, and they derived a sense of accomplishment for having understood Einstein's own reasoning. Juno wrote in her exit comment after that class:

> I feel very proud that I feel I understood everything we discussed today – especially the mathematical derivation! Ahahaha!

and she began the homework she turned in the next week with the following statement:

> I am excited. Last lecture I feel something caught on, and suddenly I feel a lot more friendly towards physics. When I got home last Friday I proudly showed the complicated equation to my parents & brothers and enthusiastically explained what I had learned about spacetime. I think I can begin to appreciate physics because I suddenly feel as though it is <u>not</u> about making arrogant universal statements a la "we are RIGHT." Physics really is a way to try to comprehend the universe WHILE ACKNOWLEDGING THAT IT IS INCOMPREHENSIBLE – or at least, very complex, mystifying and beautiful.

As it turned out, on that particular day, only five students came to class: Beatrice and Juno- the two visual arts majors, and Frank, Manny, and SS – three of the freshmen physics majors. (I learned later that it had been Manny who had made the request for this derivation on his exit card.) Throughout my presentation, Juno and Beatrice kept stopping me with questions, asking me to repeat steps, requesting further clarifications, while the three physics majors made notes and appeared to quietly discuss among themselves. Certainly, the very small class size and the flexible format facilitated the interactive questioning, however I believe that this careful presentation of Einstein's own thinking could be effective in any setting, as such an approach makes physics truly personal.

After this pivotal lecture, I continued with further discussion of Special Relativity and applications in art and in cosmology, and then concluded the main physics content with a conceptual introduction to General Relativity. Without using the full mathematical treatment of General Relativity, it is still possible to give students a robust sense of the theory in a conceptual way. I kept the thread of symmetry running through these concepts as the underlying principle which governs the laws of physics. The logical conceptual progression is as follows:

1. Starting with flat space, and not considering time, the invariant quantity is simply the length of a ruler that we can wave around. Rotations in flat space, as explained above, mix the coordinates of x and y, while preserving the orthogonal relationship between the axes. This is shown in Figure 4.4.

2. In Special Relativity, time is included as a fourth coordinate. I used again Einstein's original derivation, extending from one spatial dimension and time, to three spatial dimensions and time, to demonstrate that the invariant quantity is the path, in spacetime, measured from the reference frame moving with the observer. The notion of the light cone arises, and the conceptual basis for thinking about events as being separated in time, separated in space, or "null" - that is, moving *with* light, in which case neither time nor space exist. The first asymmetry of the laws of physics is introduced by the idea that one can travel in any direction in space, but only forward in time. Rotations in spacetime mix the coordinates of space and time, and do not preserve the orthogonal relationship between the space and time axes. This is shown in Figure 4.6.

3. In General Relativity, where we consider that spacetime is curved in proportion to the energy and momentum contained within any volume, the invariant quantity is the action, which represents the least energy path in curved spacetime. (In a second course, this would be the starting point from which to motivate the study of Newton's Laws of Motion.) This is the path that a free body would take in a gravitational field, which has been called a geodesic. I simply stated this

conceptually, starting with the idea that in curved spaces, one's measuring device is no longer a rigid ruler, but one which deforms according to the local curvature, which depends on the mass contained in that local region of spacetime. The best conceptual description of curved spaces that I have found is the one written by theoretical physicist and Nobel Laureate Richard Feynman (Chapter 42 of *The Feynman Lectures in Physics*, 1971). In most introductory physics classes, Feynman is not used, however he was the favorite author of one of the art majors, and several of the physics majors.

> **Juno**: I really enjoyed reading Feynman's article. I don't know why, it was my favorite article, because it just kind of – it was pretty LATE in the class - But to me it really was sort of another – a very FREEING notion of, um – because I was able to understand what he was talking about – because he obviously writes in a way that is quite understandable – and, um – so it made me feel proud that I was able to understand what was going on, on a physics level, but I also thought it was very, very interesting.

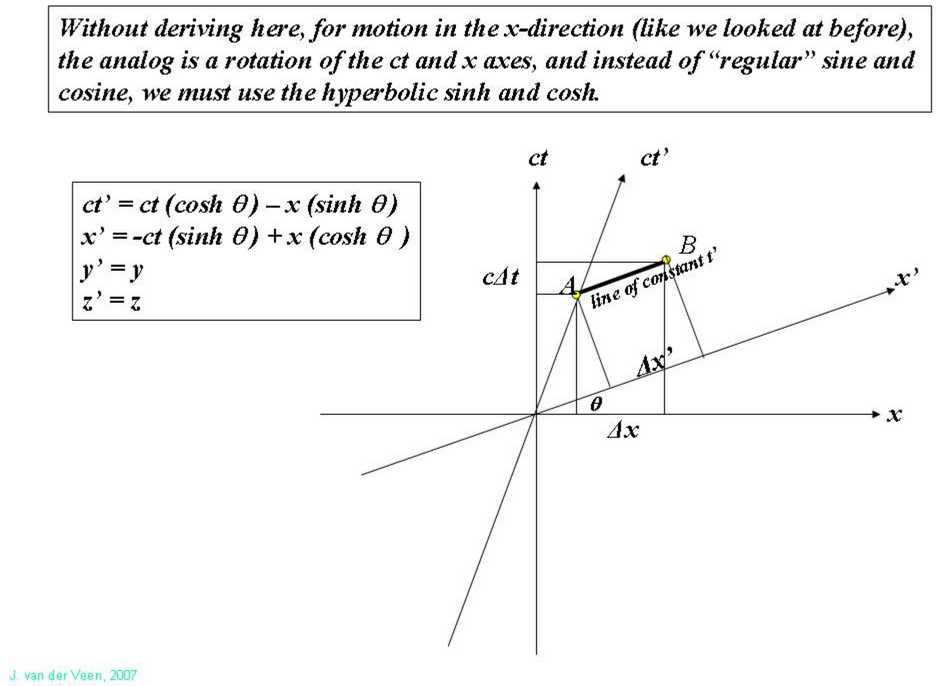

Figure 4.6. Rotation of spacetime axes in Special Relativity.

Comparisons with art made the concepts of Relativity more accessible to students than would the purely 'scientific' treatments found in most introductory textbooks. Some of the examples I used included comparing Hubble Telescope images of distant galaxies distorted by gravitational lensing with paintings by the Dutch artist M. C. Escher, and the distorted view of spacetimeof a Lorentz boost with Cubist paintings of the early twentieth century. Discussions of black holes, were enhanced with a simple simulation that I put together using a large embroidery ring, a piece of lycra fabric, and some heavy ball bearings that I borrowed from the physics demonstration room,

The ninth class was dedicated to a lecture on Symmetry by Professor David Gross, Director of the KITP and 2004 Nobel Laureate. This scheduling was mostly a result of his personal schedule and availability, however it worked well to have such a pure physics lecture towards the end of the course, especially for the arts majors. By that time, they had become thoroughly oriented towards the language of math and the concepts of symmetry and curved spacetime through readings, class discussions, and presentations, and were able to appreciate his talk. For the more advanced of the physics majors, this talk was the highlight of the entire quarter.

The lecture by Professor Gross provided an excellent and fortuitous summary for the entire content of the course. The other two guest speakers were Dr. Jean-Pierre Hebert, Artist in Residence at the KITP, who gave a talk on algorithmic art during the second lecture, and Professor Stephen Travis Pope, who gave a talk on algorithmic music during the last lecture.

4.1.7. Final Discussion: The Unreasonable Power of Mathematics

The course ended with a final discussion on the language of mathematics, taken from the final selection of the course reader, *The Unreasonable Power of Mathematics* by Mario Livio. Whereas the first such class discussion was a little strained, as it was most likely the first time any of the students had been asked to think *about* math, the last discussion was quite lively, and everyone had something to say, as noted by several students on their exit card comments:

> Discussion of the Livio article was particularly lively, and everybody spoke up at least once. I learn so much in this class. I liked [Beatrice]'s discussion of modernism/ post-modernism at the beginning of class, and how these movement in art and literature are comparable to movements in physics during the same time period.

> I feel that I could spend hours discussing our view of the universe through math, as this topic is so fundamental, and many people can be passionate about philosophy.
>
> Today was a fantastic class. The discussion was very thoughtful. The kind of discussions we had created new connections in the brain.
>
> It has been a truly rewarding experience taking this course. The discussion never fails to be intriguing, the topics are fascinating (relativity, time travel, symmetry, fractals, etc.) and the guest lectures/discussions were superb. Thanks for a terrific quarter, and definitely consider offering this course again!

Thus, one of the main goals of the course had been met: art students were more open to physics and math than they had been before, and the physics students had begun to think about their work in math and physics in a new way. I will return to the students' comments in later chapters, however I include the following selections here as justification that this curriculum, with the methods of Peer Instruction in mixed major collaborative groups, and class discussions that encouraged questioning *why* these methods and viewpoints were justified, has merit and should be further developed.

> **Juno:** The whole notion of collaboration has suddenly become something I'm interested in. Before I even took this class, I was SO SCARED of collaborating with someone …it seemed the most – the last thing I wanted to do, but now I'm really excited about it and…I think that came…that came a lot because of the discussions I had with these other people, and …. it made me think about other people, from other sciences… or from other fields of study …with other interests, I think that's what it is. It made me really appreciate people who have a

different viewpoint on something. And being very interested in talking to them, and working WITH them, and making MY work maybe a little more open to discussion.

Beatrice: Taking the class has opened the way I perceive my world and so therefore obviously it's gonna effect my work, because my perception of my existence and of the world is different.

Sam: I mean, just in terms of the conversations that I was able to have with [Beatrice] or [Juno], or like, even, even the physics majors which – like, they- they'd, um, completely introduced me to new perspectives in the world of physics as well, so it was a good opportunity to learn from other people, just in terms of the discussions, mainly.

Victor Eremita: It's opened up the subject to me…when I go to the bookstore, I usually go to the philosophy section, or the art section, but, now I'm starting t' go to the physics section, to check out what's there, and it's very exciting to me…the range of topics to explore.

Frank: For me, I think, the number one thing was the input we would get every week from the two visual arts majors in the class, because … they were… so assertive … in, um, the way they understand things, and whenever they don't understand things, they would never hesitate right away t' come out and question things, and ask why, and, that led to a lot of really good discussion and…um, they say that when you… teach other people something you're helping yourself learn it even better at the same time, and I think that, for at least myself, trying to explain some of the more difficult ideas in physics to them, helped to…ingrain it into myself even further. … But, um…but it went both ways, because some of the things that they were saying about aesthetics and visual arts was also very compelling to me. … and,

> um…basically, every week that they were there was guaranteed to bring a lot of controversy and arguments, and that was great because that's a lot of fun.

The final projects were presented the week following the last class, and will be discussed in Chapter Six.

4.2. Positive Results of the Maryland Physics Expectations Survey

The Maryland Physics Expectations Survey (MPEX) was developed at the University of Maryland by Edward Redish and colleagues (Redish, Saul, and Steinberg, 1998, hereafter referred to as RSS) to test learning gains in traditional introductory physics courses in a variety of settings, from large universities to small colleges, in a variety of contexts, from large lecture classes to intimate classes based on interactive methods. Although the student population and the course content and structure were completely different from a traditional introductory course of "Physics for Scientists and Engineers" for which the survey was designed, we decided to administer the MPEX as a baseline consistency check. The results of the original survey indicated a disappointing decline in students' attitudes towards physics after one semester of introductory instruction. Our expectation was that in using the MPEX with students in CCS-120 we would obtain results that were not consistent with traditional introductory physics courses, in that our students should show positive gains in attitudes towards physics after taking this course. Indeed, our results are not consistent with the results for traditional courses. Whereas students in traditional courses tend to show a decrease in their attitudes towards physics with no change in the percentage of "no opinion" answers, our students showed a definite increase in their positive attitudes towards physics as well as a definite increase in their tendency to have opinions (a decrease in their "no opinion" answers).

RSS defined two domains of learning – the cognitive and the affective - in which instructors hope students will gain, as a result of their courses. The cognitive domain in introductory physics typically encompasses knowledge of physics, confidence in solving problems, and the ability to apply techniques from one content area to solve problems in another. The affective domain encompasses attitudes toward physics, including the belief that physics is important in everyday life, that physics is accessible to everyone and not just "smart people," and the belief that physics is an interconnected discipline rather than a collection of isolated facts. Although instructors typically concentrate their efforts in the cognitive domain, they also have a "hidden curriculum" which aims to improve students' attitudes toward physics in the affective domain.

In their benchmark study of 1500 students enrolled in traditional introductory physics courses ("Physics for Scientists and Engineers," which starts with Newtonian mechanics), RSS demonstrated that not only did most students' attitudes in the affective domain actually *decrease* over the course of a semester of introductory physics, but students actually improved their performance on homework and exams when they adopted certain behaviors of memorizing equations and solving large numbers of problems from the book, without really trying to understand what they were doing. In other words, RSS discovered that when students adopted the behaviors which led to good grades in their introductory physics courses, their actual learning of physics concepts, understanding the deeper connections between mathematics and the physical universe, and seeing the connections between physics and their daily lives, decreased, as measured by the metric they developed.

The MPEX was developed to probe students' attitudes in six affective domains that instructors who participated in the RSS study believed should be important for any student's ability to understand and succeed in introductory physics:

1. *Independence* — beliefs about learning physics — whether it means receiving information or involves an active process of reconstructing one's own understanding;

2. *Coherence* - beliefs about the structure of physics knowledge — as a collection of isolated pieces or as a single coherent system;

3. *Concepts* - beliefs about the content of physics knowledge — as formulas or as concepts that underlie the formulas;

4. *Reality Link* - beliefs about the connection between physics and reality — whether physics is unrelated to experiences outside the classroom or whether it is useful to think about them together;

5. *Math Link* - beliefs about the role of mathematics in learning physics — whether the mathematical formalism is used as a way of representing information about physical phenomena or mathematics is just used to calculate numbers;

6. *Effort* - beliefs about the kind of activities and work necessary to make sense out of physics — whether they expect to think carefully and evaluate what they are doing based on available materials and feedback or not.

RSS developed three research questions around which they designed their survey (p. 1):

> Q1. How does the initial state of students in university physics differ from the views of experts?
>
> Q2. To what extent does the initial state of a class vary from institution to institution?
>
> Q3. How are the expectations of a class changed as the result of one semester of instruction in various learning environments?

Regarding the third question, in the conclusions of their 1998 paper, RSS stated:

> In all cases, the result of instruction on the overall survey was an increase in unfavorable responses and a decrease in favorable responses. Thus, instruction produced an average deterioration rather than an improvement of student expectations. (RSS 1998, p. 7).

In order to see if my course could have a more positive effect on students attitudes towards physics than a traditional introductory course, we planned to administer this survey as a pre-course and post-course metric. The results of the MPEX survey on the students of CCS-120 are not consistent with those reported by RSS, in that my students showed an overall *increase* in favorable responses, and an overall *decrease* in "no opinion" responses. What portion of these positive results is attributable directly to this course cannot be determined, as most of the students were also physics majors, concurrently enrolled in other physics and math classes. The surveys were conducted anonymously, hence the responses of the physics and art majors cannot be distinguished, however personal interviews and comments, some of which have already been reported above, support the positive survey results.

4.2.1. Comparison of Target Populations

The student population, the course contents and objectives, the assignments, and the grading policies for the course under study were completely different from the traditional introductory physics course for which the MPEX was originally developed. The initial expectations of the students who enrolled in CCS-120 were also completely different from those who enroll in a traditional introductory course, never the less, we report the results here as a baseline comparison with traditional introductory physics courses, to be used *with caution*. The student populations for whom this survey was originally designed take the traditional calculus-based introductory physics sequence, starting with kinematics and Newtonian dynamics. The original populations who participated in the survey are shown in Table 4.4 from RSS. The student population of CCS-120 was described in Table 4.1.

The College of Creative Studies (CCS) is a small college within the larger university, which is dedicated to serving “gifted” students, advertising itself as “A Graduate School for Undergraduates.” Instead of grades, CCS assumes that all its students’ work is at the B or better level, and credits are awarded based on the amount of assigned work completed (Dr. Bruce Tiffney, Dean of the CCS, personal communication, March 12, 2007). Students who are accepted for admission to UCSB, who wish to attend CCS instead of the general College of Letters and Sciences, must submit a separate application. Acceptance into one of the eight available majors at CCS is referenced to criteria that are unique to each discipline. Although students may change their major, they must apply to CCS in one of the eight disciplines offered; while all students accepted into CCS are considered “bright” and “gifted,” the criteria for admission into the college are determined by the faculty in each discipline. The CCS physics program for physics majors is very different from the general introductory physics sequence taught in the Physics Department “for scientists and engineers;” both are very different from my symmetry-based introductory physics course.

Institution	Instructional Characteristics	N
University of Maryland, College Park (UMCP)	traditional lectures, some classes with group-learning tutorial instead of recitation, no lab	445
University of Minnesota, Minneapolis (UMN)	traditional lectures, with group-learning research designed problem-solving and labs	467
Ohio State University, Columbus (OSU)	traditional lectures, group-learning research designed problem-solving and labs	445
Dickinson College (DC)	Workshop Physics	115
a small public liberal arts university (PLA)	Workshop Physics	12
a medium sized public two-year college (TYC)	traditional	44

Table 4.4. Original student populations surveyed (RSS, 1998, p. 3.).

Six of the eleven students who participated in my course were CCS physics majors: four first year students, and two fourth year students. Three of the four first-year students, although in their first year at UCSB, as of Winter Quarter had sophomore status, due to their Advanced Placement credits from high school. All of the CCS physics majors were taking other physics courses concurrently with my course. The two fourth year students were taking graduate level quantum mechanics, and the four first year students were taking the second quarter of the two-year introductory sequence for CCS physics majors, which focused on Oscillatory motion, Rotational motion, Angular momentum, Gravity and central force motion, and Elastic waves. Their texts for that course were Kleppner, D. and Kolenkow, R. J., *An Introduction to Mechanics,*and Resnick, Halliday, Krane, *Physics, Vol 1, 5th ed.* Two carefully selected professors share the CCS introductory physics sequence, each one remaining with the same group of students for two years. The classes are kept intentionally small, and are taught in a seminar-like fashion. The curriculum is more theoretically oriented than the regular introductory sequence.

The single non-CCS student was a geophysics and East Asian Studies double-major from the College of Letters and Sciences, who had taken the traditional Physics for Scientists and Engineers introductory sequence. There is one required text, H. D. Young and R. A. Freedman, *University Physics with Modern Physics, 11th Edition*, which is used for all five quarters. The regular introductory sequence consists of large lecture classes of 200 – 300 students in a large hall, with optional problem sessions of 25 students, run by graduate teaching assistants. A traditional laboratory class once per week, which is not tied to the lecture in any way, is added in the third quarter. The regular course makes extensive use of the Internet for delivery and grading of homework.

The four the arts majors in CCS-120 had had no college physics experience, and only one, Juno, had taken physics in high school (beyond the level of junior high physical science). Juno (sculpture major) grew up in Germany, and had taken physics and math in high school for six years, and one year of college algebra; the other three had never experienced a physics course before, neither in high school nor college, and had limited experience with any math beyond algebra. Thus, the initial conditions of the students in CCS-120 were quite different from those of the students who received the MPEX in the RSS study, never the less, the results at least indicate overall positive gains in attitudes towards physics.

4.2.2. Computation and Reporting of the Results

The MPEX scores for my class were computed in three ways:

(a) "A-D" graph. Following the procedure of RSS, the percentage of "agree with expert" responses and "disagree with expert" responses were calculated, and "no-opinion" answers were not counted;

(b) Total scores for each student, all questions, were computed by assigning +1 to "agree with expert," -1 to "disagree with expert," and 0 to "no opinion;"

(c) Total scores for each question, all students, were computed in the same manner. The calculations were done using Microsoft Excel as follows:

(1) Raw scores were input into Excel, as entered in the MPEX on a five-point scale: 5 = strongly agree, 4 = agree, 3 = no opinion, 2 = disagree, and 1 = strongly disagree.

(2) Responses were coded using a short Visual Basic Macro (VBM) that I wrote. Responses of 4 or 5 were coded as A (agree with statement);

Responses of 1 or 2 were coded as D (disagree with statement);

Responses of “NA,” 3, or blank, were coded as zero.

(3) Expert answers given by RSS for each question, given as either A or D, were compared to each student’s results, using a second VBM. Where the student’s answer matched the expert answer, a value of +1 was assigned; where the student’s answer did not match the expert answer, a value of -1 was assigned; if the student’s response was 0, it was left as such.

(4) The number of times a student’s response was +1, -1, or 0 was counted, using a third VBM.

(5) The scores for each test were averaged to obtain a numeric answer. Thus, on a continuum scale from -1.0 to + 1.0, a score of -1.0 would indicate 100% disagreement with the “experts,” a score of +1.0 would indicate 100% agreement with the experts, and a score of 0 would indicate an absence of opinion on any of the questions.

Figure 4.7 shows the “AD plot” of responses of students in CCS-120 after Redish, Steinberg, and Saul (1998). The horizontal axis represents percentage of “unfavorable” responses, meaning disagree with the “expert” responses; the vertical axis represents percentage of “favorable” responses, i.e., those which agree with “expert” responses. According to RSS, when graphed in this way, the perpendicular distance of any point from the diagonal line represents the percentage of null or neutral responses. The “expert” average response reported by RSS is represented by the green “cross” in the upper left corner. Individual changes are shown in Figure 4.8

as “vectors” from pre-test to post-test response. A comparison between the students in the RSS survey and those of the present study is shown in Figure 4.9.

In general, when plotted according to this format, the students in CCS-120 showed overall gains in the percentage of favorable responses, in contrast to the students surveyed by RSS, who showed an overall tendency to decline in the number of favorable responses. The students in traditional courses in the RSS survey also remained approximately parallel to the diagonal line at the same distance, on their pre- and post-test averages, implying that their percentage of null or “no opinion” answers remained the same. Such responses are consistent with the idea that traditional physics instruction does not encourage students to form opinions about physics. Again, the percentage of null answers by students in CCS-120 was not consistent with the trend observed by RSS for students in traditional courses. The general trend for students in CCS-120 was to decrease their percentage of null answers from pre- to post-test. Moreover, since the percentage of favorable answers also increased, the implication is that regarding questions for which students initially had no opinion on the pretest, they had developed a positive opinion by the end of the course. I believe that this increase in the quality of “being opinionated” about physics may be due to the format of this course, in which having an opinion was important for each written assignment and each class discussion. Even in the CCS physics classes, students are not regularly asked for their opinion about an author’s point of view regarding physics.

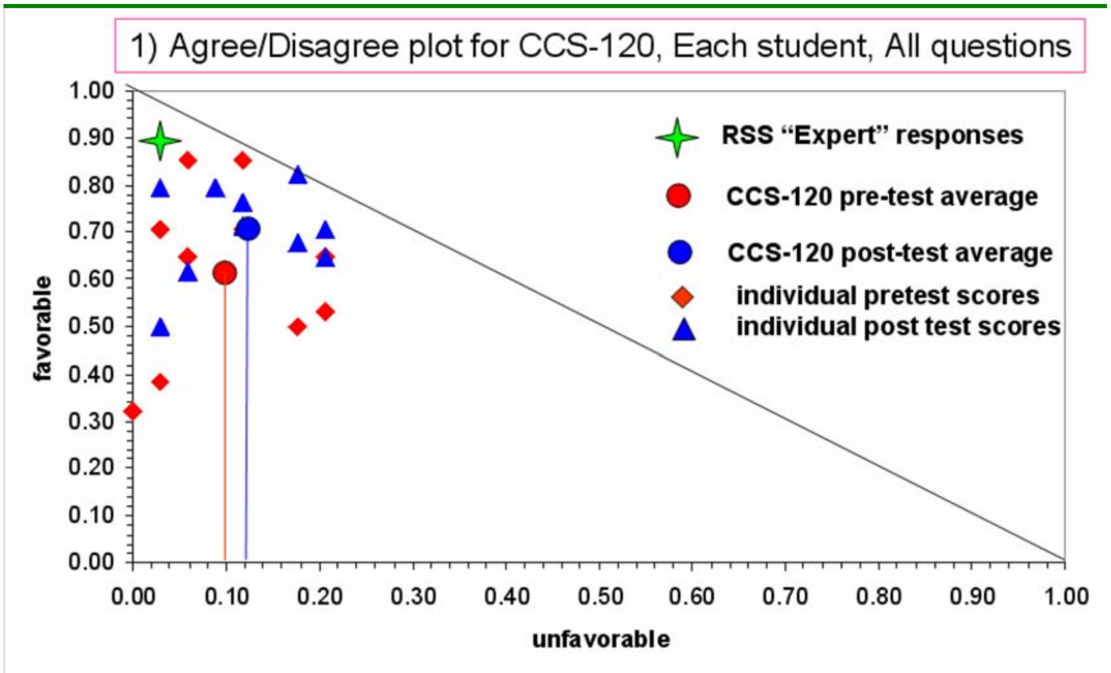

Figure 4.7. "AD plot" of responses of students in CCS-120, after RSS (1998).

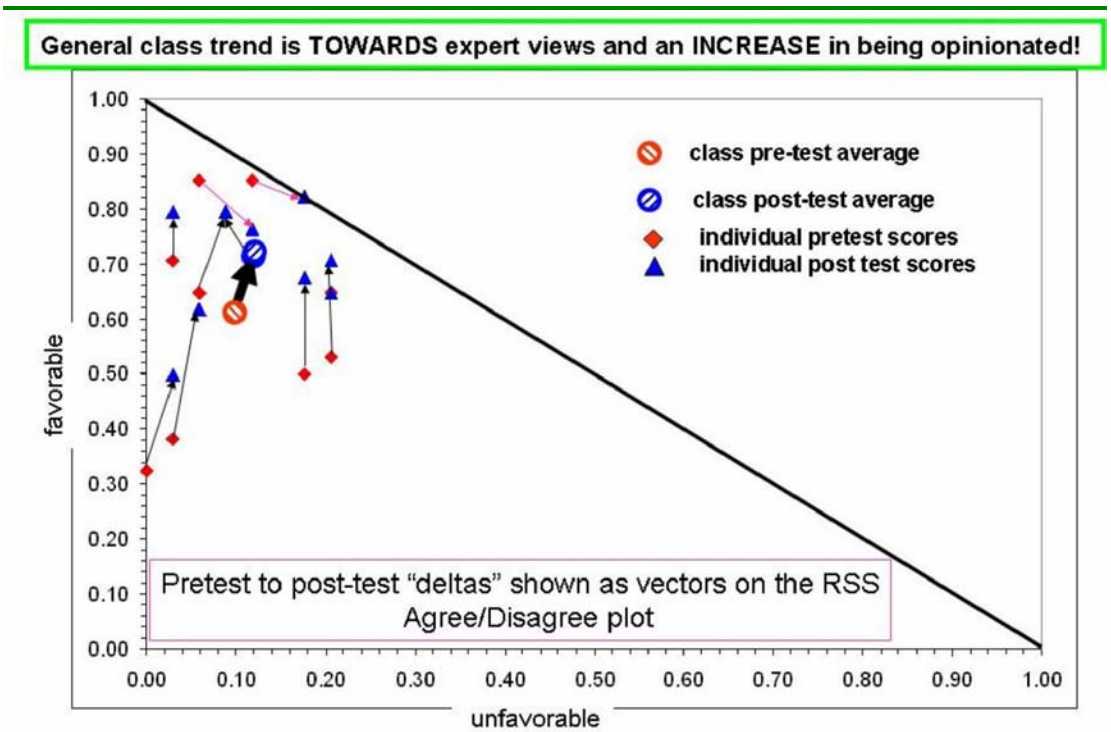

Figure 4.8. Pre-to-post test "score vectors" for individual students in CCS-120.

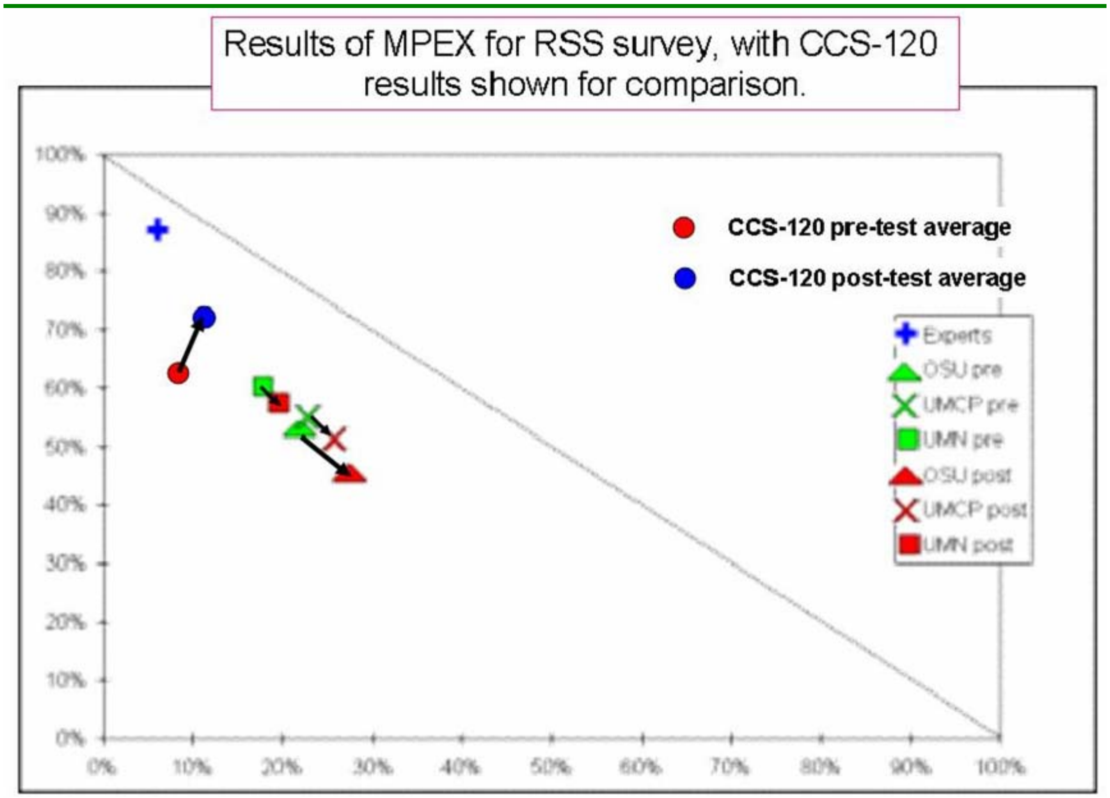

Figure 4.9. RSS 1998 data (p.9) shown with results for CCS-120. S (1998).

4.2.3. Analysis of the Results.

Besides the "Agree-Disagree" method of reporting student scores of RSS, I chose to look at the total scores, as described in the previous section. I prefer to visualize students as falling on a continuum, between -1.0 as standing for "having 100% novice opinions" to +1.0 as "having 100% expert opinions" with 0.0 indicating no opinion. Figure 4.10 displays the total pre-course and post-course scores for each student. Three observations are apparent from the chart: First, that there was an overall increase in positive attitudes toward physics over the course of the quarter; second, that students who came in with lower expectations of physics gained a larger percentage than those who came in with higher expectations; and third, that the two students who came in with the highest expectations actually declined somewhat in their attitudes over the course of the quarter. Although this result may be unsettling at first glance, it is most likely due to other factors that will be discussed below.

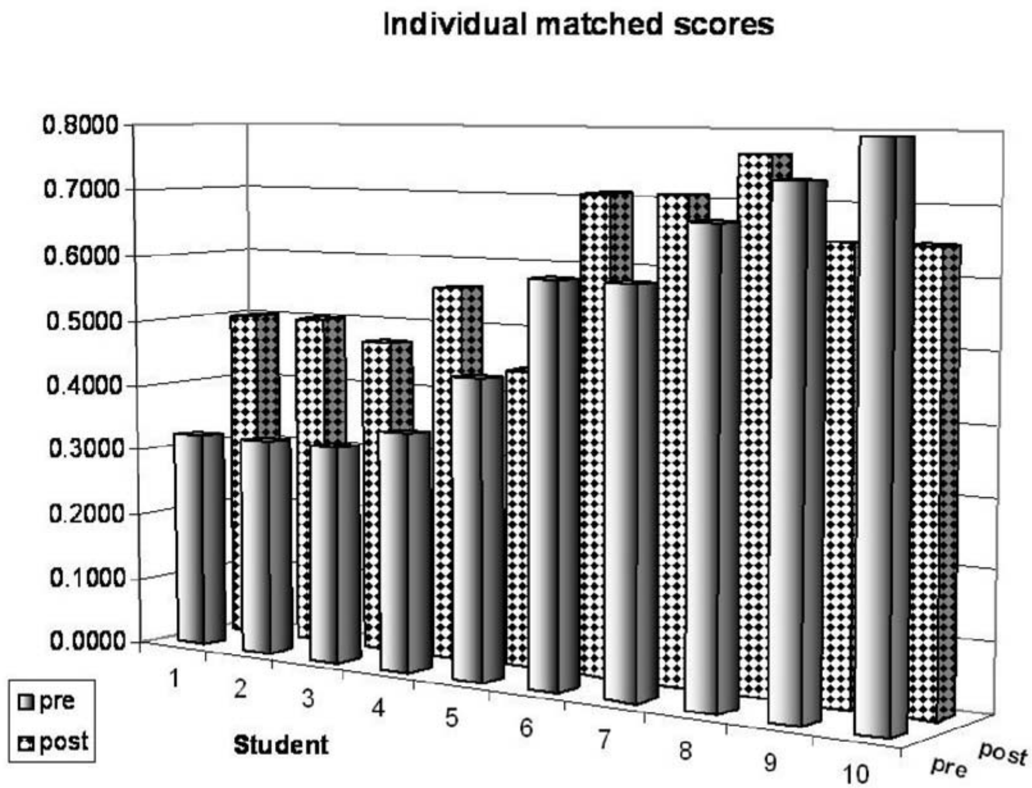

Figure 4.10. Individual pairs of pre- and post-test scores.

When the students' matched pairs of scores are plotted on an x-y graph, as (pre, post) pairs, (Figure 4.11) we can see this explicitly. Using the trend line function in MS Excel to compute a linear regression fit to these data, we find the least-squares best-fit line as:

$$y = 0.48x + 0.35$$

(dashed line in Figure 4.11). To interpret the meaning of this trend, we consider that if there were no changes in students' attitudes during the quarter, then we should expect to see a slope of one, that is, pre-course attitude should equal post-course attitude. This hypothetical line is shown in blue (solid line), and indeed one student does lie on this "gain of zero" line. Students who lie above this "gain of zero" line have positive attitude gains, "towards expert," and students who lie below this line appear to have negative attitude gains.

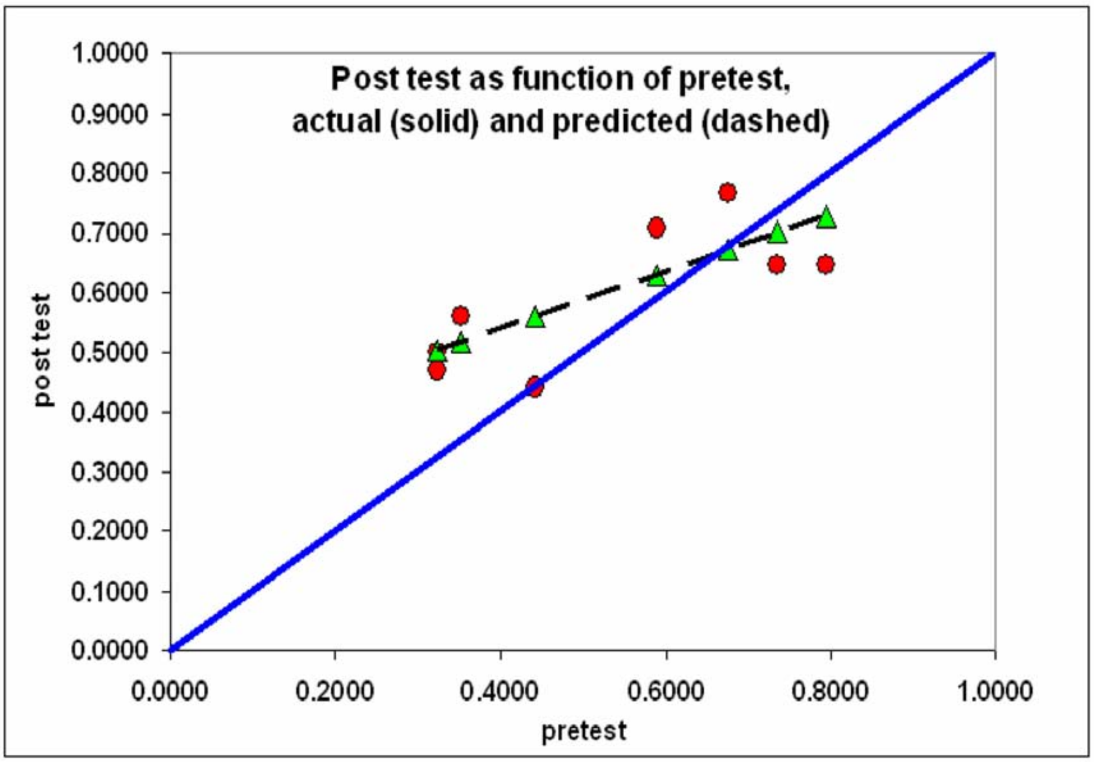

Figure 4.11. Plot of students matched pairs of pre- and post-test scores.

Predicted post-course MPEX scores were calculated using the equation of the trend line, and "residuals" computed as the difference between predicted and observed outcomes. That slope of the fitted line is less than one implies that students who entered at the “less expert, more naive” end of the spectrum showed greater gains “towards expert” than students who entered with a more expert-like attitude. The “cross over” point occurs at a pre-test score of approximately 65%. RSS discuss the possibility that students who enter a physics course with overly optimistic expectations may display a deterioration in attitude after their experience in class. All but two (students #9 and #10 in Figure 3) lie above the zero-gain line. Since the survey was conducted anonymously, it is not possible to know who these two students were, however it is likely that they were upper division physics majors, as will be discussed below. I believe that the situations in which RSS applied the MPEX and this situation are sufficiently different that a decline in attitude of these two students as regards this course is not due to a decline in their attitudes towards physics classes in general, but that these two students may represent the fourth-year physics majors for whom this course was considerably easier than their other classes.

Total score for each question, all students: It is interesting to note the number of times the average response of the class as a whole to a question evolved “towards expert” or “away from expert” or remained unchanged over the course of the quarter. For twenty-three questions, the average change in students’ opinions was in the direction of the expert response (“positive delta”); for six questions, the average change in student opinion was away from the direction of the expert response (“negative delta”), and for five questions the average response both before and after the course was to agree with the experts (favorable response, zero delta). These results are summarized in Table 4.5.

Positive delta	Negative delta	Favorable response, zero delta
23	6	5

Table 4.5. Total number questions with positive, negative, and zero change.

Figure 4.12 displays the pre- and post-test scores for each question, averaged over all students. On most of the questions, the responses showed an increase in favorable attitudes. These favorable responses will be discussed first. The few examples of anomalous, unfavorable responses can be accounted for by the inappropriateness of those particular questions to the conditions that prevailed in CCS-120. Table 4.6 displays those questions with the most favorable responses, both before and after the course. It should be kept in mind that a positive answer indicates agreement with the expert opinion, not necessarily with the statement.

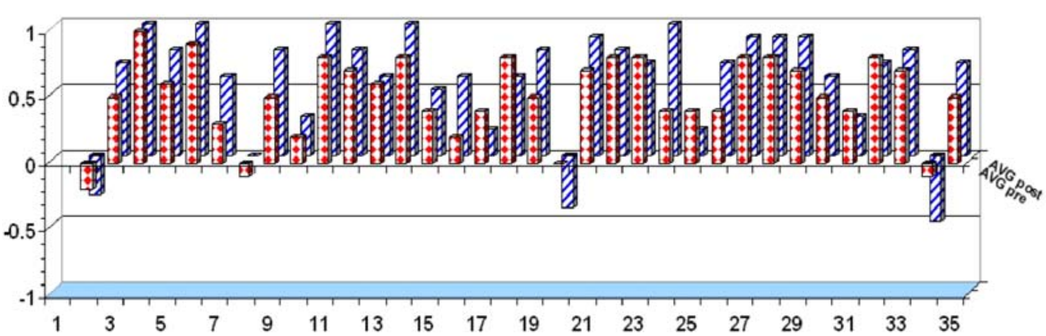

Figure 4.12. Individual questions, pre- and post-test scores, all students.

It should be noted that the only question which I altered for use with CCS-120 was question 3. The original question interrogated students' attitudes towards testing, and as I was not planning to give any classroom tests, I changed it to reflect my intention to encourage creativity in physics.

Original question 3: I go over my class notes carefully to prepare for tests in this course.

Modified question 3: Creativity is mainly important for subjects such as art and music, and has little to do with physics.

no.	QUESTION	AVG. pre	AVG post	delta
3	Creativity is mainly important for subjects such as art and music, and has little to do with physics.	1.0	**1.0**	**0.0**
5	Learning physics made me change some of my ideas about how the physical world works.	0.9	**1.0**	**0.1**
10	Physical laws have little relation to what I experience in the real world.	0.8	**1.0**	**0.2**
13	My grade in this course is primarily determined by how familiar I am with the material. Insight or creativity has little to do with it.	0.8	**1.0**	**0.2**
26	When I solve most exam or homework problems, I explicitly think about the concepts that underlie the problem.	0.8	**0.9**	**0.1**
27	"Understanding" physics basically means being able to recall something you've read or been shown	0.8	**0.9**	**0.1**
20	If I don't remember a particular equation needed for a problem in an exam there's nothing much I can do (legally!) to come up with it.	0.7	**0.9**	**0.2**
28	Spending a lot of time (half an hour or more) working on a problem is a waste of time. If I don't make progress quickly, I'd be better off asking someone who knows more than I do.	0.7	**0.9**	**0.2**
21	If I came up with two different approaches to a problem and they gave different answers, I would not worry about it; I would just choose the answer that seemed most reasonable. (Assume the answer is not in the back of the book.)	0.8	**0.8**	**0.0**
11	A good understanding of physics is necessary for me to achieve my career goals. A good grade in this course is not enough.	0.7	**0.8**	**0.1**
32	To be able to use an equation in a problem (particularly in a problem that I haven't seen before), I need to know more than what each term in the equation represents.	0.7	**0.8**	**0.1**

Table 4.6. The questions which had the most favorable responses.

Since this question is not part of the original survey, I determined that the expert opinion for this question should be *Disagree.* The perfect score of +1.0 both before and after the course for question 3 indicates that 100% of the students disagreed with this question (agreed with the expert opinion) both before and after the course. Questions 13 and 27 were considered by RSS as part of their “Independence Cluster.” The complete or near-complete agreement with expert opinions on these questions 3, 13, and 27, both before and after the course, most likely indicates that these students are highly independent as well as creative, which is consistent with their being in the College of Creative Studies. Questions 5, 26, 27, and 32 were considered by RSS as part of their “Concepts Cluster.” A high percentage of agreement on these questions indicates that the students place greater importance on the concepts underlying the equations than simply on the equations themselves. Questions 10 and 11 were considered by RSS to measure students’ attitude toward physics as relating to their own experiences, and agreement with experts on question 20 indicates a healthy connection with mathematics as a language. At the same time, answers which disagree with “expert” opinions do not necessarily indicate a naive viewpoint on the part of these students. As RSS pointed out, students often interpret a question on the survey in ways that may appear inconsistent with their behavior in class, or the opinions they give in person. To fully compare our results with those of the RSS study, we divided the overall results into the six clusters defined by RSS. The percent of agree and disagree scores per cluster were computed by taking the total number of student answers in each cluster, and finding the ratio of agree, disagree, and neutral responses per cluster. Thus, a cluster score of 1.00 would indicate that every student agreed with the expert opinion for every question in that cluster.

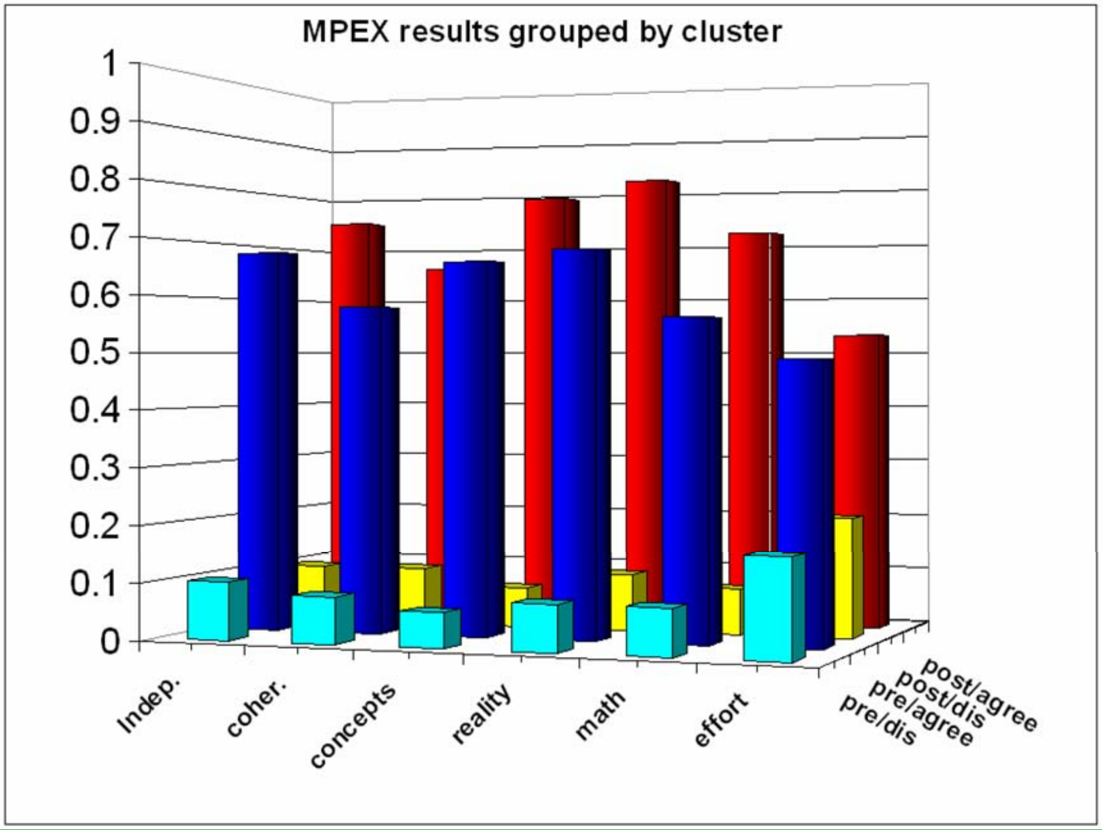

Figure 4.13. Results of MPEX grouped by clusters.

All cluster scores showed a general increase in attitude responses. Of particular interest is the positive gain in the math cluster, defined by RSS as beliefs about the role of mathematics in learning physics, whether the mathematical formalism is used as a way of representing information about physical phenomena or mathematics is just used to calculate numbers. A positive gain in the math cluster indicates that the students recognize the connection between mathematics and the physical universe. This positive gain in the math cluster for the CCS-120 students is opposite from the trend in the introductory students surveyed by RSS, who showed zero gain or decrease in their beliefs that math is connected to physical reality. This positive trend may be attributable to the large percent of time we spent talking about math.

Indeed, some of the most heated and passionate discussions, in which every one seemed to hold a strong opinion by the end of the course, were about the "power" of mathematics as a language. In traditional introductory physics courses, math is introduced as necessary to pass the course; I tried to emphasize that math is necessary as a language with which to perceive aspects of the physical world with which we cannot have direct experience by direct contact. At first, students appeared baffled by this notion, but by the end, the final discussion of the course about "The Unreasonable Power of Mathematics," was the single liveliest discussion of the quarter. This idea seemed to touch something fundamental for each student, and the discussion became a very heated and passionate one, in which all the students – art, literature, and physics – participated with equal enthusiasm. In most traditional courses students are taught to use math, but it is not typical for instructors to encourage students to ask why mathematics – supposedly a human invention – seems to be so "embedded" in nature. As I will discuss in Chapter Eight, including discussions about mathematics before, during, and after an introductory physics course, is one of the strongest recommendations that can be derived from this experiment in aesthetic physics education.

Anomalous Results Explained: Two questions stand out as being anomalous in that the majority of CCS-120 students disagreed with the experts before and after the course. These were questions 1 and 33:

> 1. All I need to do to understand most of the basic ideas in this course is just read the text, work most of the problems, and/or pay close attention in class.
>
> 33. It is possible to pass this course (get a "C" or better) without understanding physics very well.

At first glance it seems strange that they should maintain novice opinions when they are highly sophisticated learners, however when considered in the light of the physics courses that most of them were taking in addition to this class, the anomalous answers may be seen as consistent with their opinions of *this* course as being far easier than their “normal” physics courses. A quote from Sam’s interview regarding the course in Classical Mechanics, in which he was concurrently enrolled, supports this hypothesis:

> I just, had to, spend every second of class time focused on- in Physics 105A- focused on absorbing the material from the board and from the lecture, and then attempting to make some – some sort of sense of it and uh, and trying to write it down at the same time and possibly make a visual diagram of it. It was considerably more stressful.

The expert opinion for Question 1 is Disagree. According to RSS, university professors expect that students must take responsibility for constructing their own understanding, a process which they feel should go beyond simply following the information that is given to them by authorities. From Sam’s description, it appears that he did follow what RSS considered expert strategies in his Classical Mechanics class; in my class, these strategies were not necessary. In their post-course interview Frank and Manny, two first-year physics majors, freely admitted that they tended to put off reading the articles I assigned for homework until right before class, reading just enough to be able to contribute to the discussion. This also supports my hypothesis that these anomalous results are actually appropriate for *this* class.

> **Frank**: For me it's always been a problem that reading assignments tend to get pushed to the wayside because it feels like…explicit like, problem sets are more REAL, like, this has t' be handed in, and it's gonna be corrected, and- and returned, whereas, a reading assignment, if you just skim it before class, and you're just gonna talk about it, you can still hold your own if you know a little bit about the topic. So, um…I felt like I could get away with that a little bit.

> **Manny**: Bravo, I think that, I feel exactly the same way, I like – you couldn't 've put it - better, really, like those are exactly my thoughts.

The two art majors reported in their interview that they did indeed need to take notes and make sense out of them.

In conclusion, we can say that the results of the MPEX for these students are not consistent with the results for a general introductory physics course. The students' individual comments are more revealing of their true attitudes towards physics, mathematics, and this course than their responses on the survey. Some of their comments, listed below, illustrate their positive attitudes towards the process of physics, which make the MPEX results difficult to interpret in comparison with students from standard introductory physics courses:

> This class was the greatest source of inspiration for my artwork this quarter. It ignited an interest in physics that was never there before, and I'm excited to see what else I'll learn in the future. (email, March 27,2007)

Very interesting, this class addresses so many of the concepts that have haunted me for my entire life. It is nice to be able to name them now. (exit card, Jan. 19, 2007)

I wanted to discuss the universality of math, independent of humans. I thought it would yield many interesting perspectives. The guest lecturer inspired me. Now I want to do a computer (algorithm) generated art for the project for this class. (exit card, Jan. 19, 2007)

I feel doubtful that I will ever “click” with the math. I’m just very glad that my not-understanding does not make me feel desperate, as this seems sort of a “safe environment” where it is good thinking that counts, which I am capable of.(exit card, Feb. 9, 2007)

I wish we would go into more detail about the mathematical aspects. (Please.) Relativity is worth deriving. (exit card, Feb. 9, 2007)

While I have already seen the light clock on a train explanation, your explanation was very easy to understand. I am anticipating the explanation of mass and energy changing time and deforming spacetime because that link has not been made clear to me in past physics classes.(exit card, Feb. 9, 2007)

I feel as though this class is what I expected the physics class to be and I have really enjoyed the discussion and topics. I really appreciate my fellow students explaining ideas and walking me through them. I really enjoy the class. (exit card, Feb. 9, 2007)

I feel very proud that I feel I understood everything we discussed today – especially the mathematical derivation! Ahahaha! (exit card, Feb. 16, 2007)

> Divorcing the philosophy of nature from pragmatic mathematics. Perhaps it is necessary. Like god, not all statements can be proven within one theoretical framework. (exit card, Mach 2, 2007).

In Chapter Five I will present a detailed analysis of the curriculum ethnographic data – my teaching journal, students' interviews, and weekly exit cards of the students, and attempt to understand their reactions to this course in the context of other learning theories.

Chapter 5. Ethnography of an Integrated Physics-and-Arts Physics Class

> "Many people are stumped by high-school or college physics because they are presented with misshapen phenomenological equations having little to do with Nature's intrinsic essence, with Her beauty, Her symmetry, or Her fundamental simplicity."
>
> – A. Zee, Symmetry and the Search for Beauty in Modern Physics, 1992

In Chapter Four the contents of and rational behind the course Symmetry and Aesthetics in Introductory Physics were described. In Chapters Five through Seven the success of this interdisciplinary, interactive model for teaching physics with fine arts will be demonstrated through examples of students' personal comments (Chapter Five), students' written work (Chapter Six), and transcripts of video data (Chapter Seven).

5.1. Ethnographic Data and Emergent Themes

This chapter is primarily concerned with interpreting the data gathered in this class of physics and art majors, who came together, attracted by a course with an unusual title: Symmetry and Aesthetics in Introductory Physics. The field data consist of students' post-course interviews, my teaching journal entries, students' weekly exit cards, students' homework and class work, video data, comments sent to me via electronic mail (email), and the students' anonymous end-of-course evaluations.

In one sense, I cannot claim to have gathered true ethnographic field data, as a traditional ethnographer, acting as participant observer, would have done. As the instructor of the class, I was limited as to when I could write observations, which had to be done mostly after class, or after tutoring sessions. Although I made an effort to write observations after every class, admittedly there were days when I got caught up in after-class activities with some of the students, and forgot to write a timely journal entry. Of the classes that were filmed, only one was done by the Office of Instructional Development, in which I was the focus of the camera, wearing a microphone; I filmed the final presentations myself, as well as one of the guest lecturers (Stephen Travis Pope, March 16, 2007).

In another sense, if ethnographic research is defined as “the first-hand participation in some initially unfamiliar social world, and the production of written accounts of that world” (Emerson, Fretz, and Shaw, 1995: p. 1), then the weekly comments of the students after class, my teaching journal entries, transcripts of the video data and post-course interviews, can be considered ethnographic data, in that they represent written accounts of the "initially unfamiliar social world" of CCS-120, which was created every Friday afternoon at UCSB for ten weeks. It is in this sense that I have considered these data as ethnographic field notes. In reviewing the interview transcripts, weekly exit card comments, my teaching journal, and students' written work, five general themes which relate specifically to the teaching of introductory college physics, emerged:

1. Evidence that more time needs to be spent orienting students to math as a language rather than assuming that students, even physics majors, understand and accept math as a way of making sense out of the physical world;

2. Evidence that art is useful for promoting the learning of physics and math concepts;

3. Evidence that the class structure, with emphasis on discussion, peer interactions, and questioning over "right answers" created a safe environment for students to study physics, some of whom may have otherwise avoided it;

4. Evidence that as a result of reading original works by theoretical physicists, instead of traditional text books, both physics as well as art majors saw physics as a creative endeavor, and physicists as approachable people, instead of seeing physics as a collection of facts and equations, and physicists as exclusive people;

5. Evidence that this method can help students understand how to use logic to develop their imaginations to understand concepts in fundamental physics that are beyond our ability to experience directly.

These are the primary outcomes of this model for introductory undergraduate physics which support the general aims of the physics education community, as expressed in the physics education research literature: namely, to teach physics more effectively. In addition to the above themes, the interdisciplinary environment of CCS-120 revealed an unexpected outcome: the very real cultural differences between physics students and art students, which were apparent in every aspect of the teaching and learning of physics and math content. This cultural difference will be explained in the next section, and will define the theoretical framework within which to understand why the learning outcomes cited above are important to increasing diversity in the physics community.

5.2. Cultural Differences Between Physics and Arts Majors

One theme that emerges clearly from all these data is the very real cultural difference between the physics majors and the art majors. This difference has largely been missed by education research, which has tended to focus on either the problems of ethnic minorities in dominant-culture schools (Heath, 1982; Phelan, Davidson, and Yu, 1993; Ogbu and Simmons, 1998; Lee, 2003; Aikenhead, 2002; Hanrahan, 2002), or problems with teaching and learning of classical physics to dominant-culture students in mainstream introductory physics courses (Redish, et al., 1998; McDermott,1993, 2001; Mazur, 1997; Hestenes, 1996, among others). Studies of the first kind make the tacit assumption that all so-called dominant-culture students are alike, and are all equally capable of learning science *in the way it is taught* in dominant-culture schools. Studies of the second kind do not address the vast majority of college students who avoid taking physics altogether. One of the most useful outcomes of this study then, which is relevant to understanding issues of equity and diversity in physics in general, is that it exposes the very real cultural boundary between "physicists" and "artists" which exists, even within a group of students who are all from the so-called dominant culture majority of white, middle class, Euro-American students.

Anthropologist Sharon Traweek defined the culture of physics as "an extreme culture of objectivity; a culture of no culture, a world outside human space and time" (*Beamtimes and Lifetimes*,1988). One of the ways she described in which any community can exist, presumably within a cultural framework, can maintain its boundaries and procreate itself, is through education – how it transmits knowledge to the succeeding generations. In physics and in the arts, different ways of transmitting knowledge through education help create different cultural communities, even within the so-called dominant American culture. Eisner (2002) distinguished between the arts and sciences in education, in that in American education, science is considered dependable, cognitive, testable, teachable, and useful, whereas the arts are considered undependable, emotional, requiring special talent, and ornamental. Thus, even within an outwardly mono-cultural group of college students, there can exist a very strong cultural boundary that has been erected because of the way they have been trained to see the world, and themselves in it.

This boundary is orthogonal to other cultural boundaries, thus is invisible unless the other cultural differences such as language, race, or socioeconomic status are removed. The first step, then, in extracting from these ethnographic data the story of why this model was successful, is to understand the interactions of the students and instructor in this interdisciplinary physics-arts classroom from the perspective of a multi-ethnic or majority-minority culture classroom. Consider the following characteristics of such a model: The physics students formed the dominant-culture majority, both in the classroom where they outnumbered the art students by almost a two-to-one majority, and because their values more closely match those of the dominant culture in society at large. Math and the language of physics formed the dominant-culture means of communication, so that even though English was the common language, the different language usage between "math speakers" and "limited math proficiency speakers" had to be overcome. The ways of taking meaning from and making sense of the physical universe were different for the physics and art students, largely because of their different training. The expectations for the course were different for each group of students, because even though they had all received the same advertisement, their interpretations of the course description were very different. Finally, consider the instructor, although trained in both physics and dance, as a benevolent member of the majority culture, trying to find a way to transmit the dominant culture's knowledge and values to minority culture students.

When understood from this intercultural perspective, some of the seemingly contradictory behaviors of some of the students, and some of the conflicts between some of the students and the instructor can be understood, and the learning outcomes described in the previous section can be appreciated as being important in making physics knowledge more widely accessible. In the rest of this chapter, I will blend together the cultural framework and the learning outcomes, in demonstrating the success of this interdisciplinary physics-and-arts physics class with these students.

5.2.1. The Very Real Language Barrier of Mathematics

The cultural boundary between the dominant-culture physics majors and the minority-culture art majors was largely based on their respective levels of comfort with the language of math and physics. This boundary was effectively similar to those described in studies of intercultural, multi-lingual, or inter-racial classrooms. Lee (2003) noted that students with limited language proficiency, and ways of taking meaning from the world that are different from mainstream science, may have difficulty learning science in majority-culture schools. In the initial weeks of this course, the discourse of math and physics presented very real linguistic and cultural boundaries between the physics majors and arts majors.

I discovered how significant this language barrier was after the first homework assignment, when I tutored two of the art majors. I wrote in my teaching journal on January 22, 2007:

> I tutored two of the art majors in math yesterday for about 2 hours. It was fascinating and eye-opening to me to see just how little the "language acquisition" of mathematics is transmitted in our traditional education. They kept emphasizing to me that, in spite of "good educations," they never were given the opportunity, they felt, to acquire the language of math - hence their difficulty in speaking/writing/interpreting math now. It seems to be as I suspected all along: math is a very real language barrier to the physical sciences.

Although they expressed greater difficulty with mathematics than I had anticipated, they also expressed how much they were enjoying the class, which I also noted in my journal entry:

> They both said that this is their favorite class of the week, and they are happy to contribute to research that will make math/science/arts education better. Beatrice repeated that she really likes the freshness of this class, the fact that it is the first time such a class is being offered and that she is contributing to this effort, and that I am enthusiastic about it.

In her post-course interview, Beatrice spoke of her initial difficulties with the language of math:

> Beatrice: I remember when we were doing some of the math problems as well, getting confused, like when we were talking about x and y, and not realizing that that was about coordinates, and like, graphing, and thinking of it in a more, um, algebraic way of…what is it called? When the x stands for the unknown –

Corson (2001) discussed the use of "high status vocabulary " in reference to the discourse of the dominant cultural group and the problems faced by students from minority cultures in dominant-culture schools. In the context of CCS-120, we can understand physics discourse as high status vocabulary, often considered special and privileged by those outside the physics community (Bazerman, 2000). Beatrice commented on her initial difficulties with the language of physics as well as math:

> I didn't have the background to understand what we were discussing or what we were looking at. I didn't … understand the words we were using, the language that we were using, was such a issue for me, because …. I just didn't have the foundation to be able to…to come to terms with what we were discussing. And so that kind of threw me off a bit, as to…what we were looking at, and what WAS physics...

Phelan, Davidson, and Yu (1993) recommended that educators who attempt to create optimal environments for diverse populations need to facilitate students' successful navigation across cultural and linguistic boundaries. While their research was originally directed towards understanding the difficulties of minority culture students in mainstream American schools, their recommendations are applicable to interdisciplinary environments such as CCS-120, where the student population is more diverse than might be expected on the basis of race or ethnicity alone. Strategies such as small-group work where arts and physics majors were paired together, class discussions, and a final project in which physics, math, and fine arts were merged, and even the weekly anonymous feedback cards, all contributed to successful navigation of the language boundaries.

5.2.2. Arts Are Good, but Physics Is Better?

The "two cultures" phenomenon of arts and sciences, with the sciences being the more highly valued in American society, has been maintained in our system of education (Eisner, 2002). This hegemonious sense of valuing scientific knowledge over artistic knowledge emerged in some of the remarks of the students in their early homework essays. For example, compare the following responses to the question, "*Is there an aesthetic component to mathematics?"* from the first homework assignment, of one art student and two physics students:

Art student:

> I cannot speak about the greater concept of mathematics as I have no real knowledge about the subjects, however in relation to the golden ratio I believe that there is a simple yet unsettling beauty which enables the forms it creates to be interesting and intriguing.

Physics student 1:

> When you get down to pure mathematics, such as abstract algebra and number theory, there is nothing but art…. reading a book on a subject like real analysis is like going to an art museum.

Physics student 2:

> Mathematics most definitely has an aesthetic component, both in written and visual expression. Any mathematician has seen mathematical relations that he or she would describe as “elegant” or ”beautiful” and those that could best be described as “ugly.”

Notice how the physics majors do not begin with an apology for their lack of training in art before making their assertions that mathematics is aesthetic, while the art student prefaces her statement with an apology as to her lack of "real knowledge" of mathematics. The unspoken message may be that anyone is qualified to appreciate art, but only someone trained in mathematics can fully appreciate its inherent beauty.

This tacitly suggested sentiment is made obvious in the following comment by another physics student, in response to another article from the first homework assignment which discussed teaching of arts and sciences together:

> The author's comparison of art and science requiring similar levels of formal training is laughable to me…. nobody can intuit something like the structure of DNA that took years to discover, while any artist could decide how to make a sculpture or compose a song without any training.

As the course progressed, a sense of mutual appreciation seemed to develop, which was evident during the presentations of the final projects, in which all the 'physics works of art' were equally applauded.

5.2.3. Different Understanding of What It Means to Understand

Another salient difference between the physics and art majors was their different understandings of what it means to understand. Initially, the art majors tended to emphasize direct physical experience as the only reliable method for understanding something, whereas the physics majors seemed more willing to separate their personal physical experiences from their ability to understand a concept. This difference also extended to their different opinions regarding mathematics, in that the physics students approached math as a way of understanding the physical world, while the art students said they did not experience the world in terms of mathematics. An excerpt from the discussion during the third class, regarding the role of mathematics in our understanding of the physical universe, illustrates this:

Beatrice:
I don’t personally experience the world, uh,
the universe, as being, in mathematics,
that’s not HOW I experience it.
I do experience it… in rhythm,
and in a certain amount of SOUND.

Juno:
I feel like the way in which every single person
perceives what is going on around them
is always going to be perceived sort of like
through their PERSONAL individual filter.
And maybe for mathematicians that includes more math.
For artists it includes more art.

As the course progressed, the difference between understanding through logic and understanding through experience became somewhat of a challenge to the authority of mathematics, and of physicists, on the part of the art students - particularly by Beatrice. I noted in my teaching journal on February 20, 2007:

> In this class of physics majors and art majors, I am noticing a decidedly different mind set in both types of students. I find, actually, the physics students to be much more open minded than the art students! … The tenor of the physics students towards me seems to be one of questioning for understanding, not challenging me…Given a challenge of something new, they try to figure it out. If they get to something far out that they don’t totally understand, but they can somehow relate to the analogy, their reaction is more along the lines of, “Wow, this is cool!” They seem to relish coming head to head with a seeming paradox and then resolving it with a mathematical trick – like the Lorentz contraction, for example. They get pleasure, it seems, from contradicting their experience with logic to arrive at a

> new experience. There is a willingness to accept a paradigm shift – almost a thrill of embracing it – from the physics students. But with Beatrice, the conversation was different. I sensed in her questions a certain degree of resentment and resistance.

5.1.3.1. When Does It Make Sense to Not Understand?

Although Beatrice seemed to be gaining in comfort with using math, she seemed to simultaneously develop a position that physicists had "no right" to define something using mathematics as 'true' when such a definition ran counter to her direct experience. This stance made it difficult for her to come to terms with some of the concepts that are fundamental to contemporary physics, such as those of Special Relativity, which require the ability to visualize a reality that is outside our direct experience. The following excerpts from my teaching journal on February 20, 2007 reflect on this difficulty. I wrote these notes after a tutoring session in my office, when some of the students came, alone or in pairs, to discuss their projects or questions regarding homework or lecture.

> Our first "argument" was over the asymmetry of time and the nature of spacetime. She says, if time and space are not symmetric – that is, space goes in any direction but time only goes one way, you cannot say they are related. I say but even though we don't understand why this should be so, it is; and space and time are linked by the physical nature of the universe itself. She says you cannot link space and time into spacetime if time cannot go backwards.
>
> She follows the derivations that I took directly from Einstein – no intermediary text book – But still, after following the math completely,

> she still says, but this can’t be. You still cannot say that space and time are linked into spacetime. It should not be so.

Her response was quite challenging, in that she seemed to be denying the validity of the entire enterprise of physics! She continued her argumentation with me that day, regarding Feynman's explanation of why the two-dimensional surface of a cylinder is mathematically flat. This was part of a reading assignment which irritated her because of the redefining in mathematical terms of a concept which she had already defined through her direct experience. I reflected on this, too in my journal:

> She is uncomfortable with Feynman’s claim that the surface of a cylinder is a flat space. He uses the topological argument that, because parallel lines are parallel, and Euclidean shapes keep their shape on a cylinder, it is mathematically a flat space. She claims it is curved. She says, you cannot deny my experience; the cylinder is curved.
>
> She absolutely refused to accept my definition. Then R., who is a post-doc in experimental cosmology and with whom I share this office, jumped into the discussion, and tried to explain that this is a mathematical definition. Beatrice was very polite, but insisted that this is precisely what is wrong: claiming that a mathematical definition cannot replace what her experience tells her is correct. She insisted that the cylinder is a curved space because it is curved. It cannot be flat because her experience tells her it is curved. It seemed to me that she was saying that we have no right to take something from her direct experience – a curved cylinder – and define it mathematically as a flat space.

Beatrice's challenge of the authority of Feynman – a Nobel Laureate in physics! -to mathematically redefine words that have meaning in everyday language, is reminiscent of Herbert Kohl's (1994) discussion of the role of assent in learning. Kohl cited examples from his own teaching experiences when students appeared to refuse to learn when to learn what the school asked of them would pose a challenge or threat to their personal identity or integrity. Beatrice challenged me by her refusal to "learn" that the two-dimensional surface of a cylinder can legitimately be defined as mathematically flat space. She refused to separate her experience of the three-dimensional curvature of the cylinder from the viewpoint of imagining only the two-dimensional surface, as if by allowing herself to envision this mathematical perspective she would lose something of herself. She repeated several times that she would have had no problem with Feynman if, instead of making mathematical assertions, he would have said, "Let's explore the surface of the cylinder..." In fact, he did say this, in other words, by proposing that the reader imagine sightless bugs who are constrained to live only on the surface of the cylinder.

Beatrice continued her argument with Feynman the following day after class, with physics major AT, and reiterated it in the reflection she wrote for homework. She maintained that it was this sort of usurping by one physicist, of words which she understood, and redefining them in terms which she could not understand, that caused her to mistrust all physicists in general. Eventually she was able to come to terms with these concepts through her final project, which will be discussed in Chapter Six. At some point along the way, she experienced a turning point, which she described in her post-course interview as a "letting go" of preconceived notions, as she described in her post-course interview.

> …as I let go of any preconceived notions that I was trying to control, and just allowed myself to just be in the class, and experience what I was experiencing and think about what I was thinking, and not worry about it. It became clearer and clearer

Beatrice ended the course saying she would like to study more math and physics in such an integrated arts-sciences environment as this course provided. In other words, in an environment which valued her way of understanding, while providing a way for her to learn.

5.1.3.2. The Importance of Creating a Non-Threatening Environment

Hanrahan (2002) noted that successful science teaching should take into account psychological, sociocultural, and cognitive factors that students bring with them to class. She cited the importance of creating a non-threatening learning environment in promoting conceptual change, quoting an earlier study by Watts and Bentley (1987) in which they suggested that for conceptual development to take place, students must be encouraged to engage in 'free thinking' and 'free speaking,' in a climate free from fear of being wrong. Evidence that such a climate existed in CCS-120 is suggested by the following anonymous comment, apparently by one of the art majors, written on February 9, 2007:

> I feel doubtful that I will ever "click" with the math. I'm just very glad that my not-understanding does not make me feel desperate, as this seems sort of a "safe environment" where it is good thinking that counts, which I <u>am</u> capable of.

Hanrahan cited additional factors as being important in promoting learning of science, including: trust and consent between students and between students and teachers; whether students said that they felt personally affirmed; and the degree to which students were allowed to have input as to what went on in class. These factors were all cited at various times by students in CCS-120 as making the class meaningful for them. Particularly for the art students, these classroom climate factors were cited as important in promoting their learning of physics and math concepts, as noted by the following comments from the post-course anonymous evaluations, also by one of the art majors:

> I found this course to be wonderfully exciting. The instructor and the students were wonderful and passionate, which made the class a pleasure. I had to overcome and grapple with a lot of struggles with math and understanding the language of science. I wish that this class would continue, and I could continue to study the maths and science in such an integrated way. The instructor always made herself available and she spend a lot of time with her students so that she could really "teach" and "understand" her students.

Another art student wrote in the course evaluation,

> Overall, the course initiated a strong interest in physics. Before I had always thought it was beyond me, but now I can't get enough of it for art inspiration, etc.

In an editorial in *Physics Today,* physicist Jerry Gollub of Haverford College recommended the following practices in promoting successful teaching and learning of undergraduate physics:

> Engage students in arguing about ideas, facilitate peer interactions, diversify the types of practice and experiences that are included in assignments, connect physics to applications in other disciplines, …

> balance mathematical and conceptual reasoning, … and take care to learn from students through early and frequent feedback. (Physics Today, May, 2005, p. 11).

These practices were all part of the teaching and learning environment of CCS-120. Through readings, discussion, and peer interactions throughout the quarter, the art students gained their own sense of mastery over the math and physics vocabulary. In return, the same classroom practices produced a corresponding response as reported by the physics students, in that they gained their own sense of mastery over some of the terms from arts and humanities, as well as an increased appreciation for art as a way of knowing. In addition, each group seemed to be stronger in their own ways of knowing while considering that they would like further interactions with the other, for example: SS (physics major) said she now wanted to take an art history class, and Juno (sculpture major) said she wanted to collaborate with the physics department on future art projects. No one professed a desire to change majors – an observation which resonates with Lee's (2003) definition of a successful multicultural science classroom as one in which students successfully participate in mainstream science while simultaneously valuing their own ways of knowing.

In the next sections the various responses of the physics and art students to the post-course interview questions will be analyzed to illustrate their initial differences, how their views changed as a result of the course, the teaching and learning strategies that were most effective, and the overall success of this model of interdisciplinary teaching. In the last section of this chapter, I will analyze the responses of the one student who struggled more with the climate than the subject matter, and offer possible reasons and possible warning signs for future classes.

5.1.4. What's in a Name? Representing Identity by Choosing a Pseudonym.

The types of pseudonyms chosen by the physics and arts students, and the manner in which they went about choosing their names, reflects some measure of their personalities, which in turn influenced the ways in which they managed their interpersonal relations in the class, which in turn influenced to some extent their successful navigation (or lack thereof) through this unusual interdisciplinary environment.

For the physics majors, the choice of pseudonym was apparently not important. They either chose very simple names, or bypassed the process of selecting a pseudonym by using their initials. A few of the others were content to allow me to choose a name for them. Sam and AT illustrate the simplicity of this process for them:

Jatila:
I would like you to pick a name that you'd like to be referred to as.
Sam:
Ok, how about Sam.

Jatila
OK, so what name would you like to be known as?
AT
Like a name? a normal name? like a pseudonym? I guess my initials would be fine.

The three arts students who granted me interviews chose more elaborate names. Their choice of pseudonym as representational identity was apparently quite important to them. Beatrice and Juno spent almost ten minutes in the beginning of their joint interview trying to decide on suitable pseudonyms with which they felt comfortable. A brief segment of this portion of their interview illustrates this lengthy process:

> Jatila:
>
> So, I'm going to ask you to take pseudonyms…
>
> Beatrice:
>
> I couldn't think of a name –
>
> Juno:
>
> Oh, dear –
>
> Beatrice:
>
> I thought of a name, hah! but it's a bit outlandish.
>
> Juno:
>
> I feel odd with a pseudonym. It makes me feel uncomfortable…and…self conscious.
>
> <… some laughter and exchanges…>
>
> Beatrice:
>
> It's almost like an alternate identity that one must assume.
>
> Jatila:
>
> <Explains the procedure…> It's just a code.
>
> Juno:
>
> So, this…name. It will be published?
>
> Jatila:
>
> Yes. It will be part of my dissertation. So if you'd rather just be "student A" I can just make it "Student A."

After much discussion and hesitation over selecting a pseudonym, laughing at and rejecting suggestions from me that I name them after famous artists, or "Truth" and "Beauty" for the t- and b- quarks, they finally settled on Beatrice and Juno.

Victor Eremita chose his name without hesitation, apparently having given it some prior thought.

Jatila:

First I'm going to ask you if you would provide a name for yourself that hides your identity.

Victor Eremita:

Um, Victor Eremita.

Jatila:

How do you spell that?

VE:

Victor, V-i-c-t-o-r –

Jatila:

-right,

VE:

E-r-e-m-i-t-a

Jatila….

Eremita …what does it mean?

VE:

It's Latin for "the victorious hermit." It's…a pseudonym that Kierkegaard used.

Although Beatrice chose a name that was "somewhat outlandish," it seems to be appropriate for managing an artist's identity, calling to mind famous women artists such as Beatrix Potter (author and illustrator) and Beatrice Woods (artist and sculptor). Juno chose her name based on a name that she is called in her family, but what can be said of Victor Eremita, who chose to be represented with a name that means "Victorious Hermit?"

Bucholtz (1996) discussed ways in which some adolescents negotiate social relationships by creating oppositional identities which contrast with conventional heteronormal expectations. She pointed out that, in addition to speech patterns, conventions of dress and extracurricular interests, the choice of pseudonyms can also be understood as a marker of oppositional identity. She studied adolescent girls who deliberately chose the oppositional identity of "nerd girls," separating themselves from both the mainstream feminine group of "cool girls," and from conventional nerd identity, which is normally associated with the male gender.

Victor Eremita's deliberate choice of a pseudonym that means "Victorious Hermit" may be understood as possibly representing an oppositional identity in the context of CCS-120, where the two "mainstream" groups were the physics majors and the art majors. Victor Eremita, although technically an art major by the conventions of the College of Creative Studies, was distinct from the visual artists Beatrice and Juno in that he was a "Book Arts" major. He was also the only male in the class who was not a physics major. In addition, he was the only student who reported that he did not enjoy, learn from, or approve of, the discussion format as a way of learning. This sentiment is in direct opposition to both physics education research on the success of interactive instructional methods, as well as the recommendations for successful intercultural science classrooms (Lee, 2003; Aikenhead, 2002; Hanrahan, 2002, e.g.). I will discuss his situation at length in Section 5.3; next, I turn to an analysis of the students' personal statements during post-course interviews to document the sucessful outcomes of this experimental course in interdisciplinary physics and arts education, as well as offer suggestions for improvement in the future.

5.3. Students as Informants: Students' Post-Course Interviews

The interviews were done after the course was over, and the grades completed. Two of the physics majors – Frank and Manny – and two of the arts majors – Beatrice and Juno – did their interviews in pairs. The others - SS, AT, Sam, and Victor Eremita - spoke with me alone. Al, Charlie, and MKS did not respond to my requests for interviews. I asked all the students the same basic questions: Why did they enroll in the course; did they get out of it what they had expected or hoped for; what aspects did they like most and what least. For the physics majors, I asked if this course had been similar, complementary, or completely orthogonal to their regular physics classes, and if this course had changed their outlook on physics in any way. For the art majors, I asked if this course had changed anything about the way they saw themselves using physics in their work in the future. I also asked all the students if they thought this model of integrated physics and arts education would be applicable to younger students as well as teachers in training.

5.3.1. Reasons for Enrollment

Reasons given by both physics and art students as to why they had initially enrolled in this course were basically the same: because it sounded inherently interesting. The physics students said they already had some degree of familiarity with one of the arts (art or music) and were interested in seeing how they could blend their interests through this course; the art students said they wanted to learn how to apply physics to their art.

Physics majors:

SS: I enrolled in this course...because, um, well, when I chose to do physics it ... well, it was... because, kind of,... I don't want to say spiritual, because that's kind of like...too... "aaah" <waving hands> but it's like an appreciation that goes deeper than just interest in the subject...and...like...kind of a similar thing that I feel when I play music which is an aesthetic thing, and I felt the same way about some aspects of physics, so ... I guess that's why.

Manny: Well, ... it’s a lovely mixture between physics, math, and art…and symmetry. There’s not much you’d want to miss. It’s…pretty perfect in every way…It’s a nice mixture between everything that both of us like. Like music, and that type of thing. So…it was…perfect. What do you think [Frank]?

Frank: Yeah, ah, there was a really enticing course description up in the CCS building, ah…that said all this stuff, like how could physics and math be applicable to dance, or music, or art and all these things, and it just sounded like a really good way to get a different perspective on what we’re doing in the physics program, and what other people are doing in other programs. So it sounded like a great way to get some well roundedness out of the hard sciences.

AT: I thought it’d be fun. <little laugh> Mmmm – yeah, um, Interdisciplinary thing is a big plus.

Sam: It sounded cool. The incorporation of art, of humanities into physics. Like, even though that’s the entire essence, or theme of the course, it’s the reason why I signed up for it and it’s the aspect that I liked the most. Um…like I, I originally had an interest because I figured that I would get to talk about – or you would talk about –

Escher at some point….and his connection with the world of physics and mathematics at the time. The whole analysis of art in terms of physics, and vice versa, was something I really hadn't had the opportunity to do in a classroom setting before, so I jumped to take it.

Art majors:

Beatrice: Um, I have this book, that I had gotten from my mom, that is called Art and Physics, by Leonard Schlain, and I had been reading it, And I thought that it was an interesting idea …to mirror… Because in art, the three main subjects you talk about are time, space, and memory, And … in physics you have… time and space, as such a major component, they're so much … there ARE so many relationships that can be drawn between the two. …. And…um…then… when I was reading the course description,

I thought that that sounded really interesting, …so…it just seemed like a kind of natural thing for me to kind of investigate. And, it would add to my KNOWLEDGE as a person, so I thought it could give me some reference for my work, in understanding how I MAKE work, and how my work relates to the ideas of time and space.

Juno: It was like, Oooh, I just saw the words Symmetry and Aesthetics, and, I don't know…I guess the word Aesthetics triggered … sort of like, Oooo, and I thought it was really, really INTERESTING that it related to PHYSICS, oddly enough, and so I thought, Oh, this sounds so interesting that I just have to check it out. I don't know why, and, um, I thought, since I'm…this was my second quarter at CCS, and I thought, This sounds like a TRUE CCS interdisciplinary class, like, what I was really excited about TAKING at CCS, so I thought.. .this should be my first venture into the interdisciplinary realm of CCS. It was a good idea, I took it.

> **Victor Eremita**: I was starting to be interested in numbers, proportions, in art…and also…. I've always…..appreciated Nature, and I wanted to see…how…the underlying principles in Nature, and how I could apply those same principles to the art.

5.3.2. Physics and Art Majors had Different Expectations

The title of the course, Symmetry and Aesthetics in Introductory Physics, generated different expectations for the art and physics students, as to what the course would be about. For the physics majors, this course provided enrichment beyond their regular program, and they felt that the course met their expectations. They enjoyed the explanations of symmetry, and felt that this course enhanced their learning of concepts in their regular physics courses.

> **Frank**: What I especially liked about it was, it got me thinking about a lot of really big, deep questions in physics like, Does the math that we use really have any genuine connection to the physical world? Or, why are the equations that we state without proof such as, You can rotate things and it's still the same, why should those things be true? And, like, all the things that we just take for granted when we're working through problems…..ah, really should be thought about a little bit, because they're not easy questions at all. And ah, I think a lot of people are thinking about those right now, with theoretical physics and string theory and um, like David Gross was talking about …Grassmanian coordinates and all these amazing things, and I think that's really important to look into, it almost becomes a sort of philosophy when you get to that level. So…being able to think about those sort of things is not something I would get out of a typical physics class. So that was…really good.

Manny: I think that one of the most important parts about it is that in your average physics class, or – any physics class for that matter, you're not going to be studying the other artistic sides, the symmetries of it all. You're mostly be talking about the mathematical equations and the logic behind it. But there was a lot in this class that…that we studied, that elucidated a lot of other things that before just seemed as rules to many, so I think that's a good way to approach the subject. I also think that the students in the class might not – or, the ones who don't know physics as well as - as a physics major, for example, I think it really helps THEM to see more clearly what physics is all about. Like the art majors in the class. I think that's GOOD.

AT: I like the idea of the explicit link between symmetry and physics. It sounded like something that – it seems sort of – perhaps, almost an obvious statement, I don't know, it's like – Oh yeah, there's symmetric things, that balance out nicely, but on a more fundamental level I've never talked about that, so it'd be…something to…explore.

SS: I'd say in some ways [this course] complemented [my other physics courses]. A lot of things in the course I couldn't apply directly, although it definitely contributed to my appreciation and motivation, I think, even if it wasn't all applicable, I think, to like, problem sets that I had to do every week. But, um, ideas of ideas of symmetry? That...that really got me thinking a lot more, and noticing a lot more in lecture, and noticing a lot more in homework. Let's see......it's really hard t' think of specific examples. It's more, kind of like, a state of mind, and if the professor said something, I'd be like, Ooh, I could relate that back to your symmetry course. I can't remember anything in particular.

> **Sam:** [It was] Relatively orthogonal [to his other courses]…the ah, the classical mechanics was very much math oriented and the – the type of studying and the type of work and all, were very much different. Um…while I did have to use some creativity in trying to…in trying to model equations to physical situations, which is definitely not a strong point of mine, it was- it was still a different exercise, which it…which seemed to utilize different parts of my brain …

The art majors, on the other hand, felt that the course was very different from what they had expected it would be: an art or art history course, with applications from Newtonian physics.

> **Juno**: I actually thought it would be more like art history – like, and then "this" artist did "that" with physics - - and then, "this" artist knew "that" physicist, a little bit more like this one article where they're talking about Picasso and ah, Einstein – - which I thought the entire class would be. It would be like an art historical overview of artists that HAD something to do with physics.

> **Beatrice**: - me, too -

> **Victor Eremita**: …uh…yeah, … um…I…wasn't expecting it to be a PHYSICS course, though, even though that…that was the description, and everything um…. and…that….that was the greatest challenge in the class, was that it … uh… despite having all the things related to art and to …um… y' know, making it understandable…uh… I still had a very hard time grasping …uh… a lot of the concepts. It took me a lot longer to process than…uh…I noticed a lot of the physics majors did … um… So…I was taking it … as…a… a course to inspire art, but it turned out to be more like, uh… it FELT like …PHYSICS in the DISGUISE of art.

5.3.2.1. The Interplay Between Students' Expectations, Backgrounds and Satisfaction with the Course

Through the post-course interviews, it became apparent that the same course description had generated different expectations from the physics and the art majors. Perhaps the combination of expectations, prior preparation in physics, and attitudes towards physics and the arts developed during prior schooling as well as family attitudes, may have contributed to the different experiences and levels of satisfaction with the course.

The physics majors reported general satisfaction in that the course matched their expectations, namely to learn something about symmetry and contemporary physics that went beyond their regular courses, with applications in art and music. As a group, they all had rich prior experiences with physics, and positive prior attitudes towards the arts. Four of the seven physics majors were already accomplished artists, and the other three expressed a desire to round out their physics education with some artistic experiences. SS, Frank, and Manny were already accomplished musicians, and Sam, double-majoring in geophysics and East Asian Studies, was an accomplished artist who also had a public exhibit of his works in a gallery during the summer of 2007. The remaining three physics majors, AT, Al, and Charlie, stated in the first class that although they did not have a great deal of experience with either music or art, they hoped to learn more about the arts through this course. Although Al and Charlie did not grant me post-course interviews, they did state on the last day that they had thoroughly enjoyed the experience of this course.

The three art majors who granted me post-course interviews stated that they had expected either an art history course or an applied art course. Beatrice and Juno stated that, although the actual course differed from their expectations, they were quite satisfied with the learning experience it provided. MKS stated in an email that this course had provided the kind of interdisciplinary experience she was hoping to find at UCSB. Only Victor Eremita stated that the course did not meet his expectations, and although he did learn something about physics with which he was satisfied, in his post-course interview he expressed a mixture of feelings which tended more towards being dissatisfied with his experiences. Through analyzing the interview responses and exit card comments of these students, we may understand something about how prior attitudes towards physics, family background, prior educational experiences, and learning preferences, may have combined to lead to satisfaction or not with the experience of this course.

Of the four arts majors, only Juno had taken physics in high school, for six years under the German educational system. Beatrice, MKS, and Victor Eremita had had no prior physics experience. Of the three arts majors who granted me post-course interviews, Beatrice and Juno appeared to be very satisfied with this course. Although Juno reported that her high school experience with physics was rather unpleasant, she did appear to grasp the mathematics and concepts from Relativity more easily than the other arts majors. Her strong sense of satisfaction appeared to be due to the pleasant and welcome change in her attitude towards physics and physicists, which she attributed directly to her experience in this course.

Beatrice had had the least prior experience with math and physics, having had only physical science in ninth grade, and not having taken math for six years, however she reported that her family background and educational experiences in the Waldorf schools had prepared her to be open minded towards both arts and sciences. She also stated that she had first begun to have difficulty with mathematics when she entered the public school system in California, in ninth grade. While she admitted that she wrestled with the concepts of math and physics in this course, she also reported that she thoroughly enjoyed the process of questioning and pushing herself to understand. Her strong sense of satisfaction appeared to be due to the feeling that she could finally understand mathematical concepts, which she attributed to her experience in this course.

MKS (literature major) did not grant me a post-course interview, although she did say in an email exchange following the course, that this course provided the kind of interdisciplinary experience that she was seeking when she came to study at UCSB:

> This is the kind of opportunity I was hoping to find when I came to the university, and I'm delighted that I stumbled upon it so soon.

Only Victor Eremita appeared to remain dissatisfied with his experiences in this course, feeling that this course more or less "tricked" him into learning physics ("*it FELT like …PHYSICS in the DISGUISE of art*"). He had had no prior physics experience, although he had taken two prior math classes in college, pre-calculus and statistics. He reported that he struggled with the concepts, and at times during the course described his facility with mathematics as "rusty." In contrast to Beatrice and

Juno, who had expected an art history course but were satisfied with the new relationship they developed with math and physics as a result of this course, Victor Eremita expressed ambivalent feelings: on the positive side, he stated that he began to look at the physics section of book stores as a direct result of this course, and this course provided the greatest inspiration for his artwork that quarter; on the negative side, he reiterated several times during his interview how much he disliked the class discussions – the very aspects that the other students appeared to relish and look forward to.

> **Victor Eremita:** … I was almost…I felt like, Hey, this isn't what I asked for, y' know. Here I am learning more about physics, but, uh, what I WANTED was a means to an end, I wanted … to learn physics to the extent that it would help with my art, and… I DID get that, but that's not what the course was there for… in MY opinion…<…pause…> I'm working this out, I'm sorry. Um…what I perceived it to be was rather a…a….means to understand physics. Yeah, so, I wanted the first one, got the second one, but…also got the first one…to an extent.

He seemed to be divided in his experience between disappointment with the course as it did not meet his expectations, and a new interest in physics that he attributed directly to this course. His mixed feelings are expressed in the following two statements which he made in writing to me at the end of the quarter, which seem to be almost contradictory:

Excerpt from final exit card, March 16:

> I think overall, this class tended to be more oriented with physics, even as it relates to art, than it was oriented with applying physics to art. To

> be quite honest, I don’t think I’d still be in this class had it not been for the few examples of physics as it applies to art. I think future classes, therefore, should include a better development of this aspect of the relationship between physics and aesthetics.

Excerpt from an email, sent March 27:

> Thank you for doing such a wonderful, thorough job teaching this course. As I've mentioned before, this class was the greatest source of inspiration for my artwork this quarter. It ignited an interest in physics that was never there before, and I'm excited to see what else I'll learn in the future. I wish you all the best for the remaining work on your doctorate! Please keep in touch.

Thus, Victor Eremita was the only student who expressed such a mixture of bipolar feelings, on the one hand disappointed because there was too much physics, but on the other hand inspired by it. It seems that his greatest source of dissatisfaction with the course came less from the content and mismatched expectations than from the social experience of learning, in which he participated less than the other students. I will return to this point at the end of the chapter, attempting to understand his negative feelings in the context of the Multiple Worlds Theory of classroom cultural interactions (Phelan, Davidson, and Yu, 1993). First, I will discuss the more positive responses to the course of the other students.

5.3.2.2. The 'Transformative' Experiences of Beatrice and Juno

Although all three of these art majors, Beatrice, Juno, and Victor Eremita, all had different expectations as to what this course would be about, Beatrice and Juno managed to transform the experience into something more than they had imagined, while Victor Eremita left with mixed feelings. Their own words explain how this happened for them:

> **Jatila**: And, did [the course] give you what you were hoping for?
>
> **Juno**: It was very, very different than what I thought, how it would be like. I had no idea what it was going to be like, but it sounded so intriguing that I wanted to find out. …. but, um…it actually…ended up giving me a lot MORE than I thought it would, but in a very different way. …if that makes sense…
>
> **Jatila:** Can you…explain a little more?
>
> **Juno:** Sure. <…> I thought somehow … it would be a class that was geared much more towards artists rather than physicists, in a way, I mean, as a …like… I thought it was an ART class, actually, I thought it was a class that was under the rubric of art rather than physics. So I thought it would basically be artists looking at physics, saying, Oh, we can take THIS, and we can work with THAT, and um.. kind of…mainly expecting that…you know, we would use some…um…Newtonian mechanic rules to…construct something...
>
> But then when you started – when we started talking about Relativity and everything, and not even ABOUT mechanics, so much, it just kind of….blew my mind, and made me think about so many OTHER things … and … what I found MOST interesting was that it WAS mainly physicists in the class. …and [I] sort of discovered that physicists… HAVE…sort of the SAME KIND of passion about what they're doing that I have about making sculpture and…or being an artist, and that was SUCH an exciting breakthrough for me, because… it really…. to me… suddenly opened up a whole new field of thinking about making WORK, because I had started really becoming interested in

> collaboration, especially with our…final project when I saw…what…those three students who wrote those music pieces did. It was like, Oh, collaboration is fantastic! And interdisciplinary collaboration, with OTHER people, where you kind of, where you work together on something GREATER than yourself. And…so that's what I AM…doing now, and I'm intending to stick around the Physics Department FOREVER now! 'h <little laughter>

Juno continued, describing her experience in this class as "transforming" and "life changing."

> **Juno**: It's REALLY exciting, and it was just sort of this …. Basically, I just expected that it would be sort of this superficial …ahh…superficial connection of, oh, art and physics, how can we…how can we do that…but rather, it was, for me, it was much more of a…say…transforming, uh, life changing experience, and I'm, I know this sounds tacky, but …that's how it was. … It doesn't even have anything to do with physics or art anymore, it's more of a philosophical realization that….I had…because of that class.

Beatrice described a similar evolution in her attitude. Both Beatrice and Juno described a process of letting go of their prior expectations, or a leap of faith, that allowed them to enjoy the process of learning physics in the context of this integrated physics-arts environment.

> **Beatrice**: It was nothing like I thought it was gonna be either um, I think I, too, came at it – I thought it would be kind of – a discussion, between the arts and the sciences …where there would be, like a deep understanding OF arts, and discussing how physics and art kind of mirror each other, or have this relationship. Um. And so, the first day of class I was a little bit overwhelmed, because it was such – it WAS a

> physics class and that was not what I was expecting … I didn't know it would actually be a physics class. …Um, and I was confused for quite a bit…the first couple of classes as to what, um, what we were studying and how that, um … I was confused as to even, what physics was … And so, I was really lost for a little while. And then…um…….it just started…… to make sense, more and more as I let go of any preconceived notions that I was trying to control, and just allowed myself to just be in the class, and experience what I was experiencing and think about what I was thinking, and not worry about it. It became clearer and clearer.
>
> **Juno:** Actually, I want to add something to that, because I actually remember feeling SO lost in the beginning, … but then eventually it was just kind of like a … it was sort of a leap of faith that I would say, Ok, I don't really GET it, but that's fine, because it's fun <little laugh> and then, um, then eventually I started gaining so MUCH from that experience of just…being in discussion with everyone in the class, it didn't even MATTER- to me it didn't even matter that ultimately …how much … I can calculate …a physics problem now, after this class or NOT, but to have the intellectual discussion with the people who were in the class was the most…fascinating thing…<…> I'm really glad I didn't drop the class, because I was scared, which is sort of a…natural reaction- like if you encounter something that scares you, or that feels like, completely over your head, you feel like – ah' let's just not deal with it, but I'm glad I… dealt with it, because it was GOOD then.

The emotionally rich, descriptive terms, such as "transformation," "life changing," and "leap of faith," with which Beatrice and Juno described their experiences in this class are almost reminiscent of Propp's analysis of the canonical hero's journey in a fairy tale. The personal journey described, particularly by Juno, but also to an extent by Beatrice, surprised me in the parallels with an archetypal hero's journey, an observation which I noted in my teaching journal as well:

1. An initial period of doubt and confusion as they came to terms with a course which differed from their expectations (state of imbalance);

2. The state of confusion was followed by a "leap of faith" (hero emerges);

3. They sought the help of their physics major classmates (wise men);

4. Their eventual development of a new understanding and appreciation of physics and physicists, which they had previously not imagined (a new order is established).

While the effusive language and exuberant style of these two students is perhaps rather unique, in one sense the intellectual and emotional journey they reported describes the ideal learning experience for an individual: to move from an initial state of confusion, through a process of struggling with new ideas, with the help of a guide, to eventually reach a state of greater understanding. According to research in physics education which was cited in earlier chapters, the traditional methods of instruction do not often lead students to such a state; rather, as cited by Redish, et al. (1996), and McDermott (1993; 2001), among others, a traditional introductory course often produces a measurable deterioration in students' attitudes towards physics. It is apparent, from the comments of these students, that this non-traditional approach to teaching introductory physics resulted in positive attitude gains regarding physics.

The process described by art students Juno and Beatrice is also reminiscent of Csikszentmihalyi's (1990) *theory of optimal experience*, based on a concept he called *"flow."* Csikszentmihalyi defined flow as

> …the state in which people are so involved in an activity that nothing else seems to matter; the experience itself is so enjoyable that people will do it … for the sheer sake of doing it. (Flow; c, 1990, p. 4).

From the descriptions of these two art students, it would appear that the intellectual discussions about physics, with peers whom they viewed as experts, provided just such an enjoyable experience of flow, which is also supported by my observations that they would often stay an hour or more after the scheduled end of the class, continuing these discussions. In Chapter Eight I will suggest ways that such experiences can be nurtured in a variety of educational settings.

5.3.3. The Importance of Discussion and Social Interaction

Peer Instruction is the term used to describe a teaching strategy for introductory college physics, developed by Professor Eric Mazur of Harvard University, in which students spend a major portion of class time discussing concepts within small groups, rather than simply listening to lecture (Mazur, 1997). Mazur and others have determined that greater gains in understanding physics principles and concepts take place in classes which emphasize Peer Instruction as opposed to traditional lecture methods (Mazur, 1997; Crouch and Mazur, 2001; Lorenzo, Crouch, and Mazur, 2005). From the comments made by the majority of the students, it is clear that the social interactions between physics and arts majors contributed to the learning and enjoyment for both sides.

Particularly in the integrated environment of CCS-120, in which there were widely differing levels of prior physics experience, discussions proved to be one of the most important and rewarding aspects of the course. The art majors cited their discussions with the physics majors as the most important component in their learning of physics, both for the understanding they were able to gain, as well as the level of comfort and safety they felt through getting to know the physics students.

> **Beatrice:** I understood a lot of what we were discussing from them [the physics students]. I just feel like the atmosphere of the class itself created an atmosphere where everyone was willing to learn from each other and to…to understand and discover new things with each other … I learned so much about physics from those discussions, and from saying, oh, this is what I had a problem with and having a dialog about it…that, that was really helpful. I got such a warm response that I felt really comfortable and really SAFE to ask questions, and they were so willing to explain things to me, and have discussions with me – and I give a lot of credit to them as well because they helped me to learn.

> **Juno**: What I found MOST interesting was that it WAS mainly physicists in the class, and…and sort of discovered that physicists… HAVE…sort of the SAME KIND of passion about what they're doing that I have about making sculpture and…or being an artist, and that was SUCH an exciting breakthrough for me.

> **Beatrice:** For me the class became SO important because … um … of the passion – the passion of people, that the other students had in the class, and their willingness to discuss, and explore, and question, and this is the same that I feel the artists do, they question, explore, and push each other to ask questions and investigate and…I felt very

> ah…inspired by the level of PASSION that the other students had as well, and it made me very dedicated to the class, because –
>
> **Juno**: <jumps in> - It was HOME <little laugh> -
>
> **Beatrice:** - Yah, it made me feel at home and dedicated because here were people who were just as passionate about exploring and looking into things as I was, and I think a lot of – a lot of students – a lot of people that I meet aren't – aren't … individuals who question, and explore. And I felt like HERE I was FINALLY in a WHOLE room of people that were SO enthusiastic and so passionate about what they were doing, and they were ALL QUESTIONING and INVESTIGATING and asking each other things, and it was just such – an aMAzing atmosphere t' be in. And t' be in…um… a group of people where this is the climate that we were looking at the world, and looking at ourselves, and I, and I… really appreciated that.

The physics majors cited the discussions *w*ith the art majors as having contributed to their pure enjoyment of the course, for providing an opportunity to learn about art, helping them to understand physics better by having to explain it to others, and for the pure 'fun' of the discussions, and the freedom to pursue interesting questions.

> **AT**: Well, the part of the class I liked the MOST was the discussions that we had. That was always fun. Ah…t' hear different people's opinions, perhaps unexpected opinions, sometimes…they kind of …ranted and raved, back and forth about that for a little while …it's always fun…..Yeah, … it was good, because it was really open, and you know, we could just sort of talk, and sort of meander a little bit…so, …you could explore, I guess, you could say – different topics. Plus, it forced the people, who, sort of, DID physics to … like, exp-

like, ah – REALLY know what they were talking about, when talk- when explaining things or when talking about things to people who didn't, ah, y' know, avoid jargon, and ah it- it sort of forced us to be- to be honest with what we actually knew what was going on a'hahaha! <little laugh> y' know. So. That was sort of fun. I liked the mix of the class. That was a good mix. I think that was one of the reasons why it was probably as fun as it was.

SS: I really liked hearing from the art students as well because that was… I don't really…well, I have friends who are studying art, but I never really TALK with them about art…and…it was really interesting to hear that perspective. And it really made me wish I knew more about art, I think I'm gonna <little laugh> take an art history course at some point, so I can appreciate that more.

Sam: I mean, just in terms of the conversations that I was able to have with [Beatrice] or [Juno], or like, even, even the physics majors which – like, they - they'd, um, completely introduced me to new perspectives in the world of physics as well, so it was a good opportunity to learn from other people, just in terms of the discussions, mainly.

Manny: I liked being able to discuss the ideas with other people. And I felt that often, I brought up some interesting questions…<little laugh> almost too many at times, but I think it was really interesting to talk about these things.

Frank: For me, I think, the number one thing was the input we would get every week from the two visual arts majors in the class, because … they were… so assertive … in, um, the way they understand things, and whenever they don't understand things, they would never hesitate right away to come out and question things, and ask why, and, that led

> to a lot of really good discussion and…um, they say that when you teach other people something you're helping yourself learn it even better at the same time, and I think that, for at least myself, trying to explain some of the more difficult ideas in physics to them, helped to…ingrain it into myself even further. But, um…but it went both ways, because some of the things that they were saying about aesthetics and visual arts was also very compelling to me. … and, um…basically, every week that they were there was guaranteed to bring a lot of controversy and arguments, and that was great because that's a lot of fun.

5.3.3.1. The Importance of Small Group Work in Mixed Major Groupings

Especially for the art majors, the chance to work interactively in small groups with the physics majors was important for their learning of physics and math concepts.

> **Juno**:… when we started making more ourselves, when we started DOING things in class with each other, and making these little visualizations of an article, and…working on our final projects and stuff, so it- like it's – It helped ME to be actually DOING something with my hands, rather than just sitting there and taking in all this abstract information that I felt didn't really have something to do with me, again, like physics always is…<little laugh>
>
> **Beatrice**: and then, also, DOING that enabled a discussion with your partner about –
>
> **Juno:** <jumps in> - about physics –

> **Beatrice:** - that I learned so much about physics from those discussions, and from saying, oh, this is what I had a problem with and having a dialog about it…that, that was really helpful

5.3.3.2. The Value of Reading Authors Not Textbook Chapters

As stated in earlier chapters, I did not use a traditional text book in this course, as, according to Thomas Kuhn (1962), "a concept of science drawn from [text books] is no more likely to fit the enterprise that produced them than an image of a national culture drawn from a tourist brochure or a language text” (*The Structure of Scientific Revolutions,* p. 1). Instead, readings were taken from books on physics and mathematics written by theoretical physicists (Lawrence Krauss and Mario Livio) for general audiences, excerpts from Richard Feynman's *The Feynman Lectures on Physics*, and articles on physics content and physics-in-context with art, music, literature, and history. All but one of these articles written by theoretical physicists, including Einstein and other Nobel Laureates.

For the students who did the homework, the readings provided a way of learning physics from the masters, although the reading assignments were taken up differently by the arts and physics majors, as will be discussed further in Chapter Six. The arts students used terms such as "grounding," "freeing," and "important," in describing the readings. The physics majors, who already had a background in physics, acknowledged that they were interesting, but not necessarily central to their learning. Frank and Manny said that reading articles did not seem as important to them as doing problem sets, although they acknowledged the readings as important and, although they admitted to not having done all the reading, recommended that I keep the reading assignments for future courses. SS said that reading the articles by physicists made physics seem more like a creative endeavor. I will discuss this point further in Chapter Eight, as it relates to the question of making physics seem more 'human.'

Art majors:

> **Beatrice**: The articles I understood, and the articles were grounding, and the articles kind of confronted this dialog between art and physics, and what is the relationship there.

Later, Beatrice talked about how the combination of group activity and readings helped her understand the importance of symmetries in understanding what is happening on a physical level.

> Zee’s article really helped me t’ understand the IDEA of symmetry being both extrinsic and intrinsic, and that symmetries were NOT just left and right symmetries but that we had symmetries like glide symmetry, like, all these different types, … and that’s what we were, like, investigating when we were doing the Exercise, for example, with the triangle, …
>
> I was confused as to what the exercise was at first . h’’ but THROUGH having the experience of it, and then reading the article that clarified what the exercise was, it helped me to have a … deeper understanding of HOW the symmetries were then so important in physics… It just gave me a much deeper understanding because I went through that process.
>
> **Juno**: I really enjoyed reading, um, Feynman’s article. I don’t know why, it was my favorite article, because it just kind of – it was pretty

LATE in the class - But to me it really was sort of another – a very FREEING notion of, um – because I was able to understand what he was talking about – because he obviously writes in a way that is quite understandable – and, um – so it made me feel proud that I was able to understand what was going on on a physics level – but I also thought it was very, very interesting, I mean, as soon as we started talking about relativity I was totally on board, I just was – yah, I think actually the first time that we started talking about, um, time frames - And…really, about relativity - That's when I really started understanding what we were talking about.

Physics majors:

AT: I liked the readings, for the most part I really enjoyed them. The book – the Fear of Physics – that was, that was a good book – like, um, y 'know, what it talked about I certainly had read in other places, so it wasn't like – really, MIND blowing, in a sense, but I liked some of the analogies and examples he gave… And, of course the Feynman was good. I enjoy reading the stuff. So more Feynman, if anything.

Frank: [regarding the homework assignments] The ones that I probably liked the least um…. I guess, just the reading assignments, and, not because I don't like t' read, but um…. Well, I guess I can only say that I liked them the least because I did the fewest of those, and the reason that was the case is just because for me it's always been a problem that reading assignments tend to get pushed to the wayside because it feels like…explicit like, problem sets are more REAL, like, this has t' be handed in, and it's gonna be corrected, and- and returned, whereas, a reading assignment, if you just skim it before class, and you're just gonna talk about it, you can still hold your own if you know a little bit about the topic. So, um…I felt like I could get away with that a little bit.

Manny: Bravo… I feel exactly the same way, I like – you couldn't 've put it - better, h' really, like those are exactly my thoughts.

Frank: I did read Einstein and Feynman, because they're like –

Manny: - very juicy –

Frank: - yeah, but … I mean, it's really good t' have that resource, the reader, and you can always come back to it, and refresh ideas, get some inspiration. I feel like, even if everybody said [they didn't like] the readings, that you shouldn't get rid of it. 'cause that's like, really important.

Later in the interview, Frank did say that he liked the book *Fear of Physics*, saying that he "endorsed" it.

When I asked SS if her attitude towards the process of doing physics had changed as a result of this course, she cited the readings:

Jatila: So, do you think that your attitude towards the process of doing physics has changed as a result of doing this course?

SS: I think it HAS, just because of reading the …accounts of physicists …like, realizing new things and discovering …their new ideas, um …like, it's not just…like, I think I appreciate physics as more of a creative endeavor now, than I did before….Like, it's more…….yeah, I guess there's more of a personal aspect to it. Like you kind of have to think outside the box instead of just going along with your math…until you…arrive at something. … and maybe that's an incorrect perception <laugh> but that IS a perception I gained from this course.

Jatila: Um, no, that is NOT incorrect-

SS: that's not it? Ok, good <little laugh>

Her statement that the readings gave her more of a sense of the "personal aspect" to physics than she had gotten from her other courses is relevant to the initial premise stated in Chapter One, that physics has been accused of being "inhuman" (Weisskopf, 1976). The "inhuman" way in which physics is often presented has been cited as one of the factors in deterring girls from studying physics (Gosling, 2004). Zohar (2006) cited girls' need for deep understanding in physics as being seminal to their developing positive attitudes towards physics. The pleasure expressed by art majors Beatrice and Juno for wrestling with the ideas, and their deep need to understand, taken together with SS's statement that reading the works by theoretical physicists put a more human face on physics, may be useful in developing curricula with potential to correct the gender bias that still prevails in physics education. These ideas will be developed more fully in Chapter Eight.

5.3.4. The Value of The Final Project: Creating a Physics Work of Art

The final project provided a means for students to synthesize the concepts of physics, mathematics, and aesthetics which they had learned, and to combine this knowledge with an interest or passion of their own, in their chosen artistic medium. An analysis of the final projects will be presented in Chapter Six; what follows next is an assessment of the success of this assignment in the students' words. As Frank said, it hardly felt like an assignment at all, and as such, it represents an ideal learning experience.

> **Frank:** My favorite was definitely the final project, because there was just so much freedom in what we could do, that I felt like…It hardly felt like an assignment at all, it was just something that I was doing that I enjoyed, and that I wanted to show to other people. … and that I hoped they would enjoy, too. … So…I got to learn something about math and physics and aesthetics and art all at once, and create something that I really liked, so I thought that was educational, and also purely fun, and good.
>
> **AT**: I thought it was a lot of fun. I saw some really interesting things. Some, sort of – I don't think any of it was really expected. At least, the outcomes, like the usual starting points, some were more expected than others, like algorithmic music was like, oh yes, this is an idea that we talked about, so to just say, I'm gonna do this piece is like <??> but then what came out was really good, but then you have like other pieces, like [Beatrice's] installation, I believe, and- both- both theirs were really good, I think. I kind of liked both the art pieces. Those were really quite fun. …. Dead rat. How bizarre was that?
>
> **SS:** Well, obviously, the big one <little laugh> yeah, yeah, well, all the readings were interesting, but my favorite was definitely working on the music….that…I did for my project.
>
> **Sam**: The final project, I mean – um, it was an opportunity for me to both create and show off- which is great- aahh, and, em… Yeah, it was really FUN, all in all, like I got to explore aspects of my own work that I hadn't realized before

5.3.5. The Value of Aesthetic Physics at Other Educational Levels

I asked the interviewees one final question: Do you think this model of integrated physics and fine arts education, can be useful at other educational levels? Their answers indicate that they do believe these ideas are transferable to other classroom situations.

> **AT**: yeah… I think it would. I think it could ATTRACT people to physics, definitely, I don't know, I'm a really big fan of – everything is connected to everything else- you could sort of, weave your way from, one side of like, academic I guess, you know, galaxy to the other, some way, some how, you could probably get there, through tangential interests and things like that. So I think, um, displaying these really cool connections that people don't normally think about a lot is a good thing. I think it would attract people.

> **SS**: Yeah, I mean, at the level we were doing it I think – I mean, the discussions we were having I think are better for college students but I think the whole idea of relating physics to symmetry and aesthetics is an important idea to give to kids when they're really young, because …kids kind of grow up thinking that physics is this, like you said earlier, this really dry boring thing, where you just go through the numbers, but if they have this perception of it maybe… we'll have different – we'll have a lot of different kinds of people becoming physics majors.

> **Frank:** So, yeah, I think that introducing the big ideas earlier would be…a good change. … I think…knowing about art helps you know about the ideas in physics, and vice versa, because they're just two ways to try t' come t' terms with what we're doing on…on this Rock

floating around in space, like … Why are we here? They're very different languages, but I think they're heading towards the same goal.

So… I think… taking a look at the process of creating a masterpiece painting and then comparing that to how, say, Einstein came up with General Relativity, I think you see a lot of <u>links</u> between the two, in the steps that you have t' take, and the passion you have in it, and finally the resulting product, and what it has to say about the world. So, I think if kids were exposed to that at an earlier age they might become more interested in these deep questions, and – and might develop a passion early on to try to go into fields where they can answer them.

Manny: I think this class can definitely be taught t' children, or to-OR to adults…… And, the truth is…most people go through their entire lives without learning anything about these things, and so…I think it's a great idea to… try t' educate people about this, and…even if you're not really interested in learning about the math side of it, I think it's just a really interesting class t' take.

Juno: I was just actually talking with my parents about this yesterday, how bad it is that so many people are – in a way – conditioned – well, very Aldous Huxley, but um – that children grow up learning that science is scary and – especially physics and math. Somehow, chemistry doesn't have that big of a stigma, but physics and math – it's like, Oooo, Scary – and especially, I think it gets communicated esepecially to girls still – not so much any more, but still – and um, …in a way… I think this kind of science phobia is really sad, because as I started seeing now, it's a very beautiful thing, and, I WISH it would work that way, maybe it would. I definitely think one should try and then see what happens but I believe it's absolutely possible that if

> at a very, very early age children can also add THIS sort of learning to their vocabulary of how to learn and-and kind of having discussions, rather than sort of an input, which is …well…laced with, “well, no wonder you don’t understand this because you…it’s really hard, and don’t worry about this …math IS hard, and physics IS awful, and it’s supposed to make you feel miserable” That’s kind of the feeling I got from my high school math and physics encounters. ..

Beatrice said that in her early education at a Waldorf School, art and science were taught together, so she was not taught to be afraid of physics. Juno repeated, several times during her interview, how she was made to feel afraid of physics and math during her high school years in Germany. Although, unlike American high school students who are not required to study physics, all students in Germany must study physics every year, Juno recalled learning physics as very unpleasant, particularly for girls. She felt that an integrated approach of teaching physics with art could potentially make physics less frightening for girls:

> **Juno**: I’ve known a lot of people in my classes, especially girls, who were very, very afraid of math and physics – not so much chemisry? Chemistry was sort of a –neutral thing? But they were VERY afraid of physics. I mean that you’d -basically, you’d have people CRYING at tests, you’d have people freaking out because we have at test and um….but they weren’t allowed to not take it, they had to take it, and I think that was not very clever. … But at the same time, I think there’s just something that is DONE in the way that it is arranged or taught that makes people really AFRAID of it, and I think it is taught in a way that is kind of – seems very EXCLUSIVE. And I ALWAYS had that feeling about physics, I always had the feeling that scientists are exclusive, and that’s why this class was so exciting to me, because I

> realized that they're actually very INCLUSIVE people, they just don't get to…hang out with other people that much because everyone thinks they're Exclusive 'h'h' <little laugh> and um…so, if there's some way to kind of …make it a little less… FRIGHTENING…
>
> **Victor Eremita**: It makes me wish there were more such classes. …. It's not just art and physics that …. that such an interdisciplinary approach could take place, um, so I wish there were more classes like it, and you overall were very successful in integrating the two, and in getting both sides to benefit most from the combination

In summary, in the words of the students, the course was a success in promoting learning of math and physics concepts for students majoring in an arts-based discipline who may not have had access to them otherwise; it was a success in rounding out the physics education for physics majors who may not have been exposed to ideas of symmetry and the connections of physics and fine arts otherwise; it was successful in promoting dialogue between physics and arts majors who may not have otherwise had these opportunities for interaction; and it was pure fun.

Research in physics education has demonstrated that classrooms in which there is an emphasis on peer interactions have positive results for girls' learning of physics (Crouch, Oster, and Mazur, 1999; Lorenzo, Crouch, and Mazur, 2006). Comments cited from the minority of young women in the class – sculpture major Juno, painting major Beatrice, and physics major SS – support the idea that peer instruction methods, emphasizing discussion and group interactions, are important for girls in physics education. Other comments that reading the articles by theoretical physics made physics seem more human (SS), and the sense that physics is no longer fearful, and physicists are not exclusive (Juno), indicate that this model may have wider implications for improving the climate for girls in physics education.

A comment by Victor Eremita, which he made after I had turned off the recording device, indicated that he felt this model of integrated physics and fine arts teaching would benefit males such as himself is also important to note. After the interview, when I had stopped the taping, I explained to Victor Eremita my reasons for studying integrated arts-physics education, as having been initially rooted in gender issues in physics. He thought that my integrated approach was very good, as it opened up access to physics to guys such as himself, who otherwise would not approach physics. The significance for physics education of his statement is that while the physics community makes an effort to reach out to girls as an underrepresented population, the underlying assumption is that all males *can* do physics if they choose. This underlying attitude neglects the large population of males who also are turned away by physics. When I described my small study of second graders, and my assessment of personalities, he responded that as a child he never wanted to be a fire fighter or swat team member either, and that by teaching physics in these contexts, it also precludes boys such as himself. Textbooks still include a predominance of traditionally male applications, such as cars, rockets, hockey, and projectiles, in introductory texts (Gosling, 2004). Thus, this model of teaching physics with fine arts may have the potential to reach out to underserved populations who have remained hidden, such as white males who are not oriented to activities that have been presumed to be male-oriented.

5.3. Listening to The Lone Voice of Dissent

Literature on physics education research which addresses peer instruction (Mazur, McDermott, Laws, e.g.), as well as literature on improving equity in science education (Aikenhead, Lee, Hanrahan, e.g.), points to its successes in terms of learning gains and classroom climate. At the same time, there does appear to be a minority of students who do not seem to appreciate group interactions (Mazur, 2007, personal communication), and these students tend to be male more often than female (Zohar, 2006). Victor Eremita was the only student who reported having a strongly negative reaction to the group interactions, stating that he would have preferred straight lecture.

> **VE**: I think there should have been more focus on….. <long pause>…. how should I say this, leading the class from the top down? Having more of a hierarchy? rather than letting the students take over the discussions. And, I understand there are two different ways to approach that, that could just be a personal preference, but I did not enjoy the class conversations at all. Like at all, like, I can't remember – well maybe one or two conversations that I really got anything from. Um…I don't like the non-structured tangents that tend to take place. It's a pure discussion, I mean, I can have that anywhere, but I'm in class t' learn. … So… that could be a personal preference, and I know there are some teaching methods that focus on having student-led conversations, but I – it might BE that it's just not for me. But, I get the feeling that I'm not alone there, that there may be other students who are not benefiting from that approach.
>
> **Jatila**: … interesting…so, you preferred the lecture parts?

VE: Yes. Absolutely. I benefited most when it was straight up lecture.

Although he claimed that he was not alone in his dislike of the discussions ("*I get the feeling that I'm not alone there*"), none of the other students who granted me interviews expressed similarly negative sentiments about the discussions, and none of the other students indicated to me during the course, in person or on their exit cards, that they preferred lecture over discussion. Sam stated that at times he did not want the discussion to get off topic, but at other times he recognized that he was the one who wanted to stray. SS stated that at times she felt at a loss as to what to say, but she never felt there was a time when she was bored. Never the less, both Sam and SS cited the discussions with other students as one of the aspects of the class that they most enjoyed, and, as already stated, all the other students stated that the discussions were one of the most important aspects of the course for them.

Towards the end of my interview with Victor Eremita, he acknowledged that there is a certain value in discussions, as they promote dialogue between students who would otherwise never interact, but he felt such activity should be optional, left for outside of the class. Why should the discussions, which were cited by the other students as important to their enjoyment of the course, have provided such an opposite experience for Victor Eremita?

The trivial answer is that he is just part of the small, but sometimes vocal, minority of students who simply prefer lecture over interactive methods. According to Professor Eric Mazur, who introduced interactive methods into college physics teaching (Mazur, 1997), there are some students who claim to prefer lecture (Mazur, personal communication, May 23, 2007). Never the less, Professor Mazur remains committed to the superiority of interactive instruction over lecture. (Mazur, 2007).

Is there perhaps a deeper explanation for Victor Eremita's strongly negative reaction to the discussion format? Some other undercurrent that ran counter to the main stream of the class, that went unrecognized, but which can have potential bearing on designing successful integrated arts-sciences learning environments in the future? In looking back at some of his early comments, there may have been some early signals which I did not take sufficiently seriously.

The first indication that something was amiss may be found in the following anomalous exit card from the second class, on January 19.

> Jean-Pierre Hebert's lecture was informative and inspiring, especially the sand sculptures and his discussion of string theory and Calabi-Yau. The group pow-wow I could totally do without. Great for a dinner party discussion, but not more than a tangent-infested ego trip among a few of the more talkative and elitist of the group. Worth sitting through, though, to get to the fine lecture at the end. Lots of great facts and ideas there.

I did not correlate this exit card comment with Victor Eremita at the time it was written, as the exit cards were written anonymously, however in an email dated January 26, 2007, he sent me the following unsolicited apology:

> I wanted to apologize for my somewhat passive-aggressive outburst last class in regards to the discussion. I think that I was just having a bad day. Thanks for your understanding.

He did not verbalize any "passive-aggressive outburst" during the class, thus I could only conclude that he must have been referring to this exit card comment, as it was the only such comment I received that day which could possibly fit the description. Although the cards were all submitted anonymously, and there was no possibility that I had yet learned to identify students by their handwriting, still Victor Eremita must have somehow expected that I would have associated this comment with him. In an email dated January 27, 2007, I responded:

> No problem. Sorry I let the discussion get out of hand and that you were feeling quietly frustrated. Anyway, I don't remember any outburst, but feel free to email me, or come to office hours, or set up another time if you want to talk to me about anything.

He never contacted me again about this issue. What was going on, which I apparently completely missed? On that day, I felt that the discussion was particularly lively, and in my journal entry I recorded that there were questions about Euclidean geometry, the correlation of "φ" ("phi," the Golden Ratio) with "α" ("alpha," the fine structure constant), fractals, and a lively discussion generated by the first article that had been assigned for homework, "*Seeing and seeing: visual perception in art and science"* by Peter Campbell (2004). I had tried to note as many of the comments as possible and, although I had not yet learned everyone's name, in my journal entry for that day there are eight different names associated with comments, and three instances of "One student said…," thus it is likely that ten, perhaps eleven different students spoke up during the discussions or asked questions, out of a total of twelve who were present at that time. Thus, a majority of the students did contribute to the discussion, so how could one student have construed the discussion to have been an insensitive "ego trip" of an "elitist" and "talkative" few?

Most of the other students reported in their exit cards for that day that they enjoyed the discussions and enthusiasm of their classmates. One student wrote, "I wish students were this engaged in all my classes." Another wrote, "I found the discussion both interesting, stimulating, and thought provoking," while another wrote, "I would like to discuss further the mathematical relationships between art and physics. It is a fantastic class." Still another wrote, "Thoroughly interesting discussion. The “artists” (even though we all are) keep the “scientists” honest. You better be ready to define/explain it if you say it!"

Could this division between "scientists" and "artists" have contributed to the disparaging remark about "elitist" and "talkative" students which Victor Eremita appeared to claim as his? Bazerman (2000) expressed the idea that scientific language is seen as something special and privileged, having a “special status separate from the turbulent, murky, and illusion ridden language of the rest of the human world.” (Bazerman, 2000, p. 296). According to Bazerman, there is a general mistrust of scientific language for its "status" and its "opacity." Thus, it is possible that the unconscious use of discipline-specific language by some of the physics majors in the class may have unintentionally made Victor Eremita uncomfortable, which may have caused him to write disparagingly of his fellow classmates.

Research on boundaries and border crossings in educational settings may offer some additional insights as to Victor Eremita's apparent frustration with the discussion, which was centered around the readings that were to have been done for homework. In their Multiple Worlds Theory, Phelan, Davidson, and Yu (1993) defined boundaries and borders that separate groups of students from each other and from school authority figures. They defined boundaries as real or perceived lines between people with different sets of values, beliefs, expectations, and emotional responses, when the differences are experienced as equal. Boundaries are neutral, and people appear to move freely between cultural worlds separated by such neutral boundaries (ibid.). Borders are real or perceived lines that separate cultural worlds which are perceived as unequal. They say,

> When borders are present, movement and adaptation are frequently difficult because the knowledge and skills in one world are more highly valued and esteemed than those in another (Phelan, Davidson, and Yu, 1993, p. 53).

Phelan, Davidson, and Yu suggested several types of borders which exist independently of the usual categories of class or race, including linguistic, sociocultural, and gender borders. Thus, even though students may be from a homogeneous ethnic, economic, or racial group, in an integrated, arts-physics environment, borders of these other types could potentially be expected. The language of physics, being mathematical and technical in nature, is different from the language of art, and the cultural components and expectations of physics students and art students are different. To the physics student who commented that the "artists … keep the scientists honest" this difference was apparently a neutral and navigable boundary; was it possible that, to Victor Eremita, this difference may have been perceived as an impenetrable border? If so, his statement that the discussion appeared as *"not more than a tangent-infested ego trip among a few of the more talkative and elitist of the group,"* may possibly be understood as an expression of frustration at a perceived impenetrable border.

The important point in these observations is to expect that, in organizing integrated arts and sciences courses, unlike traditional introductory physics courses, there may be an unusually heterogeneous mixture of students, with widely differing backgrounds. Thus, certain differences between arts-based and science-based students may be expected, which may be perceived as cultural, linguistic, psychosocial, or gender-biased. In such situations, an instructor should make every effort to see that perceived borders are reduced to neutral and navigable boundaries. A discussion which is intended to promote dialogue can have the opposite effect if the language is perceived as an impenetrable barrier, thus causing further isolation if one person feels somehow unable to participate in the discussions.

If indeed an inequality regarding scientific discourse was present in the initial phases of the course, why did it not manifest with an equal sense of frustration in the other art majors, Beatrice, Juno, and MKS? Juno remarked in her exit card for January 19 that she felt overwhelmed *"because of all the math/physics jargon that I really need to pay attention to, to understand,"* yet this feeling did not prevent her from contributing to the class conversation. According to my notes, Beatrice, Juno, and MKS, all participated in the discussion, which centered around the articles that had been assigned for homework. MKS (literature major) in particular, offered some rather astute comments regarding the article by Einstein that had been assigned. She commented, *"Very interesting, this class addresses so many of the concepts that have haunted me for my entire life. It is nice to be able to name them now."*

The discussions that took place between the physics students and art students throughout the course were seminal in equalizing the communications between the two groups of students and, as already described, allowed those who participated to develop an appreciation for the members of the other group. Besides the formal discussions during class, I observed during the "cookie breaks," that groups of arts and physics students would engage in animated conversations, which often persisted as long as an hour after class.

I often observed that Victor Eremita did not engage in these informal discussions, and he did not stay after class with the others. Whatever difficulty with language was initially present for the other art majors, they were able to navigate through it by discussing and asking questions of the physics students. This observation leads me to question whether there may have been an even subtler layer, beyond simply the "math/physics jargon," that may have influenced Victor Eremita in ways that would not have been felt by the other art majors. The following incident perhaps, in retrospect, may provide at least a partial answer: During the first class Juno had remarked, with a certain irony, that the females in the class seemed to be in the arts while the males were in the sciences. I had also noticed this imbalance, and commented in my journal entry for January 12:

> Interestingly, there is ONE female physics major from CCS, and three female art majors. The art majors are very outspoken, asking lots of questions, and offering comments. The only female physics major ...

was so quiet, that one of the art majors commented that all the females were in the arts while all the males were in the sciences, not even noticing that one girl was sitting quietly among the male physics majors. I discussed at that point that it [the gender imbalance in physics] is a problem, and shared what I have found in my research about why women don’t seem to go into physics. But, in the class, at the time, it did not occur to me (or any of the girls) to say, hay, there is one girl in physics here – and this girl in question did not even jump up and say, hay, what about me. Strange…

Equally strange, in retrospect, was the fact that although I immediately noticed the single female physics major, as noted in my journal entry, I had not similarly commented on the single male art major, who also did not "jump up and say, hay, what about me."

The distribution of students by major and gender is shown in Figure 5.1.

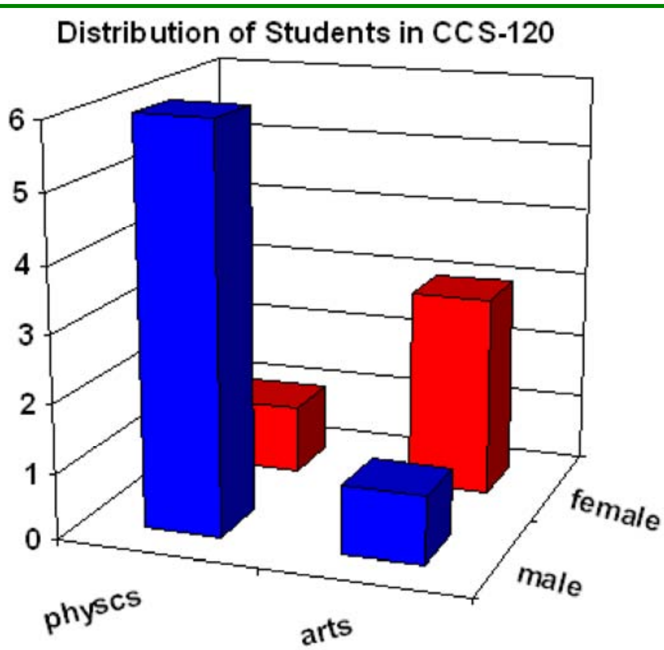

Figure 5.1. Distribution of students in CCS-120 according to major and gender.

Although I was acutely aware of the single female physics major from the first day, early in the quarter I failed to notice the corresponding anomaly of the single male arts major, and ask what it was like for him. Apparently, Juno did not notice him either, when she made her remark. SS, the single female physics major, did not appear to be uncomfortable with her role, and appeared to be very much included in the group of physicists. She seemed to be particularly friendly with Frank and Manny, with whom she shared other classes, rides home on weekends, and with whom she worked on the final project. Thus, one possible interpretation as to why Victor Eremita may have taken such a dim view of his classmates as to label the discussion a "*tangent-infested ego trip"* may be that, aside from his natural preference for lecture over discussion, he may have felt an additional burden of isolation due to the fact that he was both the only male who was not a physicist, and the only artist who was not female.

At the present time, a great deal of effort is concentrated on attracting girls into physics and engineering, in the form of government grants to study the problem, newspaper articles, and programs specifically targeted at recruiting girls into science. The tacit assumption is that, because these fields are dominated by males, all males are naturally good at these "traditionally male" subjects. Thus, the minority of males who are not naturally "good at" the "traditionally male" subjects of science, math, and engineering, may feel at a disadvantage. In my post-course interview with Victor Eremita, he alluded to this possibility, as discussed in the previous section.

Ultimately, I am committed to the discussion format. Perhaps my evaluation of Victor Eremita's dislike of the discussions as having a deeper meaning than simply a learning preference for lecture over discussion is not correct. On the other hand, all of the subtleties that can emerge from the above considerations in an integrated arts-sciences environment, including technical language which can be intimidating, and subtle sociocultural issues which may operate below the conscious level, should be attended to so that natural boundaries between arts and science students are not perceived as un-navigable borders.

Chapter 6. Where Good Thinking Matters: Analysis of Learning Outcomes Through Students' Written Work

"Seeing the world in new ways is one of the greatest avenues for creativity and personal engagement with the world" (Mihaly Csikszentmihalyi, 1996).

"Traditional instruction does not challenge but tends to reinforce a perception of physics as a collection of facts and formulas. Students often do not recognize the critical role of reasoning in physics, nor do they understand what constitutes an explanation" (Lillian McDermott, 1993).

There were two main objectives of the course Symmetry and Aesthetics in Introductory Physics. The first was, in the broadest sense, to introduce the foundations of contemporary physics, based on the principles of symmetry and Noether's Theorems, utilizing connections with art and music to facilitate conceptual understanding of the math and physics. The second was to interrogate the ways in which physics and fine arts are eqally creative endeavors, and to explore the similarities in the ways that artists and scientists perceive, interact with, and represent, the physical universe. In this chapter, I will discuss how these objectives were realized by examining the students' written work.

6.1. Overview of Homework Responses

One measure of the success of homework assignments in a class is to examine the percentage of assignments that were completed. The percentage of homework returns in any course is based on complex set of motivational factors, which can be understood in two general categories: motivation that is driven by grade outcomes, and motivation that is not directly driven by grade outcomes. Grade-dependent motivation includes the importance to the students of the grade in that particular course in comparison with their other courses, the percentage of the course grade which is based on the homework, and the relationship between the homework and the examinations in a particular course. In traditional introductory physics courses for non-physics majors, students tend to complete the problem sets because they feel it will help them to do well on the exams, and because homework counts for a certain percent of their final grade. In courses for physics majors these reasons are also important, however the main reason for completing homework is as a means to learn physics. If grades are not motivating factors, reasons for completing assignments include whether or not assignments are perceived as interesting or meaningful to the students, whether or not assignments are perceived as accessible or too difficult, the time necessary to complete assignments in comparison with other courses, and extenuating circumstances in students' personal lives which are unrelated to school, such as illness or family tragedy. In the College of Creative Studies grades are not given; rather, it is assumed that all work is of high quality, and credit points are awarded based on the percentage of the work completed. Thus, in CCS-120, grades were not motivating factors in whether or not an assignment was completed, therefore the percentage of homework turned in may be more indicative of the other factors, such as interest, relevance, and level of difficulty, which are more genuine measures of the effectiveness of the various assignments.

6.1.1. General Percentage of Returns on the Homework.

There were two types of assignments in CCS-120: the weekly readings and small assignments, and the final project. The goal of the final project was to create a "physics work of art," the realization of one or more principles of mathematics and physics which were discussed during the course, through a chosen medium. In addition, the students were to write a five-page (minimum) paper explaining how their works of art expressed and utilized the principles of math and physics which motivated their piece. The weekly assignments were originally structured so as to include three components: a short math application, an arts exploration, and a reading assignment dealing alternately with physics content and physics-in-context with art, music, literature, or history. As will be discussed in this chapter, as the course progressed, the assignments devolved so as to consist only of reading and writing.

The final project was the most successful. If, in the absence of grades as motivating factors, the percentage of return on an assignment is a measure of the success of the assignment, then the final project can be said to have been the most successful, as one hundred percent of the students presented a final project. In their interviews as well, when asked which assignments they liked best, all the students who granted me interviews named the final project as their favorite, even to the extent that it did not feel like an assignment. The final projects will be discussed in detail in Section 6.6.

The smaller assignments were variable in their success rate*s.* Other than the final project, there were six separate homework assignments, with a total of twelve distinct components, which are shown in Table 6.1. The first two assignments followed my original design of including all three components of math application, arts exploration, and reading with written analysis; in the third assignment, students had a choice of math or arts application, with reading and written analysis; and the last three assignments consisted only of reading and written analysis. There is a clear difference in the returns on the homework between the physics majors and arts majors, in terms of both the percentage of all the assignments submitted by each student, and the types of assignments that each group tended to complete.

Assignment	Component	Ratio arts/physics
Homework 1	Math application: fractals. Draw and calculate the fractal dimension for the Koch Snowflake and the Golden Plant.	.25/.86
	Writing 1: Summary of Einstein article	.5/.86
	Drawing: Visualization of Einstein article	.75/.86
	Writing 2: Responses to other articles	1.0/.86
Homework 2	Math exploration: Complete a table of music notation and inverse powers of two	1.0/.29
	Music application: Write a rhythmic pattern using western music notation	.25/1.0
	Writing: Responses to articles	1.0/.71
Homework 3	Choice of math or music: Math exploration: complete the symmetry table of a square Music application: apply symmetry operations to a musical phrase to produce variations on a theme	1.0/.43
	Written responses to articles	1.0/.43
Homework 4	Summaries and comparison of 3 articles	1.0/.57
Homework 5	Commentary about Feynman chapter 42	.5/.14
Homework 6	Commentary about Krauss and Livio final readings	1.0/.14
Final project	Physics work of art	1.0/1.0
Final paper	Written analysis	.5/1.0

Table 6.1. Homework assignments, broken down by components.

Regarding the total returns on the homework, the arts majors were more consistent as a group than the physics majors, with an average completion rate of 77%, and a standard deviation of 4.2%. The physics majors turned in an average of 58% of the assignments, with a standard deviation of 28%, and a large spread that ranged between 17% and 100% completion rate. The homework returns for each student, displayed according to arts and physics major groups, are displayed in the graphs in Figures 6.1a and 6.1b, where each bar represents one student.

Regarding the types of assignments, the physics majors tended to complete all of the math and music assignments in the first two weeks, but their returns on the reading and essay assignments fell dramatically about half way through the quarter. The arts majors' trend was just the opposite: their returns on the math and music homework in the first two weeks were sparse, but increased when the assignments turned to more or less free-style reflections about the readings. The percentage of homework turned in for each homework component listed in Table 6.1, for the two groups of students, is shown in Figure 6.2.

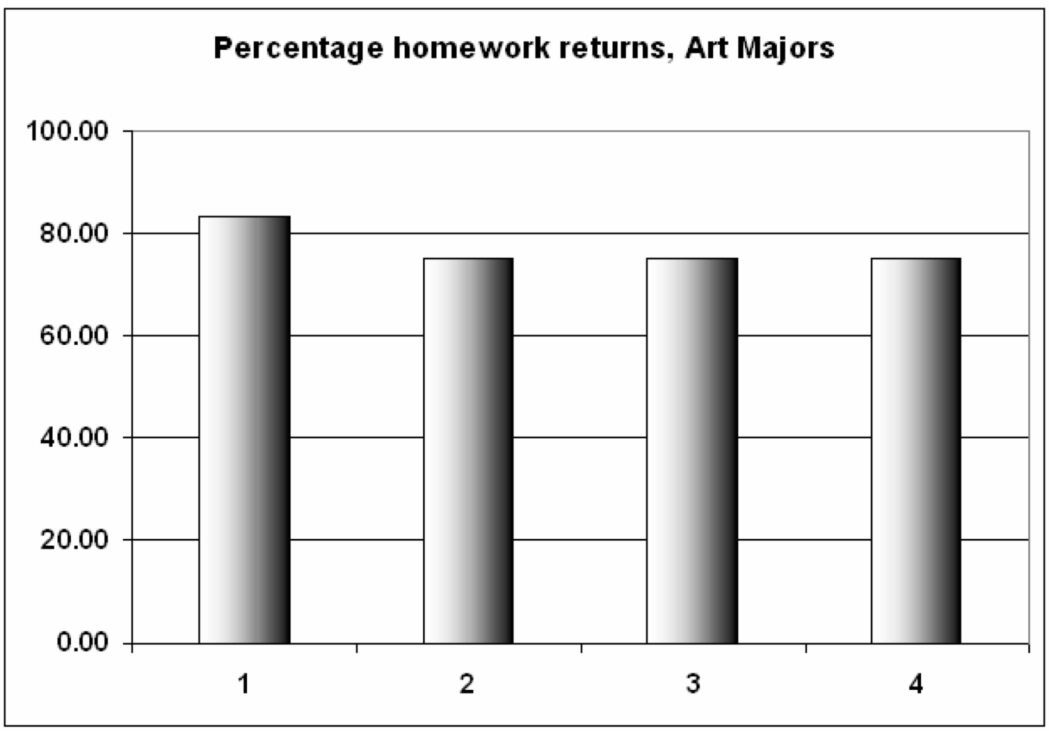

Figure 6.1a. Percentage homework returns for Art Majors

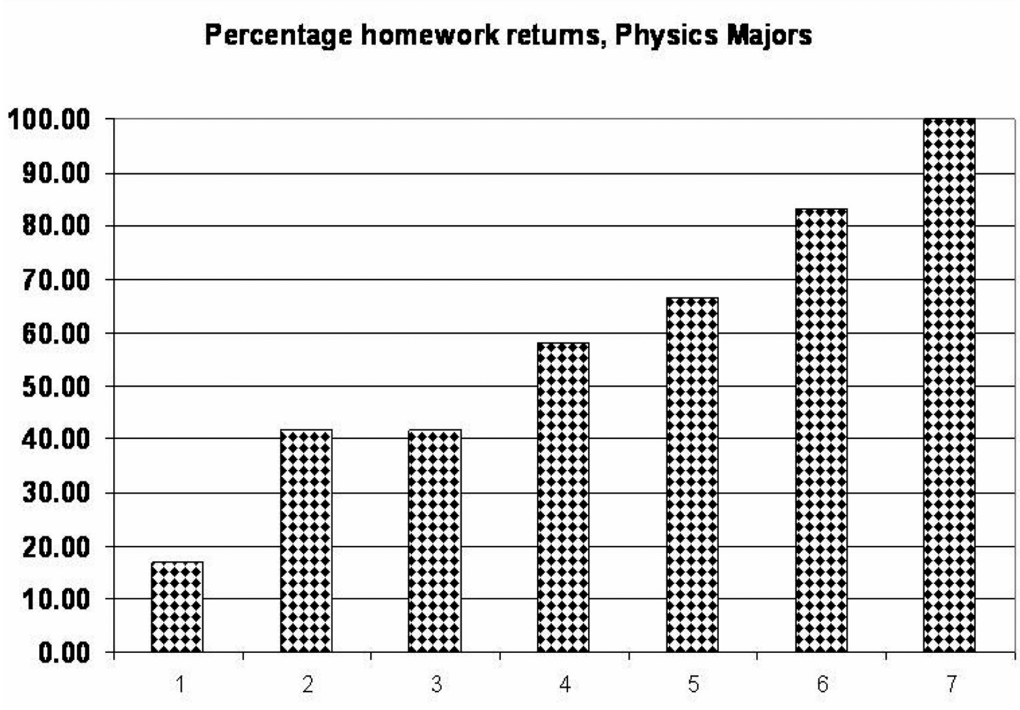

Figure 6.1b. Percentage homework returns for Physics Majors

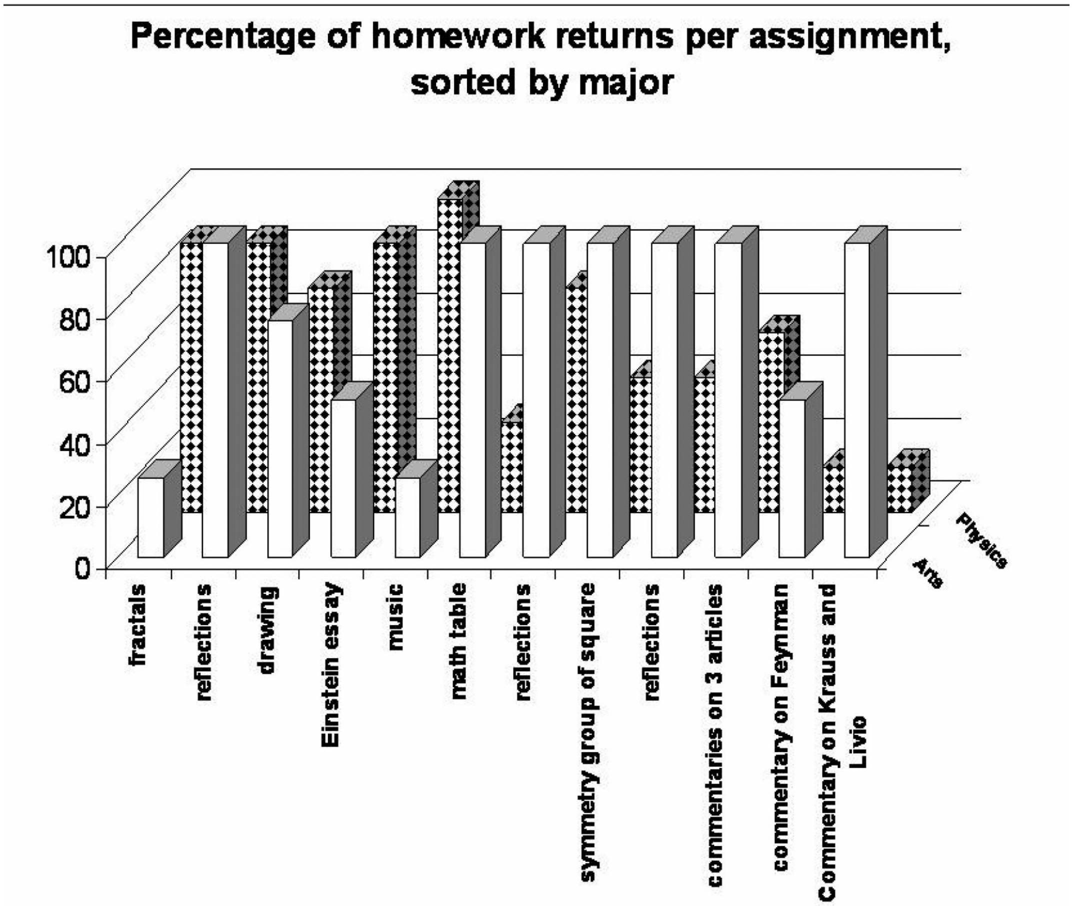

Figure 6.2. Comparison of homework returns, Arts & Physics Majors

6.1.2. Possible Reasons For Not Completing Homework.

In the traditional introductory physics classes at UCSB there is generally a high and consistent percentage of homework completed, as homework tends to have a significant influence on students' grades. Reasons for failure to do a homework assignment in the regular physics classes tend to be primarily illness or time management. Such were not the reasons given by students in CCS-120 for not doing homework, with the exception of one student who contracted bronchitis mid-quarter, and later made up a number of assignments. The physics majors who did not turn in reading/writing assignments gave either no reason, or informed me during their interviews that such assignments did not seem "real," in the same sense that problem sets are real because they are corrected and evaluated. They freely admitted to having skimmed the articles before class so as to be able to contribute to the discussions. The early assignments, for which I distributed concrete questions that were to be answered, had a higher rate of return from the physics majors than the later assignments, for which I used a more free-style format of simply writing a reaction to the article rather than answering specific questions. The physics students said that they enjoyed reading Krauss' book, and the articles by Feynman and Einstein that I assigned, although they did not turn in the written reflections. In the CCS environment of no grades, apparently the mere threat of "no credit" was not a sufficient motivation for the physics majors in choosing to do an assignment or not. The reason given by the arts majors who offered explanations for not doing an assignment, was that it simply "did not work" for them. As with the CCS physics students, the mere threat of "no credit" was apparently not sufficiently motivating for the arts majors to choose to do an assignment or not. Thus, without grades as motivating factors, perhaps the perceived level of difficulty may have had the opposite influence for the arts and physics majors in their decisions to complete an assignment or not. For the physics majors, their comments suggest that reading assignments which did not seem "important" (were too easy) were not completed, while for the arts majors, math assignments that "did not work" for them (were too difficult) may not have been completed.

6.1.3. Level of Difficulty as a Motivating Factor.

In comparison with traditional physics homework, the assignments in CCS-120 could not be considered difficult, as there were no lengthy problem sets. On the other hand, the readings, though mostly non-mathematical, were conceptually and linguistically more challenging to read than typical introductory physics texts.

The problem with math. My intention regarding math was not to eliminate it from a conceptual physics course, but rather to make the math more accessible by treating math as a language. While this attitude seemed to have been well regarded by the arts majors, still difficulty with math may have been a factor in some of the homework that they did not turn in. Broadly speaking, when the math assignment consisted of no more than filling in a table, most of the arts majors (but only a few of the physics majors) completed it; when the math assignment consisted of an application of a math concept, one or none of the art majors (most of the physics majors) completed it.

In the first homework assignment, the math component consisted of a short application of fractal geometry, as a follow up to the discussion about fractals in class. Only one of the arts majors attempted the fractal homework, without completing it, while the other three did not even attempt it. All but one of the physics majors completed the short fractal assignment. In the second homework, the math component consisted of completing a table comparing western music notation with inverse powers of two and drawing a suitable geometric representation. All of the arts majors, but only two of the physics majors, completed this table. The music application in the second homework assignment, to create a repeating rhythmic pattern using western music notation and represent it with geometric shapes, was taken up differently by the physics and arts students: only one of the arts students turned in this portion of homework two; four out of seven of the physics majors completed the music application as assigned, and the remaining three physics majors took it in a different direction, with a completely creative interpretation involving making electronic music using the software package Mathematica. The third homework assignment included a choice of math exercise or music application. Again, most of the physics majors did not do this portion; three out of the four arts majors chose to do the simple math exercise (complete the symmetry table of the square), and one chose to do the music application.

I noticed that throughout the course, the arts students made comments in class and on their homework such as, "I will never understand the math," "I have not done math in several years," and "Math is not my strong suit," so that I gradually eliminated the math component from the homework, relegating all math activities to class time, and keeping only the reading and writing components of the homework. Thus, difficulty or discomfort with math may have been a factor that effected the homework returns of the arts majors, however as the course progressed and they had more opportunities to discuss math in class with the physics majors, the arts majors reported increases in their comfort level, interest, and comprehension of math concepts. One possible recommendation for future integrated math-physics environments would be, then, to reserve mathematical applications for homework for later on in the course.

6.1.4. Interest And Personal Relevance as Motivating Factors

My elimination of the math applications from the homework may have caused a decrease in the interest level on the part of the physics students, which may have contributed to the diminishing returns regarding their homework as the course progressed. This interpretation is suggested by the comments of Frank and Manny:

> **Frank:** The [assignments] that I probably liked the least um…. I guess, just the reading assignments, and, not because I don't like t' read, but um…. Well, I guess I can only say that I liked them the least because I did the fewest of those, and the reason that was the case is just because for me it's always been a problem that reading assignments tend to get pushed to the wayside because it feels like…explicit like, problem sets are more REAL, like, this has t' be handed in, and it's gonna be corrected, and- and returned, whereas, a reading assignment, if you just skim it before class, and you're just gonna talk about it, you can still hold your own if you know a little bit about the topic. So, um…I felt like I could get away with that a little bit. So, I didn't do as many of the readings...
>
> **Manny:** Bravo...I feel exactly the same way, I like – you couldn't 've put it -better, h' really, like those are exactly my thoughts.

Yet they both agreed that I should not eliminate the reading assignments should I offer this course again, as the readings are "really important." On the other hand, the art majors described the readings as "grounding" and "making sense," and they tended to write copious reflections about the articles. It is noticeable on the graph that the math component of the first assignment and the music component of the second assignment had the lowest returns from the arts majors, but nearly one hundred percent returns from the physics majors. It may also be of interest that the physics majors turned in more of the writing portions of the first two homeworks, in which there were specific questions to be answered, than the later homeworks, in which I asked only for a brief summary followed by a reflection or reaction to the article. This type of less structured assignment tended to be appreciated by the arts majors, as expressed by Victor Eremita in his interview:

> **Victor Eremita**: I liked the approach of…of having two responses, one being a reiteration, or a summary of what you read, and the second part, ah, any comment you wish to make about what stuck out to you. That approach to homework I found most helpful, instead of …um, y' know, the question and answer form…

Thus, it may be that interest level and difficulty motivated the arts and physics majors differently. In the absence of the pressure to complete homework induced by grades, one possible interpretation may be that the arts majors tended to avoid the assignments that they felt were too difficult, and the physics majors may have not spent the time to do the assignments that they felt were somehow not important. In future integrated arts-sciences environments, if one of the goals is to encourage students to become more comfortable with the types of intellectual activities towards which they are less inclined, for example arts students with mathematics, and physics or engineering students with expository writing, then it is important to find ways to make math accessible and writing more enjoyable.

The remaining factor to consider is the time to complete the assignments for this course, in comparison with the time to complete assignments for the students concurrently enrolled in more difficult physics and math classes.

6.1.5 Time to Complete Assignments as a Motivating Factor.

My original intention for the homework was that each weekly assignment should include a component of math-as-a-language, a component of art (whether art, music, or dance), and component of physics content through reading works by theoretical physicists and some written analysis based on the readings. The time to complete the readings and written analyses should have taken from three to four hours each week, and the combined math and arts components I estimated should have taken from one to one and a half hours, depending on the level of detail a student chose to exercise. Thus, the total weekly time allotment for homework for this four-credit elective should have been between four and five and a half hours. At UCSB a typical introductory physics course, which meets for three hours per week, carries a credit load of three credit points, and a homework expectation of five to ten hours per week. Thus, for a four-credit course which met for three hours per week, I considered a homework expectation of between four and five and a half hours to be reasonable. In the last month, when the students should have been working on their final projects, my intention was to reduce the reading/writing assignments to allow time to focus on the final projects. Considering the concurrent enrollment of the physics majors in extremely challenging courses (such as quantum mechanics, relativity, statistical mechanics, and higher level math courses), and the fact that the difficulty of homework in such courses always increases as the course progresses, it is reasonable to surmise that time may also have been a contributing factor in the diminishing homework returns from the physics majors.

In summary, a possible interpretation of the differential homework returns of the physics students and arts students, is that each tended to present a higher rate of return on the homework assignments with which they were most comfortable. Regarding assignments that involved some degree of mathematics, it appears that the arts students tended to complete the math and math-like assignments which involved filling in a table, but not those which involved applications such as fractals and music, while the physics majors tended to complete the mathematical assignments which involved applications, sometimes extending my assignment to a more challenging level according to their own interests. Regarding the reading and writing assignments, the art majors tended to complete the reading and writing assignments, perhaps appreciating the free-form style of writing reflections more so than directed questions. The physics majors tended to complete more of the initial assignments that involved directed questions, but tended to diminish on their homework returns as the assignments devolved into reading and writing free-style reflections on the readings. Another factor that may have contributed to the diminishing homework returns from the physics majors in CCS-120 may likely have been the time pressure to complete difficult assignments in their major classes, which in some cases included graduate level physics courses.

Since grades in CCS-120 were not motivating factors, it is reasonable to suggest that the homework returns were genuinely based on students' attitudes towards the assignments. Thus it is instructive to explore the way in which students responded to the assignments in designing future integrated arts and sciences environments. The actual homework assignments can be found in Appendix B; in the next sections examples of the completed assignments will be discussed.

6.2. Draw Your Physics Homework? Art as a Path to Understanding Physics

The art exploration for the first homework assignment was to draw a visual representation of an article by Albert Einstein entitled "Physics and Reality."   In this article, Einstein described his view of the nature of science as a continuous search for connections between what we can perceive with our senses, and phenomena that take place at scales well beyond our normal perception. His use of richly metaphoric language in this article seemed to lend itself readily to a first attempt at exploring the use of drawing to understand concepts in physics that was different from the usual vector diagrams to represent problems in Newtonian mechanics. In addition, because this article described Einstein's opinion of the nature of the scientific process, I thought it would provide an important opening discussion topic for this course, to examine the processes and practices of physics. This article was one of three assigned for the first assignment, the others being an exploration of teaching art in the physics classroom (Peter Campbell, “Seeing and seeing:visual perception in art and science,” 2004) and a discussion of the language of mathematics from a book by Mario Livio (*The Golden Ratio*,2002).

I asked the students first to write a summary of Einstein's article, then to draw a visual representation of what they thought Einstein was saying in the article, and finally to write a personal reflection about what it was like to be asked to do such an assignment. Their interpretations of this article, both verbal and visual, reveal a wide range of initial attitudes towards art and science, as well as a range of perceptual preferences, from concrete and literal, to abstract and metaphoric.

The question from the homework which motivated this assignment was as follows:

Q2. Einstein, *Physics & Reality*:

> Granted, this essay is a bit tedious to read, as it is written in a style that was popular in the early 1900's, and which is no longer much in use. Nevertheless, read it a few times, make notes, underline, etc., until it makes sense to you.
>
> (a) Write a paragraph or so, explaining what you think Einstein is saying, in your own words.
>
> (b) Can you visualize in your mind what Einstein is talking about? Draw a pictorial representation that reveals the way you conceptualize/visualize what Einstein is trying to say about physics and reality. It can be anything you like, from a simple diagram using shapes and words, to an allegorical representation using images.
>
> (c) After you have completed your pictorial representation, tell me: what is your reaction to being asked to do this? Was it natural for you? Do you visualize concepts easily? Or was it difficult, and a strange experience to be asked to draw a representation of your own mental images?

The responses of the physics students and art students will be considered separately, and then compared.

6.2.1. Physics Students' Visual Representations of an Article by Einstein

Five of the seven physics students turned in the drawing as well as the summary of Einstein's article, with a range of responses from concrete and literal to allegorical and symbolic to highly abstract.

Literal interpretation. Al, fourth year physics major, submitted a visual representation of the article that resembled a flow chart or concept map, rather than a picture. Interestingly, in a subsequent drawing assignment (drawing the world lines of authors), he also drew a similar type of literal and concrete visual representation. Instead of writing a reflection of what it was like for him to draw his understanding, he added one sentence of explanation to his drawing: "It is fairly easy to draw this as there is something fundamentally simple going on: using logic to refine logic."

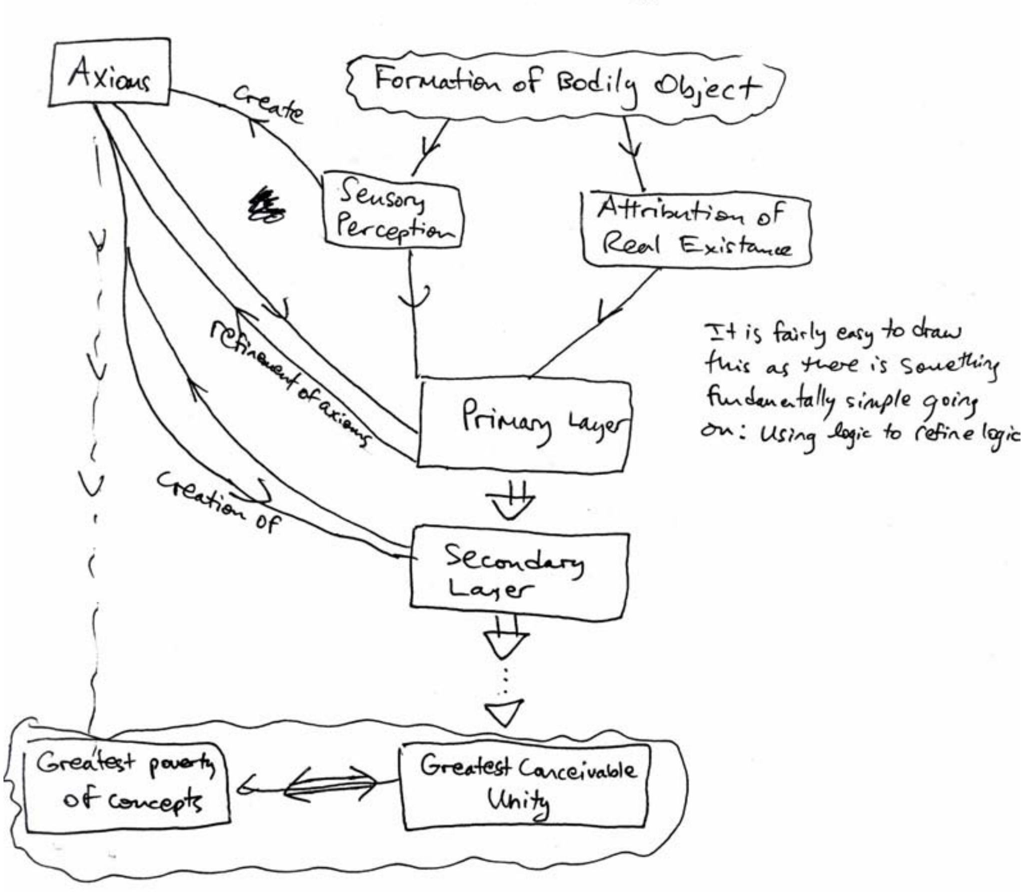

Figure 6.3. Al's visual representation of Einstein's article.

Al drew an absolutely literal representation of the most concrete aspects of Einstein's article, which are described in the section entitled "Stratification of the Scientific System." In Al's summary of Einstein's article, he stated,

> Einstein’s main argument is that the aim of science is a comprehension, as complete as possible by the use of a minimum of primary concepts and relations. Einstein says that the scientist establishes a set of rules, defines the object they are studying and gradually probe the object’s qualities while at the same time adjusting the rules.

Al included the role of sensory perception in his diagram, but did not mention it in his essay, although Einstein's description of the nature of science placed a heavy emphasis on the role of sensory perception in forming a conceptual basis for external objects, which we then imbue with a separate existence apart from our senses. Al seems to have represented this by the parallel arrows he has drawn from the first "cloud" which he labeled "Formation of Bodily Object" to the two boxes of "Sensory Perception" and "Attribution of Real Existence." Al representated "Formation of Bodily Object" as a nebulous cloud, a symbolism which is often used to convey a thought, and more concrete box-like shapes to represent "Sensory Perceptions" and "Attribution of Real Existence." This bit of symbolism is perhaps the only non-literal aspect of Al's flow chart. The rest of Al's representation is a concrete map of the practice of doing science, as he understood Einstein to have described.

Metaphoric and symbolic interpretations. The rest of the drawings by the physics students employed various symbolic and metaphoric representations to convey their interpretation of this article. I received drawings from AT, SS, Sam, and Charlie. Their drawings and interpretative summaries of Einstein's article yield interesting insights as to their individual approaches to processing information.

AT, first year physics major, summarized Einstein's article succinctly:

> Einstein proposes that the goal of science is reductionist by its very nature. To take the entirety of our sensory experiences (and now, things that are well beyond it) and congeal it, if you wish, into a form which is both elegant and complete. He suggests that we must strike a balance between seeking logical unity through “abstraction” and a direct connection with our experiences.

Figure 6.4. First year physics major AT's interpretation of Einstein's article

Unlike Al's concrete and literal interpretation, AT has taken a more metaphoric approach, in representing Einstein's hierarchy of layers of abstraction, each of which attempts greater logical unity with the layers below, yet is poorer in concepts and relations, and farther removed from sensory experiences. The arrows in Al's flow chart, representing sensory input, observation, are replaced in AT's representation with what appear to be books. In Al's map the entire process of doing science is simultaneously visible, whereas in AT's drawing there is a sense of continual upward movement toward some mysterious realm. AT has represented this process in a self-similar, repeating pattern that is reminiscent of a fractal, indicating the repetitive nature of the process of observing and refining. Einstein stated at one point in this article that we shall never understand how it is that by mere thinking, we can comprehend nature, a feeling which AT seems to have captured in his drawing, with its sense of extending beyond the limits of the page. In reflecting on how it felt to be asked to draw his understanding of this article, AT responded that it was quite natural, as to him, mathematics and visualization are inseparable.

> Yes, it was quite natural. I think of calculus, differentials, and many other things visually. I am so entrenched in math that I use rudimentary forms of ‘visual calculus’ even when I play games. To imagine a curve of a damped oscillator is as intimately connected with a spring as the word ‘apple’ is to holding one in your hand.

One of the goals of using art in physics is to facilitate the development of such a connection in a wider population, a connection which AT seems to already have developed.

First year physics student SS, wrote a concise summary of Einstein's article:

> At the basis of Einstein's argument is the concept that all that we perceive to be "reality" ... is ultimately based on our sensory perceptions. Therefore, scientists can only aspire to describe a "definitive system" of reality based on the "primary layer" of sensory observations and subsequent layers of connection and observation. ... Einstein hopes that, given the success of science so far, we will be able to approach a more and more unified system of science. This will, of course, suffer from the uncertainty of being based on a lattice of mental connections, but one hopes that it will bring us to a more accurate, helpful system of describing the outside reality of whose existence we seem so sure.

She represented her interpretation of Einstein's description of the process of science using completely abstract visual symbols (Figure 6.5), and described the process of drawing as natural, though novel for an academic assignment:

> Doing the visual representation felt very natural to me. I tend to visualize concepts in my mind as part of the process of understanding and thinking about them. For example, when listening to music, a large part of my enjoyment and comprehension comes from shapes, colors, and physical textures I see and feel in my mind. I must say it was new to be asked to put the images provoked by this article down on paper (since I've never been asked to do something quite like that before), but the act of drawing it felt natural and satisfying.

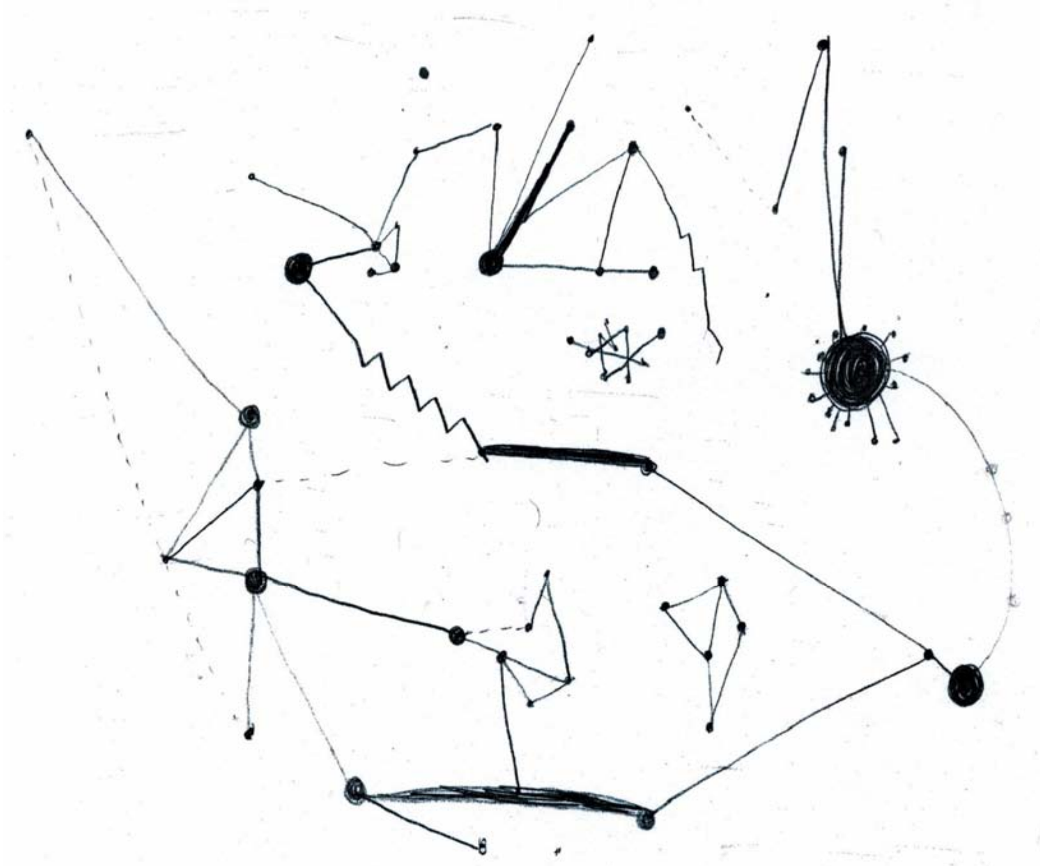

Figure 6.5. First year physics major SS's interpretation of Einstein's article..

In the article, Einstein expressed a sense of anticipation that our current incomplete understanding, based as it is on our sense perceptions and conceptual derivations from our perceptions, may one day be filled in. SS has captured this process in her drawing, by essentially creating a one-to-one mapping from her interpretation of Einstein's words to the symbolic representations in her drawing.

> In my visual representation, each dot represents a sensory perception of the nebulous reality (shaded area) . The size and substance of each dot may represent the accuracy of our measurements, or the number of times the sensory perception has been repeated and confirmed by different people/methods. The lines between sensory perceptions are

> mental connections we have made. The lines may be faint if they are based more in mental speculation than sensory evidence. (For example, string theory may be represented by a large complex web of faint lines and dots.) Some perceptions and connections are completely separate from other webs. Some connections are broken, as they have been shown by substantial sensory experience to be unlikely. There are not well-defined layers, since, as Einstein stated in his article, "the layers…are not clearly separated. It is not even absolutely clear which concepts belong to the primary layer."
>
> Although my visual representation has a lot of holes and seemingly random structure, one could imagine those holes filling up with more sensory experience and connection, finally creating a whole, unified picture that gives shape to the shadowy gray of reality which it describes.

These three physics students, Al, AT, and SS, have presented a range of interpretative styles, from Al's concrete and literal diagram, to AT's metaphoric representation of the general sense of the article, to the abstract symbolism of SS, which, though not as obvious as Al's verbally-based concept map, is nevertheless a concrete mapping from concept to symbol. Each of these representations allows for an understanding of how each of these students processes information.

Sam, fourth year geophysics major drew a representation that was somewhere in between the highly metaphoric representation of layers and pillars of books drawn by AT, and the literal symbolic representation drawn by SS. His drawing shows a series of sharp peaks and deep valleys, which are all connected beneath a smooth, slowly varying curve that he has labeled ""Limit of Understanding (arbitrary)."

Below the deepest of the valleys are the words “Unity of Knowledge,” and the peaks are labeled “Individual Disciplines of Knowledge.”

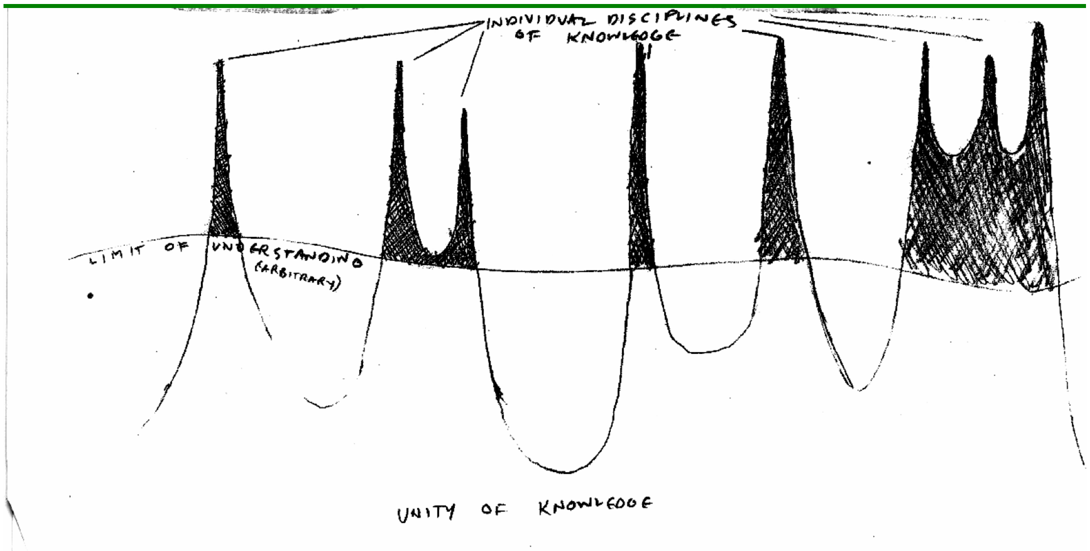

Figure 6.6. Sam's visual interpretation of Einstein's article.

Sam's summary of Einstein's article begins with a personal evaluation:

> Einstein is clearly of the opinion that science is something deeper than the sum of all its disciplines. To me, this is a message of inspiration or hope to all those questioning the validity of existence. The fact that processes of the universe can be analogized and understood at intuitive levels to humans reinforces the notion that there is an underlying connection between all things.

He seems to be referring to the following statement from Einstein's article, the famous quote in which Einstein remarked that the "eternal mystery of the world" is the fact that by our thinking we can comprehend it:

> The very fact that the totality of our sense experiences is such that by means of thinking...it can be put in order, this fact is one which leaves

> us in awe, but which we shall never understand. One may say "the eternal mystery of the world is its comprehensibility." It is one of the great realizations of Immanuel Kant that the postulation of a real external world would be senseless without this comprehensibility (Einstein, 1936, reprinted in Deadalus Magazine, 2003).

Sam also stated his personal connection between art and science:

> Art has been absolutely vital to my current comprehension of any and all areas of science.

Thus, it seems that for physics majors AT, SS, and Sam, there is a natural connection between the logical and intuitive aspects of understanding, as all three expressed their use of either art or mental imagery in the way they grasp concepts in physics or mathematics. Charlie, fourth year physics major, took a rather different approach to summarizing Einstein's article, with a surprising irreverence:

> Einstein is saying in a very roundabout and overly complicated way that the basic assumptions made in science in the past, which were assumed to be true, no longer appear to be so. Scientists need to look at their most basic assumptions (axioms) such as the nature of time and space, gravity and light and rebuild their theories from better assumptions. In my opinion he is rather inefficient with his words, building up a complex description about layers or degrees of concepts and then subsequently breaking down these barriers with fuzzy boundaries.

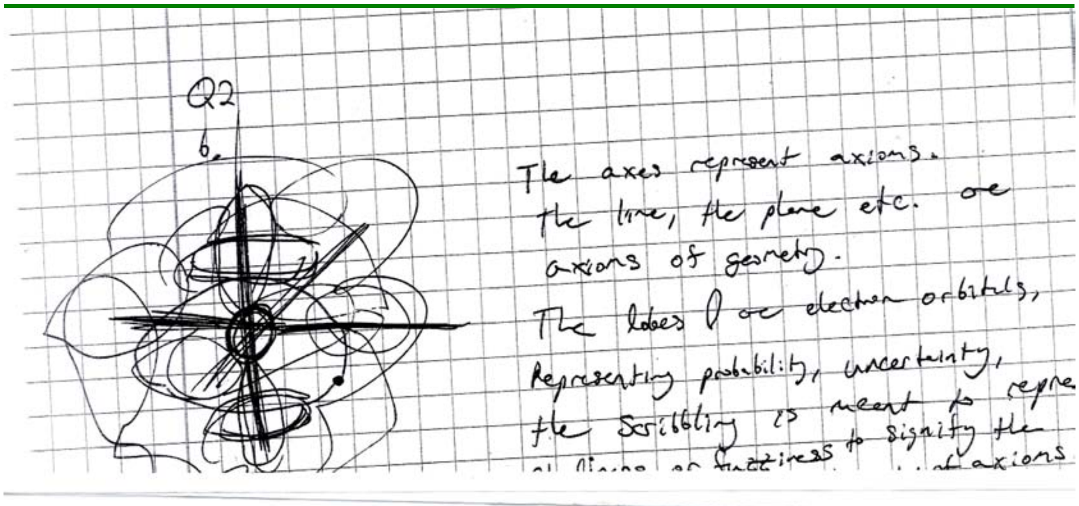

Figure 6.7. Charlie's visual interpretation of Einstein's article.

Charlie wrote a brief explanation the symbolism he used, next to his sketch (Figure 6.6):

> The axes represent axioms. The line, the plane, etc. are axioms of geometry. The lobes are electron orbitals, representing probability, uncertainty, the scribbling is meant to represent cloudiness or fuzziness to signify the [something cut off in the copying process] of axioms.

Although he did not write a reflection on his reaction to being asked to draw his understanding of the Einstein article, a sentence from his response to the first article that I assigned, “Seeing and seeing; visual perception in art and science,” (Campbell, 2005) is perhaps revealing of a skeptical attitude towards the use of art to understand physics.

> The author's comparison of art and science requiring similar levels of formal training is laughable to me. ... nobody can intuit something like the structure of DNA that took years to discover, while any artist could

> decide how to make a sculpture or compose a song without any training.

This attitude, that "any artist" could create an artistic product "without any training" reveals an underlying prejudice that, by the end of this course, was hopefully dispelled. Compare the relative values placed on science and art conveyed in Charlie's statement, with the following statement expressed by Juno in her interview:

> I think there's just something that is DONE, in the way that it is arranged or taught, that makes people really AFRAID of it [i.e., physics], and I think it is taught in a way that is kind of – seems very EXCLUSIVE. And I ALWAYS had that feeling about physics, I always had the feeling that scientists are exclusive.

Juxtaposing these two statements by Charlie and Juno, one a physics major and the other an art major, it is perhaps understandable how the sense of scientists' being exclusive might be communicated to non-scientists, if such prejudices may be unconsciously communicated through attitudes and interactions.

"art and science requiring similar levels of formal training is laughable to me... any artist could decide how to make a sculpture or compose a song without any training "	" I always had the feeling that scientists are exclusive."

The need to change this perception on both sides underscores the potential benefits of an integrated arts-sciences curriculum such as CCS-120 in dispelling such prejudices. Although Charlie did not submit a reflection on his drawing process with the first homework assignment, by the end of the quarter he demonstrated that, as a result of this course, he had begun to integrate more visualization into his approach to programming, which he described in writing about his final project.

In summary, the drawings and essays of the physics students reveal insights into their attitudes, and ways in which they perceive and process information, which may not necessarily be apparent through the traditional physics homework, with its complete reliance on problem solving. What did this drawing and writing exercise reveal about the arts students?

6.2.2. Art Students' Responses to Einstein's Article

The response of the art students to this assignment revealed a variation in their perception of science through the summaries they wrote, moreso than through the visual representations they drew. Of the three art majors who did this assignment, all used various symbolic or metaphoric representations, however only Victor Eremita wrote an objective summary, while Beatrice and MKS wrote more subjective interpretations of Einstein's article. Juno did not do this assignment at all, substituting instead an essay of her own choosing in which she compared the writing styles of Lawrence Krauss and Mario Livio, which she sent via email a week after the assignment had been due.

Beatrice’s annotated sketch is shown in Figure 6.8. She began her summary of Einstein's article by saying,

> Einstein is saying that a physicist must start to philosophize because the foundation of our experience is shifty. Because science is thinking, it is then natural to examine the process of thought.

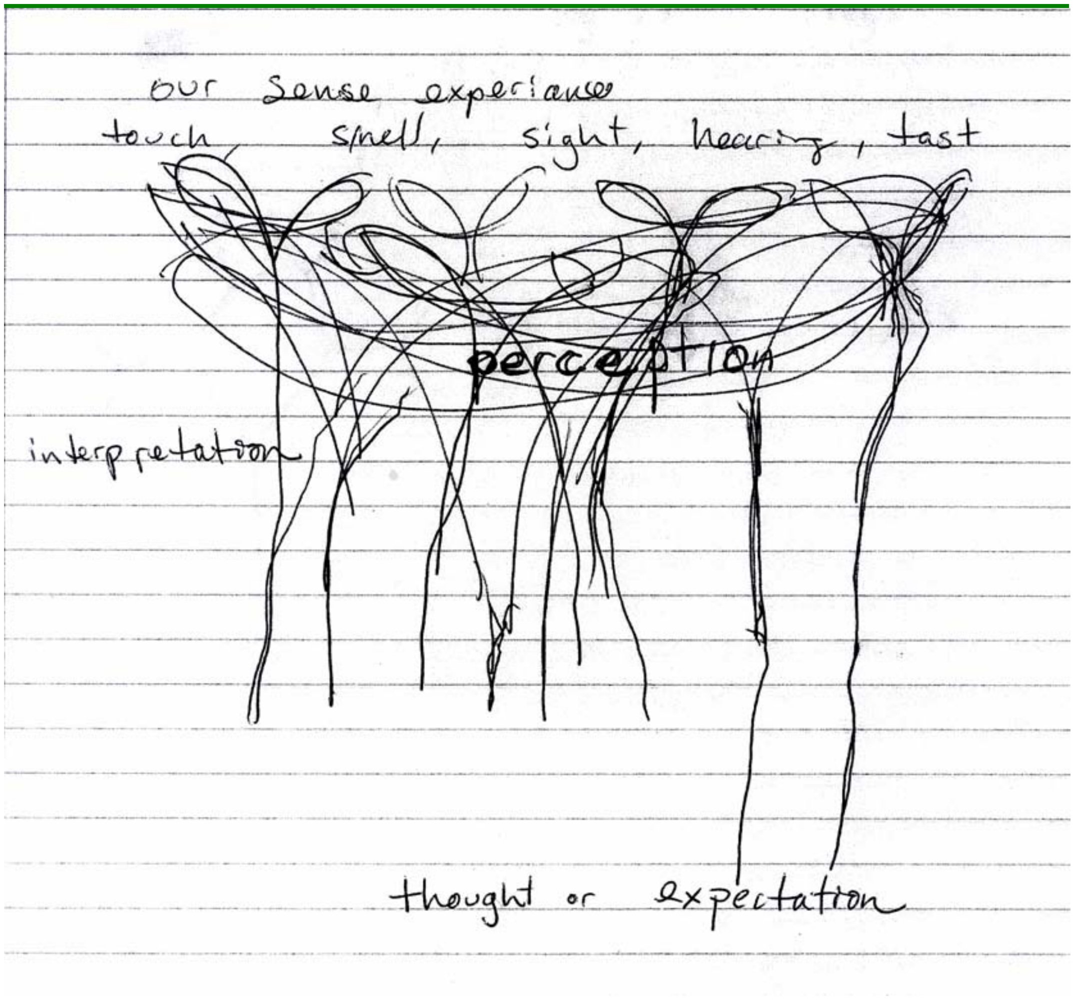

Figure 6.8. Beatrice's visual interpretation of Einstein's article.

Einstein began this article by stating his opinion that, at a time when the foundations of physics have "become problematic," that it is the physicist, more than anyone outside physics, who should take on the role of philosophizing about science, as physicists understand better than anyone else what is really going on in their own realm. He was referring to the revolutions in physics which had recently swept over the world: his own Relativity Theory, Quantum Mechanics, and the emergence of Noether's symmetry as the unifying principle behind all the observations. It is interesting that Beatrice extracted the meaning "*the foundation of our experience is shifty,*" from Einstein's words, as I do not believe this was his intention. The physics students, reading the same article, did not extract this interpretation. On the other hand, Beatrice, more so than the physics students, seemed to pick up on Einstein's emphasis on sensory impressions as the foundation of science, which he emphasized in the early portions of his article. Even more to the point, she has, in one sentence, captured the motivation behind his article, which the other students did not extract: Einstein's desire to investigate the very process of thinking itself.

As was discussed in Chapter One, Einstein was influenced by the educational philosophy of Johann Heinrich Pestalozzi, who advocated the process of *Anschauung* – developing mental visualizations which are abstractions based on making sense of seemingly unrelated sense impressions. This early training influenced his development of Relativity, which he developed from his desire to resolve the paradoxes inherent in electromagnetic theory in the early twentieth century. Einstein's research led him to investigate the process of thinking itself (Miller, 1989), which is the essence of this article. Einstein is reported to have said that his thinking was primarily visual, and his mathematical work followed his development of images (ibid.)

The theme that one's direct experience is the only means by which one can determine reality was one to which she would return repeatedly throughout the course. Beatrice displayed an ability to extract concepts from written descriptions, to interpret philosophical articles and utilize her ability to visualize to understand science and philosophy. The difficulty for her appeared to be in making that transition from sensory impressions to visualization, and finally to mathematical expressions. Her insistence on the viewpoint that it is only by direct experience that one can understand the world caused her to argue against several concepts in contemporary physics, such as spacetime, curvature, and the fact that time is asymmetric while space is symmetric. She stated on several occasions, that it was not fair of physicists to redefine terms from daily language in mathematical terms, and that this practice caused her to mistrust physicists in general, as a group. In retrospect, perhaps my not understanding her viewpoint at the time added another dimension of frustration.

This attitude of mistrust of physics as a result of the technical language used by physicists has been discussed by Bazerman (2000): “Scientific language serves to establish and maintain the authority of science, largely through exclusion and intimidation.” It is also true that, to really understand the principles and concepts of physics, even classical physics, one must be able to reason independently of direct sense experience; in other words, to use logic and mathematics to establish connections between disparate phenomena which are detected at the sensory level. This is perhaps the single most difficult obstacle for beginning students to grasp, and instructors to get across: to see past the "primitive" sense experiences (DiSessa, 1993), to the underlying physical explanations. I am suggesting that perhaps art can help bridge this gap.

MKS, first year literature major, also having no prior physics experience, but having studied philosophy and linguistics, derived still another interpretation of Einstein's words.

> In this essay, Einstein .. describes a subjective reality which is built on the framework of "sense perceptions" tied together by logical deductions. Einstein then describes an ontological hierarchy, a pyramid of sorts, in which primary concepts and statements of reality are narrowed down until we are left with the point of the pyramid, which is the essence of reality. Einstein also addresses solipsism, or the belief that nothing you perceive can be proven to exist in an objective reality.

Her assessment of Einstein's "ontological hierarchy" of concepts is accurate, however her interpretation that Einstein was likening the process of physics to "solipsism" is not. He did not use this term even once in his essay, but described the process of science as a way for individuals to compare and verify their experiences via a set of objective measurements and principles - the opposite of solipsism.

MKS' drawing was a rather literal expression of her description (Figure 6.9.). She drew a simple pyramid, the top of which she labeled "essential reality." Beneath the pyramid she drew two circles, each labeled "Primary Concept," linked by a line, which she labeled "Statement about reality (natural law)." She stated that she liked drawing a visual representation of her thoughts, although she would have preferred to have been asked to write a poem or "metaphorical passage" to express her understanding, as literature was her "real forte."

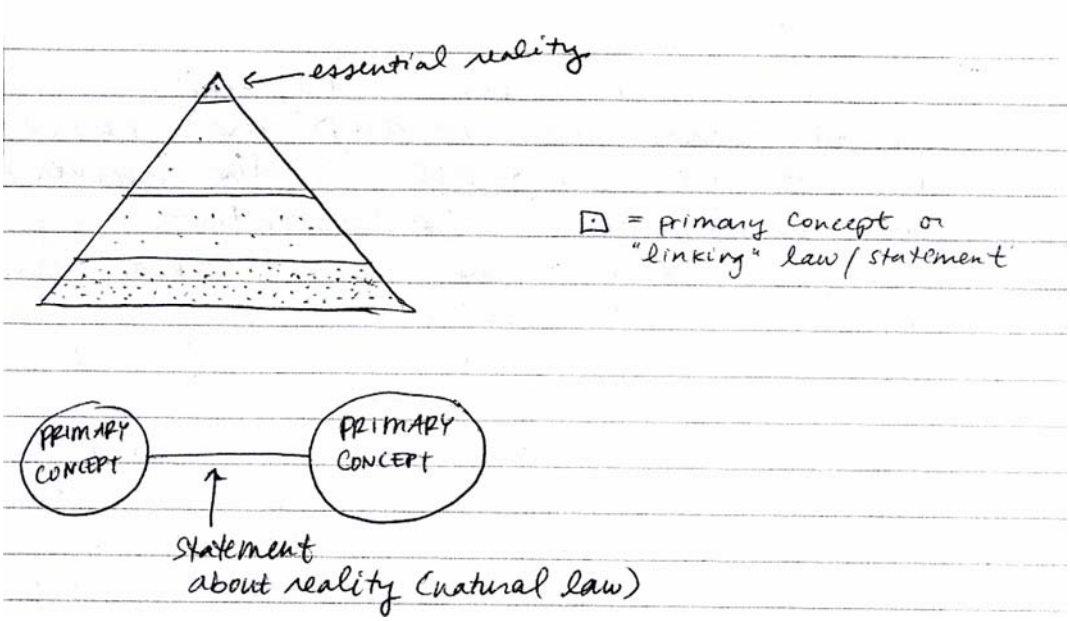

Figure 6.9. MKS's interpretation of Einstein's article.

Victor Eremita objectively summarized Einstein's words:

> Given the existence of sense experiences, the first step in comprehending reality consists of forming primary concepts of various kinds of physical objects. The second step consists in attributing a significance to the primary concepts themselves, independent of the sense experiences. The third step consists in classifying primary concepts through propositions, which both define the concepts and draw connections between them. Further steps logically deduce the preceding steps ad infinitum and are only justified insofar as they correctly signify the sense experiences from which they ultimately are derived. The means of completing these steps is thinking; the end is comprehension. The aim of science is a comprehension as complete and logically unified as possible using the fewest possible primary concepts and relations.

He submitted his assignment via email, and must have forgotten to send the drawing, however his description is more than adequate to convey his thought process and the purpose of his visualization:

> This pictorial representation shows a physical object, a cat, being perceived visually by a human. The sense experience of seeing the cat is conceived, as represented by the thought cloud. This primary concept is then used to form propositions, namely that cats like to chase mice and eat fish, but they don't like to get wet. My sketch came very naturally and easily, but only because I spent a lot of time trying to understand what Einstein meant. First I grasped the concepts, then the visual representation followed.

In summary, this assignment – to write a summary of an article and express one's understanding with a visual representation – revealed a variety of learning styles and levels of comprehension among the students, from purely mathematical and logical, to purely visual and sensory. The goal of physics education should be to blend both ways of understanding, as Einstein himself described the aim of science as:

> "a comprehension, as complete as possible, of the connection between the sense experiences in their totality, and, on the other hand, the accomplishment of this aim by the use of a minimum of primary concepts and relations" (Einstein, 1936).

Drawing is thus a useful exercise both for students as a means of organizing their thinking about a subject, as well as for instructors to understand the learning styles of their students. Moreover, I suggest that the use of drawing can facilitate the connections between observations and concepts, which in turn can facilitate understanding the of these connections through mathematics.

In retrospect, I believe I should have spent more time in class having the students share and discuss their visual representations of Einstein's article, similar to the approach I used in asking them to present their music homework in class. (discussed in Chapter Seven). Such an interaction may have presented opportunities to refine their thinking which merely submitting their drawings to me did not offer. Later in the quarter, I returned to the idea of drawing visual representations of concepts in an activity that was done in class with a partner: drawing the world line of an article, which will be discussed next.

6.3. World Lines of Authors: a Visual Analysis of Scholarly Articles

The idea for this activity originated from the fact that we had gotten behind in discussing the homework articles, and I needed to generate a way of going over an accumulation of six articles that had been assigned, read, and needed to be discussed. To have simply taken an entire class period to have everyone discuss each article would have become tedious. I do not recall exactly how this idea came to me, but it seemed quite logical, and ultimately it was successful. We had just been discussing Special Relativity and the concept of the "world line" – the trajectory of any particle through spacetime, and the idea that something comes into one's horizon when its world line intersects one's light cone. It struck me that in any piece of writing, the author is taking the reader on a journey through time and mental space, in which "events" take place, and that it might be an interesting way to cement the concept of a world line and apply this concept to understanding the mental journey of an author through an article. The instructions which I distributed were as follows:

> We have SIX articles to discuss today:
>
> Arthur Miller: Einstein and Picasso
>
> Steven Weinberg: Physics & History
>
> Tony Zee: Symmetry and Beauty in Modern Physics
>
> Richard Feynman: Curved Space
>
> Lawrence Krauss: Chapter 4 of Fear of Physics
>
> John Baez: The Meaning of Einstein's Equation
>
> Here's what I propose we do: Take ONE article, with a partner, and chart the "world line" of the article. Use pictures, words, equations, as you like. Every author takes you on a journey through time and mental space – the world line. Can you follow him? Does it make sense? Represent this journey on paper and present it to the class.
>
> To help you get started thinking about visualizing the world line of an article, discuss these questions with your partner first, and then draw the world line.
>
> 1. What is his starting place? What is his premise?
>
> 2. What is his viewpoint? His perspective, from where he is coming?
>
> 3. What is his initial trajectory? That is, in what direction does he seem to be going when he starts this journey?

> 4. What is the shape of the path? Is it linear, spiral, or jagged, or something else? Is it well defined or fuzzy?
>
> 5. What are the bifurcations, tangents, and meanders along the way? Does he split off on a direction and never return? Or does he meander like a river? Or does he dart off and come back like a squirrel? Or what?
>
> 6. What opinions does he give you along the way? Are these like treasures that he leaves you to find and open, or are these like droppings of stuff you'd rather step around? Or what?
>
> 7. Is the article mostly for teaching, or mostly giving of opinion? Are there signs along the way where the author is posting information that makes you react? Are these oases where you can rest, fountains where you can get refreshed, or demons that you want to fight?
>
> 8. Finally, where does he end? Does he end in the place where he seemed to have aimed in the beginning? Does he end where he started? Or does he end in some new location?

Unfortunately, not everyone was present on that day (March 2, 2007), so not all the articles were presented. The partners and their selected articles were as follows:

1. Sam and Beatrice presented Tony Zee's article "Symmetry and the Search for Beauty in Modern Physics";

2. AT and MKS presented Arthur Miller's article "Einstein, Picasso;"

3. Juno presented Richard Feynman's Chapter 42 on Special Relativity;

4. Al and Charlie presented John Baez's article "The Meaning of Einstein's Equation."

I wrote in my teaching journal after class,

> This activity worked really well. It was very interesting to see the ways that the groups came up with to represent their article. Each group took the front of the room and presented their time lines, then entertained questions and discussion. Some interesting observations emerged.

Feynman's Chapter Forty-two: I worked with Juno (sculpture major), as she had no partner, due to an odd number of people in class that day. We talked about Feynman, and she repeated how much she appreciated his writing, how the math he displayed was not necessary to understanding what he was saying, and how she could follow him all the way through. She related how she really liked him as an author because he made physics simple, yet did not make her feel as though he was talking down to his readers. She envisioned his chapter 42 as a smooth spiral, which ends where it began, but at a higher level. She did the presentation to the class by herself, too, and was totally comfortable presenting Feynman's ideas and fielding questions from the class. Her spiral world line is shown in Figure 6.10.

Zee's article, Symmetry and the Search for Beauty in Modern Physics: Beatrice (art major) and Sam (geophysics and East Asian Studies major) took Tony Zee's Symmetry and the Search for Beauty in Physics. Their diagram began at a point, and split into a series of swirls and connected curves, ending in a picture that included a tiger, Da Vinci's man figure, and a flower (strategically placed over the man figure). They indicated along the way where the author talked about symmetry by drawing little shapes. Although Beatrice is the art major, I observed that Sam did most of the art work on this piece. In the presentation, they talked about the author’s ending question: "Did God make the tiger, or did the tiger make God? " and compared this to the practice of doing physics. Beatrice indicated that she really loved this article, and would like to meet the author. The world line they drew is shown in Figure 6.11.

Miller's article, Einstein, Picasso*:* MKS (literature major) and AT (physics major) took the article on Einstein and Picasso, and drew the world line as an arc with two sine curves that are 180 out of phase, intersecting every half wavelength. The left side is labeled "Einstein," and the right side "Picasso." They indicated that the points of intersection of the two curves represent moments in the article when the author was describing similarities in the lives of Einstein and Picasso, such as “worked alone” and “women were important to them, but a negative influence.” The starting point was labeled “revolutionary” and the end point was labeled “representing simultaneity.” At one time, somewhere in the middle of the trajectory, they drew a larger region of overlap, indicating where the author speculated that Einstein and Picasso may have interacted directly. In this region of their drawing, the "Einstein" side has the label "Artist as Scientist" and the "Picasso" side is labeled "Scientist as Artist" indicating possible crossover. Their trajectory is shown in Figure 6.12.

Baez' article, The Meaning of Einstein's Equation: Al and Charlie, fourth year physics majors, presented this article. Actually, this article I had been intending to present myself, but since we were running out of time, I asked them to present it, as they were the only students in the class whom I felt were capable of doing so. I knew, when I included this article in the reader, that it may be too difficult, however I felt that it contained sufficient material that was conceptually accessible, and it was to have been read towards the end of the course, that the risk was reasonable. I asked Al and Charlie if they would be willing to present this article, to which they readily agreed, as they had already taken the graduate level class in General Relativity. I had brought to class that day a copy of Sean Carroll's book on General Relativity for reference "just in case" – and they took the opportunity to refer to it.

In my teaching journal for that day, I noted that I found it interesting that these two students approached this assignment not as a true collaborative task, but as students in a traditional undergraduate physics lab, in which the partners divide up the tasks, work separately, and compile them at the end to submit one report. Charlie wrote out the answers to the questions, while Al did the drawing – with little attention to the answers Charlie was writing. In the end, the diagram they displayed to the class resembled a flow chart explaining the Einstein equation, rather than a world line that represented the author's trajectory through time and mental space. This flow chart representation of Baez' article, shown in Figure 6.13, stylistically resembles the visualization Al drew of Einstein's article from the first homework assignment (see Figure 6.3).

Felder (1996) discussed the variety of learning styles encountered in undergraduate engineering programs, and suggested ways in which instructors could encourage students to use their strengths while strengthening their weaker areas. Perhaps this flow chart style of representation, shown by Al in both visualization exercises, is due to a strong learning preference for concrete and literal thinking.

Ultimately, one of the goals of teaching physics in an interdisciplinary environment such as CCS-120 is for students to strengthen their weaker areas – for concrete, literal thinkers to improve their abilities to visualize and reason abstractly, and for abstract thinkers to be able to organize their thoughts a bit more logically. The coming together of these abilities for the physics and art majors was most apparent in their execution of their final projects: to create a physics work of art (or work of physics art), which will be discussed next.

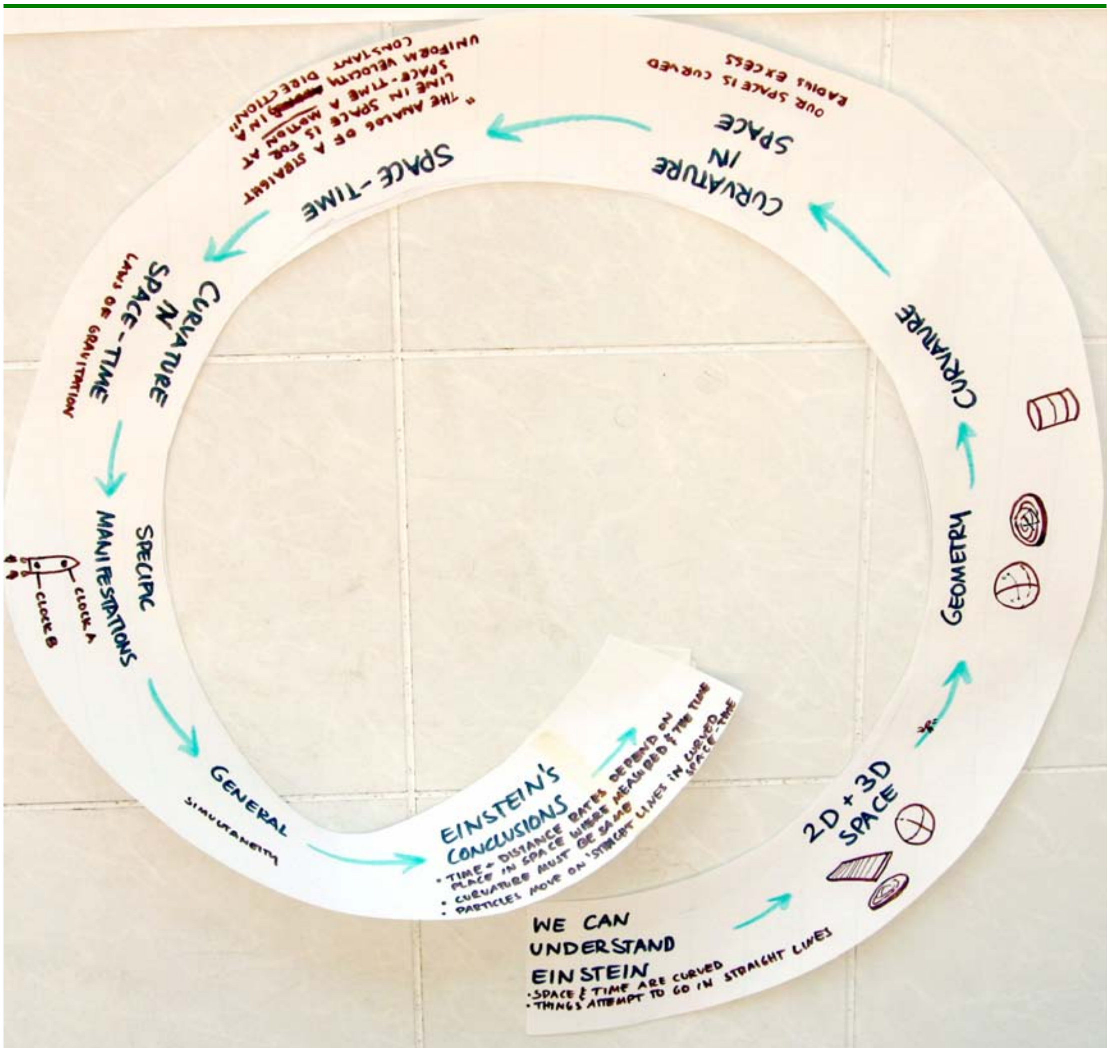

Figure 6.10. Juno's three-dimensional spiral world line of Feynman's Chapter 42

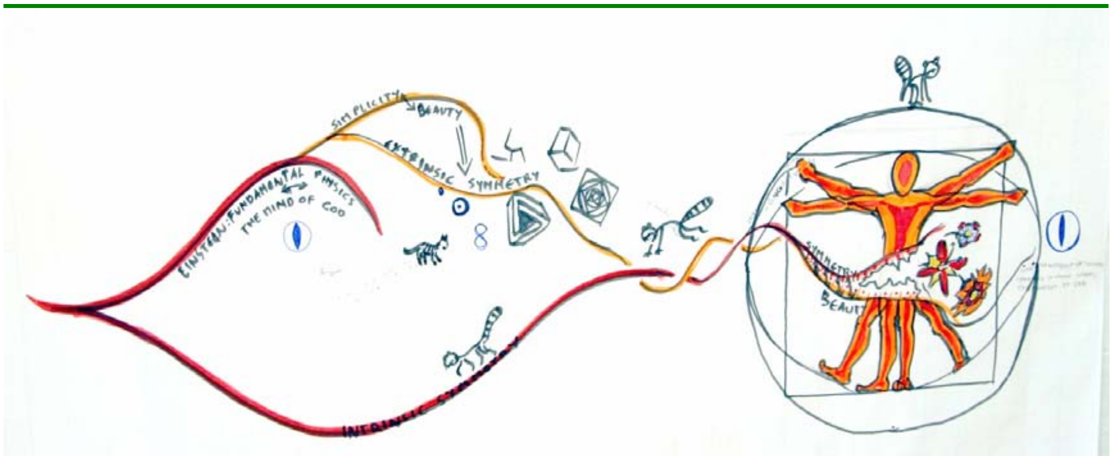

Figure 6.11. The world line for Zee's article, by Beatrice and Sam.

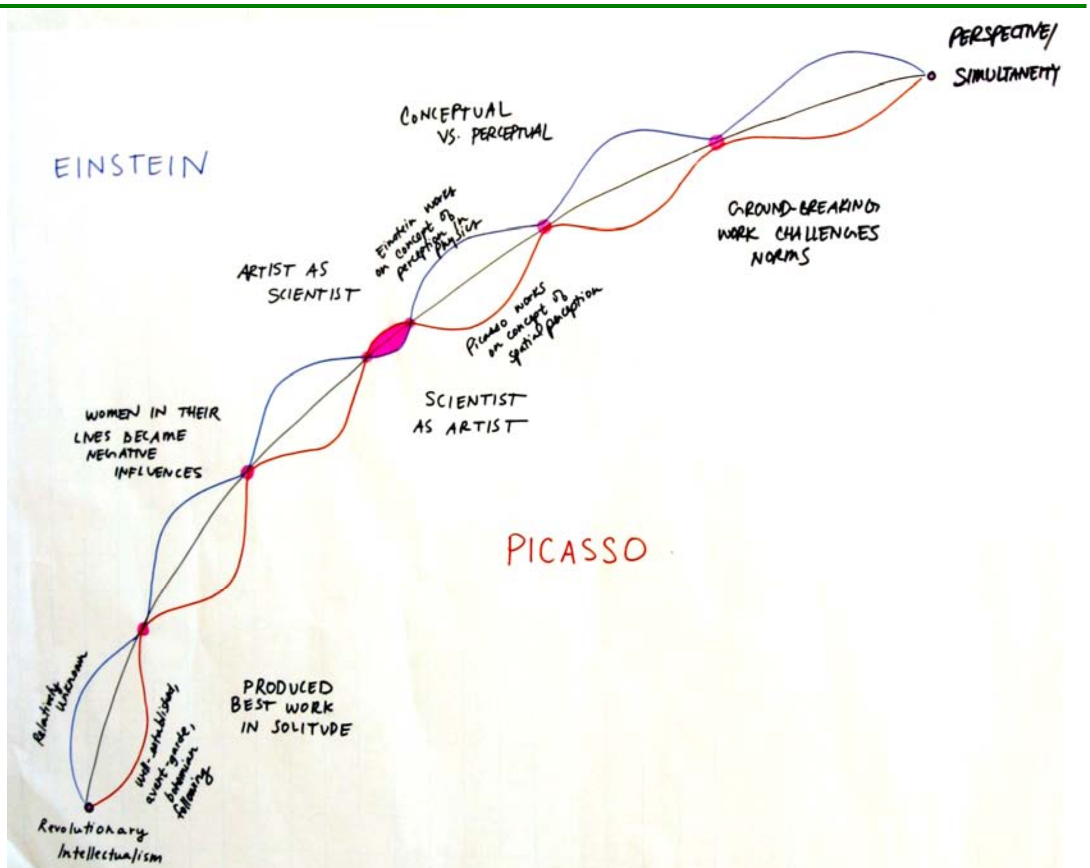

Figure 6.12. World line for Einstein, Picasso article, AT and MKS

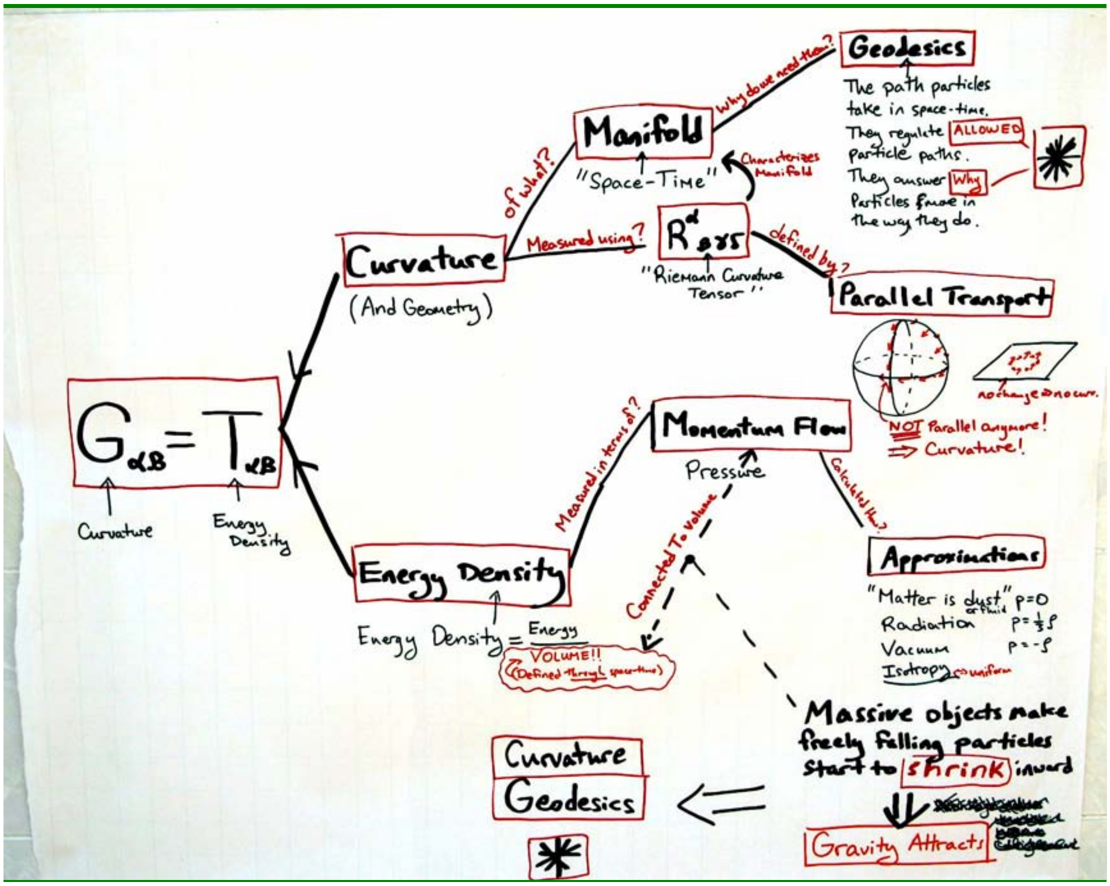

Figure 6.13. Al and Charlie's representation of Baez's article.

6.4. Final Projects: Physics Works of Art/Works of Physics Art

As has been discussed in Section 6.1, the final project was the most successful assignment, in that everyone did it, and all the projects represented students' efforts at having really wrestled with the math and physics concepts that were presented in the class, as well as the aesthetic principles of art, music, and symmetry. Each student explored in depth some aspect of physics, mathematics, and art, in a truly meaningful way. As Frank commented,

> My favorite was definitely the final project, because there was just so much freedom in what we could do, that I felt like…It hardly felt like an assignment at all, it was just something that I was doing that I

enjoyed, and that I wanted to show to other people. … and that I hoped they would enjoy, too. … So…I got to learn something about math and physics and aesthetics and art all at once, and create something that I really liked, so I thought that was educational, and also purely fun, and good.

The final projects are listed in Table 6.2.

Student	Project
Al	Computer-generated art based on mapping simple dance movements
Charlie	Algorithmic music based on mapping color space onto musical space, using Java applications and Midi sound software
AT	Projective geometry: Unbending curved space onto two dimensions
Sam	A physics and math-inspired self analysis of his gallery of art work, a reproduction of an Escher drawing, and an attempt at creating the symmetry operations of additive color mixing
Beatrice	Art installation of hanging sculpture, inspired by investigations of General Relativity
Juno	Art installation: a projection of a solitary dead rat, the sounds of the Lorentz transformations being written, and an invitation to participate
Victor Eremita	A golden-spiral inspired heptagonal book, in which the dimensions of the pages were inspired by the Fibonacci series
Frank	Fibonacci's Dream: a piece for two pianos and flute, based on symmetry principles, in which each measure is in "n/4" where n is a Fibonacci number between 1 and 55.
SS	Golden Sections: a piece for two pianos and flute, also based on symmetry principles and the Golden Ratio
Manny	Mandelbrot Music: algorithmic representation of the Mandelbrot set
MKS	Fibonacci meter poem about contemporary physics, inspired by this class

Table 6.2. Listing of students and their final projects.

This assignment really did provide a way for students to expand their awareness of the "other" side, in that art students explored physics in ways they had not previously considered, and physics students explored art in ways that were new to them, each producing work which surprised them for its artfulness as well as its expression of physics principles. From physics majors Al and Charlie, whose first attempts at producing visual representations of physics were rather literal, to art majors Beatrice and Juno, whose initial opinions of physics were somewhat intrepid, it is clear that each side grew towards a greater appreciation of the other. I will discuss a few of the projects in detail, and then relate these works of physics art / physics works of art to research on creativity, as it applies to aesthetic education.

6.4.1. Computer Simulations of Dance Movements as Art

Fourth year physics major, Al, investigated computer simulations of simple dance movements, producing graphic art that resembled Golden spirals and Fibonacci whorls by mapping the arm and wrist movements in the vertical plane. Starting with the arm stretched upward, bringing it down in an arc to a horizontal position, outstretched from the shoulder, Al created a series of computer-generated images that map the range of possible positions of the wrist in space. He wrote about his project to measure the ideal elegant motion:

> The resulting shapes are quite beautiful. They are disturbingly similar to the golden spiral. Artistically they are quite gorgeous. If asked to visualize the possible hand positions without doing this project, I would have deduced a very different answer than the actual result we have obtained through simulation. A natural generalization of this work is to classify what an elegant motion or pose is in a particular dance. One could define a perfect hand transition for example from "I" to "T." Then the elegance of any other motion can be measured by how far the motion deviates from the perfect one. It is interesting to note that if one were to flail their arms randomly, there is a nonzero chance to recreate an elegant motion!

Thus, physics major Al's exploration into aesthetics was to apply his mathematical inclination to the question of quantifying elegance. This type of question has been raised by physicists before, in a variety of settings. Michael Leyton of Rutgers University theorized that the human sense of aesthetics is based on maximizing transferability, which he related to the same principles of symmetry and groups that underlie contemporary physics (Leyton, 2003). Others have linked a sense of beauty with a sense of simplicity and familiarity (Schwartz, 2006). Incorporating arts and a sense of aesthetics into the teaching of any content area can help students develop their sense of how judgments of "goodness of fit" are made (Eisner, 2002). It is thus natural that a student of physics should be encouraged to explore the connections between elegance in mathematics and the arts. As Eisner (2002) suggested, the incorporation of arts as a way of knowing can help students develop their sense of qualitative reasoning in any content area.

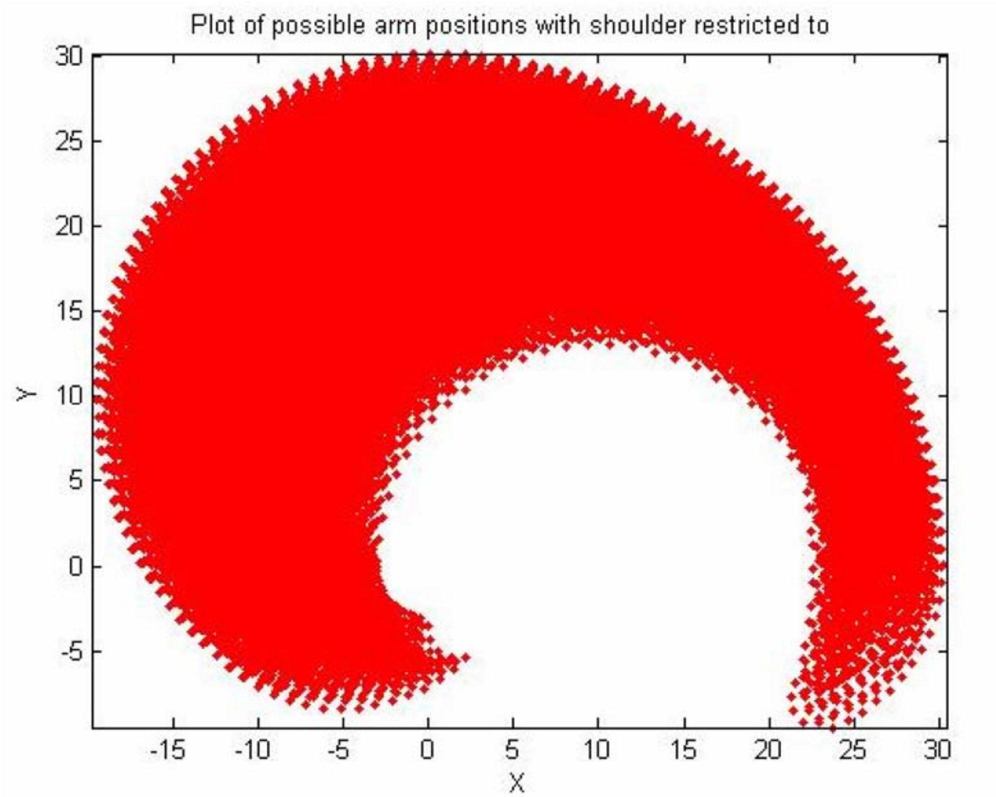

Figure 6.14. Al's graphic art based on simulation of an arm making an arc

6.4.2. Music from Fractals

Charlie's physics work of art was an exploration of algorithmic music. He investigated the problem of mapping an image from one "vector space" involving position and color, to another "vector space" involving time and pitch. Whereas Al was interested in mathematically quantifying the concepts of beauty and elegance of movement, Charlie was interested in mathematically quantifying images and trying to see if this process could produce an audibly pleasing sound that could be considered musical. He visualized the process of playing music as an instrument "operating" on a musical score, in a way which he envisioned as vector operations, such as taking the dot product of two vectors. Figure 6.15 is an image capture of the program he wrote, in which he sampled an image (the diagonal line which is in the process of being traced from upper left to lower right), and assigned a color in RGB space to the sound of a musical instrument which was available in his computer. Charlie's change in thinking about art, from the initial opinion he expressed in the first homework essay, is evidenced by his analysis of his own thought processes about physics and music, prompted by this project

> It is interesting to me that some of the students in the class were commenting that one of the barriers to understanding physics is learning how to speak the language, or learning to use the symbols, notations and conventions of physics. It is intriguing to me that music has its own set of notations and symbols that any musician understands but many of them are incomprehensible to me. For me, working on this project made me think of music from a more physical point of view. I thought about how I might use the notation of physics to represent musical cues. For example a musical instrument playing a note expressed as a dot product with a score.

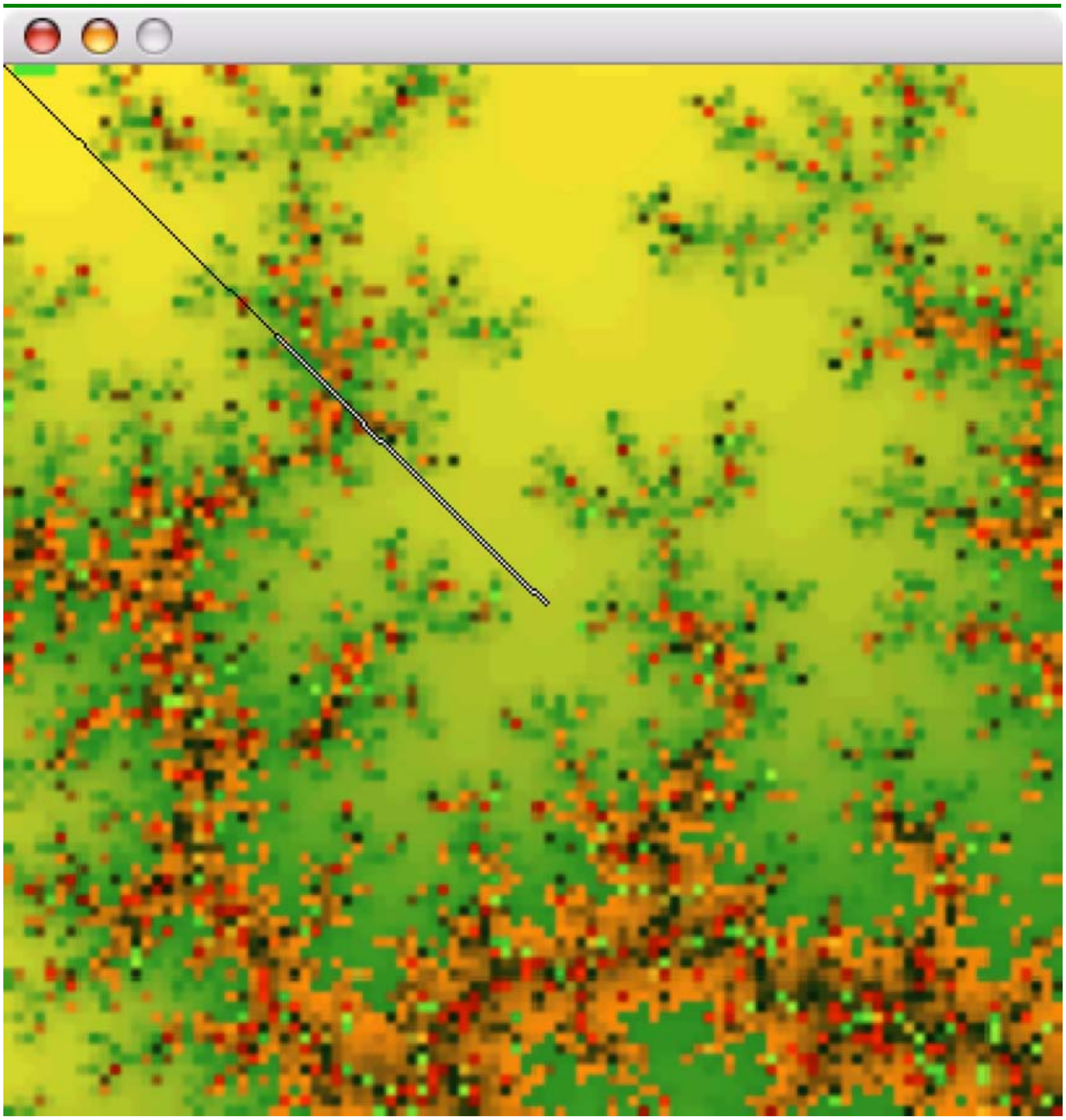

Figure 6.15. Charlie's sampling algorithm, creating music from an image.

6.4.3. Gravity-Inspired Art Installation

Art major Beatrice chose to present her struggle to understand concepts in physics through an art installation which consisted of suspended patches of knitted fabric, which she made, that illustrated the deformation of spacetime by mass. She accomplished this effect by filling the fabric with dry beans, so that the suspended pieces of knitted cloth bulged in response to the weight of the beans. Beatrice's installation are shown in Figure 6.16.

Figure 6.16. Beatrice's gravity-inspired art installation.

In writing about her creation process, she described the various concepts with which she had wrestled throughout the course, including time, space, curvature, gravity, and symmetry. She reviewed the articles with which she had had trouble, describing her evolving understanding of concepts which had at first been unfamiliar to her, and demonstrated her personal conceptual breakthroughs with these concepts through her artistic applications. She began her paper,

> During the course I felt a continual frustration with the use of language. There are several key words when discussing the principals of Physics that I associated with other meanings because of my Fine Art background or/and because of my ignorance of science discourse. Some of the words that seem to have carried particular weight were time, space, symmetry, and gravity. Determining the definitions of these words was a challenge because as an artist I have attached my own perception and definition to these words.

She reviewed some of the key articles from the course, including the Einstein article, Feynman's "Chapter 42" which she had argued with earlier, Zee's article on symmetry and the lecture by David Gross. Just as Charlie had envisioned music as a mapping process, in her own way, Beatrice similarly described the spacetime mapping of the yarn, through her knitting process:

> In order to create each square I must start with a finite distance in the ball of yarn to create each square. I then manipulated that distance by knitting the yarn that then took a specific amount of time to transform that finite distance to a new relationship of time and space. The knitted square comes to represent that inherently linked relationship and each one of the fabric pieces is a unit in time and space. The process of knitting the fabric enabled me to have a specific relationship and experience to the link of time and space.

Finally, she wrote:

> The creation of the final project was important for me to be able to digest many of the concepts that we discussed in class. It gave me the ability to develop an understanding and a personal reference to concepts that I found challenging. This was an invaluable part of my

> study of physics and I greatly appreciated the opportunity to learn in an integrated manner.

This realization of Beatrice of learning physics through her medium of art is reminiscent of some of the reports of teaching physics to dancers by Kenneth Laws. Professor Laws has written extensively on the physics of ballet, and about teaching principles of mechanics and mathematics to young dancers (Laws, 2002). In particular, he has cited how the connections between physics and ballet enable ballet students to improve their performance in both their studies of ballet in the studio, and physics in school (Laws, 2002).

Vera John-Steiner investigated creative thinkers in arts and sciences, arranging them into four general modalities of thinking, which she called visual, verbal, emotional, and scientific, based on the way they reported their inner language of thought (John-Steiner, 1997). According to her interviews and posthumous investigations, creative people think in a variety of images, music, patterns, words, numbers, algebraic symbols, mnemonic techniques, and spatial relationships, which led her to conclude that internal symbolic representations of concepts are unique to each person. John-Steiner found that physicists and mathematicians often think in pictures and images, and that creative people are passionate about their work. As described earlier, both of these traits – the linking of art and physics and the passion of the other students, were cited by students in CCS-120 as important to their learning physics.

The rest of the projects were equally fascinating combinations of physics and art. First-year physics majors Frank, SS, and Manny, already accomplished musicians, collaborated on a project in algorithmic music. Beginning with an exploration of symmetry in melody combined with a variable time signature such that the length of successive measures reflected the Fibonacci sequence (1, 1, 2, 3, 5, 8, 13, 21, 34, 55), to a mapping of the Mandelbrot Set into an imaginary space consisting of pitch and timbre, these three students created a fascinating progression from acoustic to electronic music. Victor Eremita, book arts major, created a book in spiral form, in which each page was a triangle, bound together into a sort of heptagonal spiral. In his paper, he described principles of natural science, from physics to the relationship of physics to psychology, which he related to his book. (Figure 6.17). Physics major AT investigated the mathematical representations of curves which, when projected onto a non-Euclidean surface, may appear to be drawn on flat space when observed from a distance. He painted a set of wine glasses, each one depicting a different curve (Figure 6.18). Literature major MKS wrote a free-style poem which expressed some of the ideas which stood out to her from the readings, written in Fibonacci meter, in such a way that the visual representation on paper appeared to be a series of Gaussian distributions (Figure 6.19).

Figure 6.17. Victor Eremita's physics-inspired spiral book project.

Figure 6.18. Two of the wine glasses designed by AT.

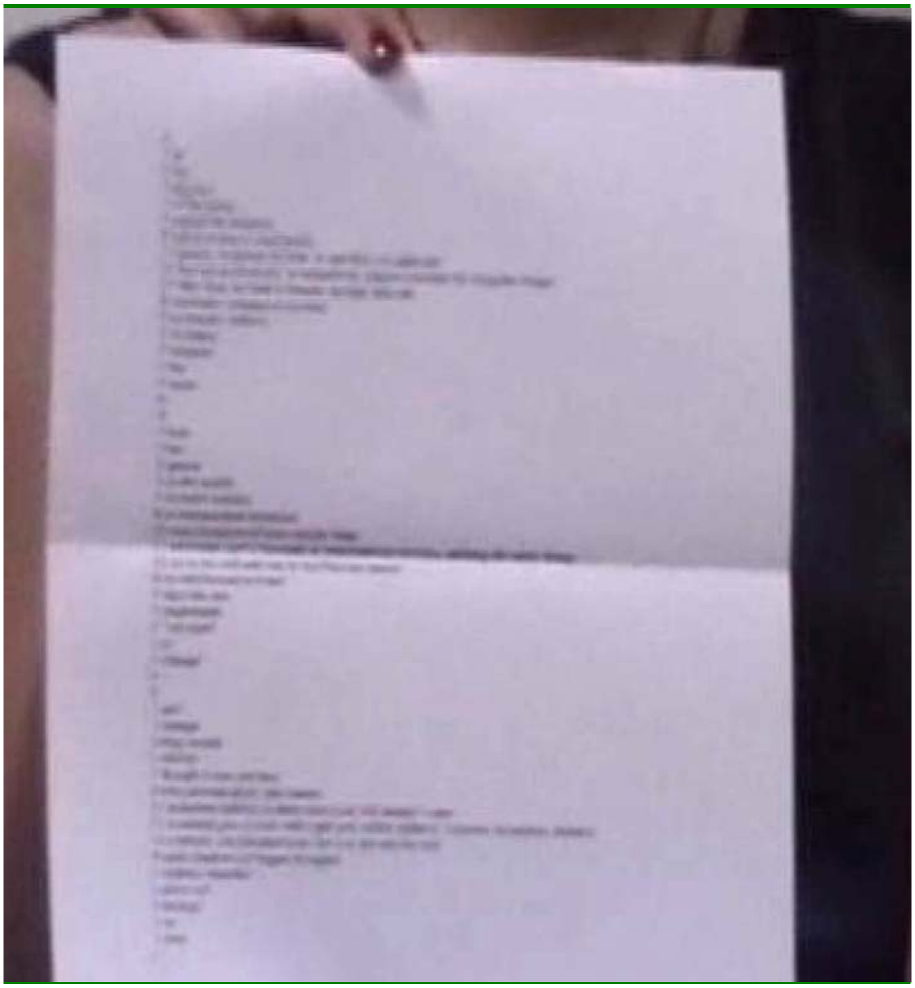

Figure 6.19. Fibonacci metered poem, by literature major MKS.

Numerous education theorists have called for the integration of arts into academic learning, from Dewey (1927), to Eisner (1987, 2001), to Maxine Greene of Teachers' College. In CCS-120 it has been demonstrated that arts and aesthetics can be effective in teaching physics and mathematics, both for physics majors as well as arts and humanities majors.

I have ended Chapter Six by demonstrating how the physics and art students who were initially separated from each other in knowledge and appreciation for each others' ways of taking meaning from the world through either math or art, evolved towards a greater appreciation of each other's ways of knowing. In Chapter Seven I will return to a moment early in the course, analyzing two short segments of video data that were recorded during the third class period. The views expressed by the students early in the course provide another benchmark by which the success of their final projects may be measured.

Chapter 7. Window into the Classroom: On Math, Music, and Meaning in Physics

> "Language, a human invention, is a mirror for the soul. Mathematics, on the other hand, is the language of nature and so provides a mirror for the physical world" (Lawrence Krauss, Fear of Physics, p. 27).
>
> "Music is the arithmetic of the soul, which counts without being aware of it." Leibnitz

The data presented in this chapter were recorded during the third class period, which was to have been a transition between the math orientation portion, and the introduction to symmetry. In the first two class periods, I had presented a variety of applications of mathematics in nature and art, including the Golden Ratio, Fibonacci series, fractals, Platonic solids and Penrose tilings, the goal of which was to make explicit the mystery of mathematics as it appears in nature. In the second class, the fist of three guest lecturers, Dr. Jean-Pierre Hebert, gave a talk about algorithmic art, and his role as an artist in the Institute for Theoretical Physics. The third class was divided approximately into three sections: a discussion about the role of mathematics in our perception and description of the universe, which was based on readings that were to have been done for homework; presentations by the students of their music homework; and a lecture by me on an introduction to symmetry. The discussion about math as a language of nature, and the simplifications that are necessary in physics in order to make sense of the world ("a cow is a sphere") were quite lively. Thus, whether or not the majority of the students actually did the reading before coming to class, they certainly did have opinions about mathematics.

7.1. Is Math the Language of the Universe?

7.1.1. Introduction to the Question of Math as a Language

Mathematics, it has been argued, shares many characteristics with language, in that students must "make sense" of mathematics by originating their own assertions which have not been taught (Hickman and Huckstep, 2003). According to Piaget, all humans acquire the ability to reason mathematically sometime between the ages of six and twelve (Siegler, 1998). In traditional introductory physics courses, professors assume that students enter the course already accepting the paradigm that math is a tool to model the physical universe (McDermott, 1999). It has been demonstrated, however, that many students fail to see the connection between equations and the physical situations which are being described, although they may become proficient at solving problems (Osborn, 1990; McDermott, 1993; Redish, Saul, and Steinberg, 1996; De Lozano and Cardenas, 2002; Hobson, 2006). Thus, beginning a physics course by discussing mathematics as a *way of knowing* can help make physics more accessible to non-physics majors, as well as improve understanding of the link between physics and mathematics for physics majors. It may also be important in dispelling fear of mathematics in other populations, including elementary school teachers, to consider the philosophy of mathematics.

The reading assignment that was to have been done for this class period consisted of the first two chapters of *Fear of Physics* by Lawrence Krauss, entitled “Looking where the Light Is” and “The Art of Numbers.” As part of the homework, I had asked the students to reflect on the following statements from the reading:

> (p. 27) “Language, a human invention, is a mirror for the soul. Mathematics, on the other hand, is the language of nature and so provides a mirror for the physical world.”
>
> (p. 48) “…the connections induced by mathematics are completely fundamental to determining our whole picture of reality.”
>
> (p. 52) “If our abstractions of Nature are mathematical, in what sense can we be said to understand the Universe?”

To paraphrase the third quote, *If math is the way to understand physics, in what sense can we claim to understand physics?* Understanding the relationship between mathematics and the physical universe combines a complex set of ontological and epistemological resources (Hammer and Elby, 2003; Elby, 2004). Even among the communities of practicing physicists and mathematicians, as well as physics and mathematics educators, widely differing views on the nature of mathematics are found, including math as a social construction (Ernest, 1992), math as a language (Hickman and Huckstep, 2003), and math as a convenient method for representing physical phenomena (Redish, Saul, and Steinberg, 1996). Among theoretical physicists, mathematics – in particular symmetry principles - may be seen as having a deterministic, rather than a purely descriptive, role in nature. According to 2004 Nobel Laureate in physics David Gross,

> Today we realize that symmetry principles are even more powerful- they dictate the form of the laws of nature. (Gross, 1996).

Mathematicians often describe their own work in terms of scientific discoveries, thus tacitly ascribing to mathematics a kind of a priori existence. For example: Galois is quoted in a letter before his death to have said, *I have made some new discoveries in analysis. The first concerns the theory of equations, the others integral functions* (Livio, 2005, p. 144). Byers (1998) discussed Emmy Noether's *discovery* of the relationship between symmetry and the conservation laws, and David Hilbert's *discovery* of the variational principle which gave the field equations for General Relativity.

Astrophysicist Mario Livio suggested a compromise between the two opposing views of math as a social construction and math as discovery of something beyond humans:

> Our mathematics is the symbolic counterpart of the universe we perceive, and its power has been continuously enhanced by human exploration (Livio, 2002, p. 252).

My purpose, then, in opening these discussions was to encourage the students to interrogate their own views on the relationship between mathematics and the physical universe, rather than to simply start using math without first justifying its usage. I also felt it important for me to understand where they stood on the issue of math and the physical universe, to better adjust my own teaching trajectory. Regardless of the ultimate viewpoint they would choose, I wanted to convey to them over the period of this course, that they should be cognizant of these philosophical issues in mathematics and physics, for it is those questions which have no right answers that are often the ones which shape the character of the discipline.

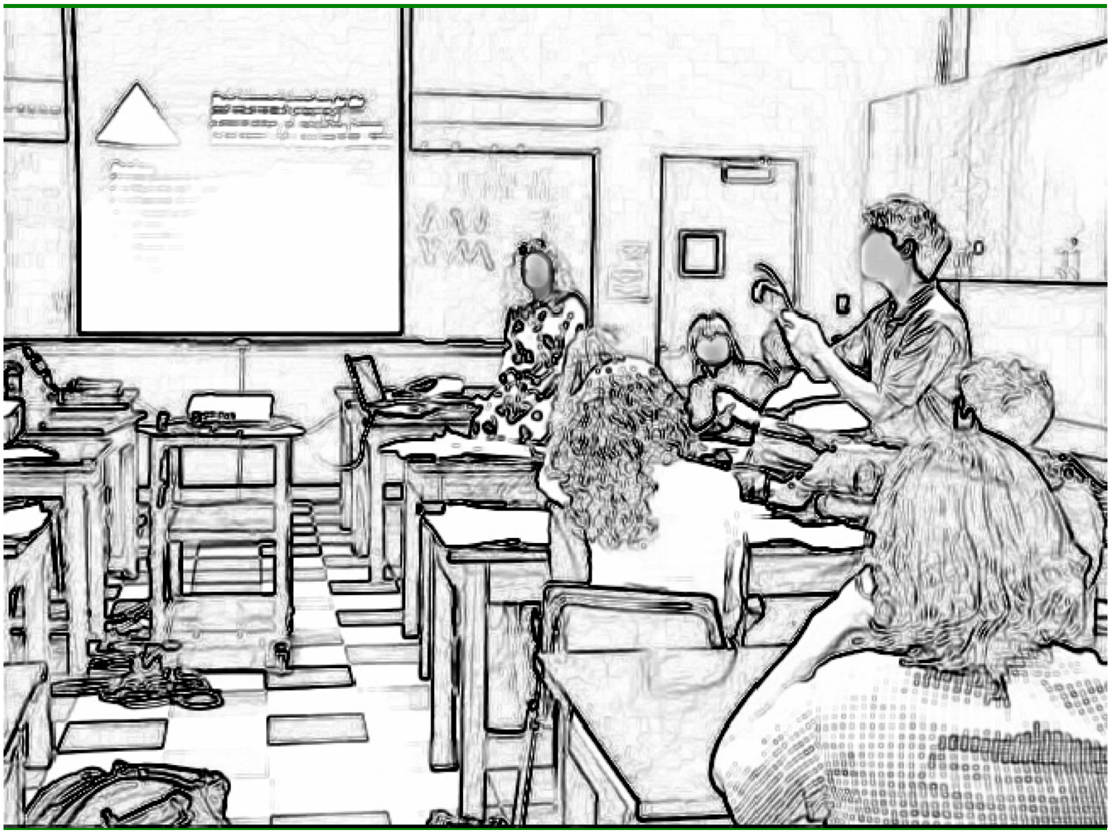

Figure 7.1. Class discussion regarding the nature of mathematics.

7.1.2. Students' Responses to the Question of Math as a Language

Let us turn now to the recorded conversation with the students in CCS-120, in which they responded to my questions, and to each others' opinions, near the beginning of the course.

Jatila:
Is the Universe mathematical?
Is it a logical question, or is it even absurd to ask?
What do you think?
<There is a pause during which nobody says anything.>

Manny:
I'll start. I think that mathematics, in its pure form,
is strictly an invention of humans.

ah, I think that the universe does use mathematics
intrinsically as its clockwork,
if you will, but -
I think that mathematics,
in its own definition,
is something that we have created
to just model the universe.
So, I would say - no,
I wouldn't say the universe would be mathematical.
Ah, I think it's something deeper than that,
that goes past the gestalt of – of - human thought.
Does that make sense? At least…<voice trails off>

Frank:
Yeah, uh, I tend t' agree that
the purest, abstract - mathematics that –
that we've come up with in the past couple of centuries,
is completely removed from the physical universe.
And, though we may find applications of it,
um, that tends to come after the fact that we have mastered it.
Like, ah, we have people making all sorts of
higher dimensional group - theoretical um, manifolds
and all this weird stuff,
and then some decades later,
physicists decided, hey, this is like a really great thing-
works for us to do something with string theory in.
And the mathematicians are like:
okay, if you feel like it, sure, but –
but we think it just IS.
So, I think mathematicians cook some stuff up,
and physicists try to see if it is applicable to the universe, but
I think, um, any applications tend to be
just the result of common sense more than anything else.
Like if you put two apples next to each other,
you could say that what you've done is one plus one is two,
but really I think all you've done

is put two apples next to each other.
And we come up with convenient ways to describe that,
with this really compact, efficient language that we call math.

Jatila:
So, it's an efficient language. Why?
...um somebody else want to jump in on that?
<pause, look around; nobody responds>
Why is it then, that certain numbers just always seem to pop up?
Like, what IS it about this ϕ that just seems to appear everywhere,
and, as we'll look at next time, the speed of light.
Why is – why is that the way it is?

Manny:
I think that what we're saying is that,
it -it really depends on how you define mathematical.
If, by mathematical, you mean the numbers, and formulas,
that we use as humans,
then I'd say NO,
I think it's something even STRONGER than that.
And it just so happens that
the easiest way for humans to understand
what's going on in the universe,
which is something much more powerful than math,
but IS mathematical in nature,
that's the best way that WE can understand it.
I think that we ah, that we …
TRY t' explain it with math,
but it's something MORE than math,
so I think that t' answer your question,
Why does ϕ keep popping up?
Because the universe is like using a META-math of some kind
and we're just ah, we're just approximating it with our -
<word got lost as someone dropped something and a loud noise obliterated his last word on the recording>

Discussion of the responses of first-year physics majors Frank and Manny: Frank and Manny were both physics majors in the College of Creative Studies, had both taken Advanced Placement Physics in high school, and were enrolled in higher math classes. Both were quite accomplished at using Mathematica to model problems, and both were interested in algorithmic music. Here they both expressed the view that mathematics is a human invention, not a discovery, however while Frank felt that mathematics of the past two centuries is completely removed from the physical universe, Manny used a teleological argument that the universe "uses some kind of meta-math," attributing somewhat human-like qualities to the universe. He also expressed what may be considered a weak anthropic principle: it is *because* the universe 'uses' something like math only more powerful, that our invented math can be used to approximate the universe. By the end of the quarter, both had changed their views.

It is interesting to notice the emotional distance Frank assumes between mathematics and physics, when he says that the mathematicians do not appear to care what physicists do with their work. Another statement that I found surprising is Frank's assertion that placing two apples next to each other is distinct from the concept of *one plus one is two*. Counting, addition, and subtraction arose out of the apparently universal human propensity to enumerate objects (Livio, 2002), whether in base ten or any other base, yet studies have shown that many students do not make the conceptual connection between solving mathematical problems using algorithms learned in school, and solving them in familiar contexts with real objects (Carraher, Carraher, and Schleimer, 1985). In his post-course interview, Frank reported a different opinion, which he attributed directly to the discussions he was able to have in this course:

> It [i.e., this course] got me thinking about a lot of really big, deep questions in physics like, Does the math that we use really have any genuine connection to the physical world? Or, why are the equations that we state without proof such as, You can rotate things and it's still the same, why should those things be true? And, like, all the things that we just take for granted when we're working through problems…..ah, really should be thought about a little bit, because they're not easy questions at all. … I think that's really important to look into, it almost becomes a sort of philosophy when you get to that level. So…being able to think about those sort of things is not something I would get out of a typical physics class. So that was…really good.

As the conversation continued, Sam (geophysics major) and art majors Beatrice and Juno expressed different opinions. Sam's appeared to be based on a more concrete approach to math as a way of enumerating, while the art majors expressed the opinion that math is simply one of many ways of experiencing the world.

Sam:
Yeah, like if, well if, if we –
used a different counting system,
and π and all those numbers wouldn't be what they are now,
so that kind of demonstrates
how our picture in math as a language
is a human creation.
Like if we used a hex system instead of decimal,
or, um, yeah, any other different base,
those numbers would have completely different meanings,
but their – what they –

they would have different values,
but what they represented would still be the same.

Jatila:
So they would have different VALUES in our LANGUAGE,
but they would be representing the same thing.
Beatrice…?

Beatrice:
I was gonna say, that they're a symbol, if you will –

Sam:
<jumps in> - yeah -

Beatrice:
-sometimes they're a representation,
so I don't know, I can't say mathematics in particular,
but they're representing …reality of the situation.
I don't personally experience the world, uh,
the universe, as being, in mathematics,
that's not HOW I experience it.
I do experience it, as you suggested, in rhythm,
and in a certain amount of SOUND,
um, which IS inherently - that our education is mathematical -
–that's our SYMBOLISM for that rhythm or that sound.
That's more not how I perceive it, or I'm in tune with it, but
it CAN be looked at as mathematical,
but again, that is our interpret-
our LANGuage, that we use to inTERpret the < word is lost on recording>
Or that's ONE language that we can use.
I think we COULD use DANCE, and we could use RHYTHM as another way to –

Juno:
I'd just like to add something to this if it's ok.
Um, I feel like the way in which every single person
perceives what is going on around them

is always going to be perceived sort of like through their
PERSONAL individual filter.
And maybe for mathematicians that includes more math.
For artists it includes more art.
But, um, I don't know if it's,
I don't know if it's abSURD necessarily,
but it's ONE of the possible FILTERS
to say, Oh, Yeah, I mean, this is aMAzing how this keeps popping up,
but I think what's really kind of the ESSENCE of that
is the AMAZING and not the math.
So that you can say – it- well, to ME it –
I think, um, math ENTAILS amazement.
And I think to many other people, too,
that it's non-MYSTICAL,
It's like, it's CLEAR, you can UNDERSTAND it,
and, so the implication is that if
mathematical NUMBERS keep popping up somewhere,
and you SEE them all over,
is that there IS something we can understand.
But maybe, the numbers are THERE
but we still can't understand it,
hah, so that kind of –
So I don't know if that makes it ABSURD to ask that,
maybe it is, but maybe you can't know, …

Sam, fourth year geophysics major, expresses the view that on the one hand math is a human invention, backing it up with the argument that if we used a different counting system we would have different numeric values for constants such as π, but he qualifies this by saying that although their values would be different, the concepts they represent would be the same. Thus he does acknowledge that there is a connection between math and the physical universe that exists, even if the specific numeric values are socially constructed.

Beatrice, an art student with no prior physics training, and not having had any math in college, expresses still another viewpoint: that although math may represent a reality for some, it is not the way that she experiences the world. She then attributes a person's ability to experience the universe through mathematics to our education being inherently mathematical, which is why "we" use math to interpret the world. However, she asserts that math is only one language with which to interpret the world, dance or rhythm being equally valid. It may be interesting to note that her choice of verbs - experience, interpret, represent - does not include understand. Beatrice maintained the position, almost to the end of the course, that to understand something she had to experience it.

Juno seemed to be initially expressing agreement with Beatrice, that each person has his or her own way of experiencing the world, and math is just one possibility. "I feel like the way in which every single person perceives what is going on around them is always going to be perceived sort of like through their PERSONAL individual filter." She said that for artists, this filter includes art, and for mathematicians, it includes more math, implying that nature is not inherently mathematical, it is simply the individual's preferred mode of perception that allows one to see the universe as mathematical. She seems to have implied a lack of personal choice in this matter, as one's personal filter seems to be tied to one's inherent personality type. She ended by saying that math is amazing because we can understand it, because it is 'clear.'

> I think, um, math ENTAILS amazement.
> And I think to many other people, too,

that it's non-MYSTICAL,
It's like, it's CLEAR, you can UNDERSTAND it,
and, so the implication is that if
mathematical NUMBERS keep popping up somewhere,
and you SEE them all over,
is that there IS something we can understand.

Thus, Juno is perhaps expressing two different viewpoints: one, that math is only one possible filter by which one can perceive the world; and the second that the quality of being amazing arises out of the fact that math is clear and non-mystical, as by math she has indicated numbers, which are concrete, and not the more abstract mathematics of symbolic representations, implicit in the statements of Frank and Manny.

Perhaps there is another subtler layer of interpretation beneath Juno's statements. If math is one possible filter through which people experience the world, is this a trait with which people are born, or which people can acquire? If the former, is she implying that people who are born with 'math filters' are somehow privileged over those born with more subjective filters such as art? At the time this conversation was recorded, I did not yet know of her background, but in her post-course interview she described her experiences with math and physics in high school, which hint at a possible perception of hegemony between those who "do math" and those who "don't." She described the sense of belittlement communicated to her by her math and physics teachers:

> well, no wonder you don't understand this [i.e., math and physics] because you…it's really hard, and don't worry about this …math IS

hard, and physics IS awful, and it's supposed to make you feel miserable" That's kind of the feeling I got from my high school math and physics encounters.

In conclusion, this short segment of conversation recorded in the third class period indicates a range of experiences and expectations regarding math and its relationship to the physical universe, both between physics and arts majors, and among physics majors themselves. These observations support the claim that it is important to question the role of mathematics in the description and determination of our understanding of physical phenomena with students, instead of assuming that the connections exist. Research in physics education, cited earlier, has shown that successful teaching should take into account the variety of initial positions of the students; the results of this study support this claim. This practice may be especially important in changing the negative attitudes towards mathematics that are often perpetuated by the way it is traditionally taught, and which may be unconsciously communicated to younger children by elementary school teachers (Gellert, 2000).

If we take as "expert" any of the opinions expressed by physicists: that math is a language of nature (Krauss), that mathematical principles of symmetry define the structure of the universe (Gross), that mathematics describes the connections between concepts in physics (Redish), or that mathematics is our symbolic counterpart for the universe we perceive (Livio), then one of our educational objectives should presumably be to bring students to an understanding of at least one of these viewpoints, even if we do not expect them to actually *become* experts in one year. The message contained in these data is that we should explore the range of initial positions of our students before we start teaching physics through the portal of mathematics. Otherwise, the understanding that they take away from physics class may be different from what instructors believe they are imparting.

7.2. Can we use Music to Teach Math?

The discussion about math continued for approximately twenty minutes, during which time the class further discussed the ideas of math as a language, the preference for symmetry or asymmetry, the validity of approximations in physics, and the validity of making assumptions from observations. Next, I directed the discussion towards the topic of symmetry, and the introduction of the music homework that was due on this day. I presented my solution, and called for volunteers to present theirs. In this section I discuss the results of the physics students who presented their solutions and, perhaps more significantly, the art students who did not, as relates to the theme of mathematics and ways of perceiving.

Bamberger and diSessa (2003) found that mathematical concepts of ratios, proportions, and fractions were noted by college music students in discussing their learning of concepts in introductory music courses. Based on this evidence, they then used musical concepts to teach mathematics to middle school students. In this homework assignment, I was hoping that students could build on concepts of rhythm in music to make connections with ideas of symmetry and symmetry operations in mathematics.

The music homework that was due in this class involved two parts: part one involved completing a simple table relating music notation to inverse powers of two, and finding a way to represent the division by two's graphically. In the second part I asked the students to create a rhythmic pattern and represent it graphically. I was planning to ask students to get into mixed-major groups and use each other's patterns to investigate symmetry operations of translation, reflection, and glide symmetry. What transpired was not what I had anticipated: all of the physics students completed the assignment, and were eager to share their creations with the class. Some of them took the assignment in a completely different direction than I had intended, creating complex models for creating sound using Mathematica. They seemed to delight in sharing their creations with the rest of the class, even commenting in their exit cards how much they enjoyed sharing their music homework.

The situation was quite different for the arts majors. Two of the four arts majors claimed to have completed the assignment, but did not volunteer to share their creations with the class; the other two arrived empty handed. Thus this sharing activity quickly devolved into a situation of those who had and those who had not completed the assignment. Unfortunately, this boundary fell precisely along major lines, dividing the physics majors (haves) from the non-physics majors (have-nots).

7.2.1. What, No Music Homework?

When I called for volunteers to put their rhythms on the board, the majority of the physics students seemed to naturally fall into the behavior which is familiar in physics classes, of staking out a portion of blackboard and putting up one's homework solution. Those who were awaiting a turn at the blackboard talked among themselves, and on the recording the general sounds of writing, shuffling, discussing, and laughing can be heard. During this activity, the arts majors remained on the periphery, not participating in the general group process. One of the arts majors sat quietly with two of the physics majors who were not at that moment putting their solutions on the board, while the other three arts majors sat together on the other side of the room, at the back. While the physics students were putting their rhythms on the board, I went over to talk with this group who appeared to be “left out” of the general camaraderie in which the rest of the class was participating, and the microphone clipped to my clothing recorded the conversation. The groupings are shown in Figure 7.2.

Figure 7.2. Putting music homework on the board.

Beatrice:
I think I did mine right, I don’t know
I just did it in SHAPES.

Jatila:
That’s fine, that’s fine
It’s just an idea…

Juno:
I have to admit I was really confused by these directions,
because I’ve had years and years of piano practice,
and so like, PAUSES…
is how I usually envision .. stuff being separated.
And rather than just GROUP them … here…

and so I tried to think, like, ok,
if I group two quarters, then it's one half
and that's how I … like, envision this. and that –

Jatila:
I envision it in, in terms of measures.
So, without having a staff or anything,
if you just did it in terms of measures –

Juno:
Measures, you mean, like, the…

Jatila:
Like one measure of music is how many BEATS per measure
Like, if I do four-four, that's four quarter notes per measure

Juno:
Right…that's what I did here.

Jatila:
Or, 9/8, or 8/8, or 15/16, or something.

Beatrice:
I didn't –
 I can't –
I don't have an ear for music at all,
I'm just -
I could never compose it,
but I have to MOVE to be able to do it -

Juno:
I saw her, she was dancing all over the place..
<both: laugh >

Beatrice:
I can't, just like, DO it,
it doesn't work for me,

or even like, t' break down my rhythm,
I couldn't do it.

I was quite surprised by these responses. Why was my music assignment completely comprehensible to the physics students, but apparently completely incomprehensible to the arts students? Feeling rather at a loss for words with such an unexpected confrontation, I asked if this assignment was a "totally weird thing to be asked to do."

Jatila:
Was it a totally weird thing to be asked to do?

Beatrice:
No, no, it makes complete sense –

Jatila:
- good –   - good, ok –

Beatrice:
to me, it's just -
Like that's <can't make out word> for me to say,
but for me, I don't interpret… the world through mathematics,
but I can interpret it through the way I FEEL,
and the way that I MOVE,
and that's the way that I can SEE it.
And it CAN be broken down mathematically,
but I don't look at it in mathematical terms.

In this statement Beatrice acknowledged that she has understood my intention to link music and mathematics, but implied that she disagreed with my premise, which she correctly intuited to be that music can help one understand mathematics.

Although I had not stated this assumed connection overtly in my assignment, this was my underlying intention, which she correctly perceived. By telling me that my assignment "did not work" for her, she has refuted my premise that music – at least the way I had approached it – could be used to help the mathematically uninclined to learn mathematics.

Meanwhile, the physics students had finished putting their homework on the board, and can be heard on the recording talking loudly. Not wanting to give up, I asked Beatrice one more question:

Jatila:
But, do you think that,
if people have to learn math and physics,
that these are ways that could make it
less intimidating, and more interesting, and more real –
Beatrice:
Yah, If I can't – well, I wrote that - in –
when you asked how do we KNOW that we understand.
I mean, for me to break it down, it has to -
I have to feel it, like a physical thing for me to do,
then I'm like, Okay, that makes sense now,
and then by communicating that to someone ELSE,
I have - it becomes fluid
and then I really understand –

Juno:
have a MASTERY of it.
But also, like the question you asked on the homework –
How do we understand things.
I'm kind of saying the same thing, actually,
Because when I – for me to understand something,
I have to - MOVE some part of my body,
for example, If I'm trying to understand some
… like… some progression in history,

or some, like abstract concept for art history,
I always WRITE it, but I never re-read what I write.
I just - WRITING it helps - gets it in -

I did not probe any further at that time, as it was apparent that the physics majors, having finished putting their solutions on the board, were ready to continue with the class. After some shuffling and settling down, we began with the presentations.

Jatila:
Ok, so, ah, SS, you wanna show us?

SS:
Sure. So I just did 5 eighth notes per measure,
and I did, um,
So grouped them so that you would clap on the first note
of each group, so… it would sound like
<and she claps her rhythm>
And, my initial representation is a bunch of triangles,
whose height corresponds to the length of time between claps.

Jatila:
So…<clapping her rhythm and counting>
One-two One-two-three – One-two One-two One
One-two One-two-three – One-two One-two One
Interesting! <continues clapping without counting>

Al and Charlie presented their interpretations of my assignment next. Beatrice, who had just made very clear to me her stance of not seeing the world through mathematics, can now be heard on the recording participating in the discussions.

Al:
So we did a couple a' things, ah, the first one's that,
where…we used a Mathematica to -

Charlie:
<jumps in> There's a program Mathematica that um,
that we were guessing we could do this in,
And you can generate a tone, by putting a sine wave in, so
If you do, if you do the sine of 220 Hertz, times 2π,
that gives you, like a C, or something like that..
<general noise on the tape>
But, we could put in another function at once,
so what we did is, we took 110 Hertz,
and we applied it every two seconds,
for two seconds, so there's one beat,
And then we applied the 220 Hertz tone, which is a little higher,
And we applied it every second, instead of every two seconds.
And then we have, I didn't bother to draw it in,
but here's a concert C 440 Hertz,
two times the second harmonic,
and then just for FUN, we put the 880 Hertz
and instead of using SINE, we used um…

Manny:
You used a triangle?

Charlie:
Sine of 880 Hertz
<sound of writing on the chalk board>
times…ah, ok, there's a square wave function-

Beatrice:
A square wave function? Can you…

Charlie:
a square wave function times e^t.

<There is suddenly a surge of overlapping voices,
until someone says loudly, “shhh!”>

Charlie:
The way that I presumed beats is with the square wave function
So it’s – it’s either on or off.
So here it’s ON for a second, and here it’s OFF for a second
So now instead of turning it on and off every second,
I turn it on and off every e^t seconds,
and e^t goes like this <drawing it on the board>
It goes exponentially higher,
So that means that the rhythm will go faster and faster and faster.
And it uses this pattern <can’t make out the last word>

Charlie made a sketch of the function e^t as he was talking, which I thought at the time was an excellent explanation, however in retrospect I wonder if to the arts majors he may have been using terms that were so strange that they did not even know the right questions to ask at that point. Beatrice asked for an explanation of a square wave, to which Charlie did not respond. His sketches are shown in Figure 7.3.

Then there is some discussion about what frequency constitutes a concert C, but this is hastily qualified as being merely a point of clarification, and in no way meant to diminish the value of their work.

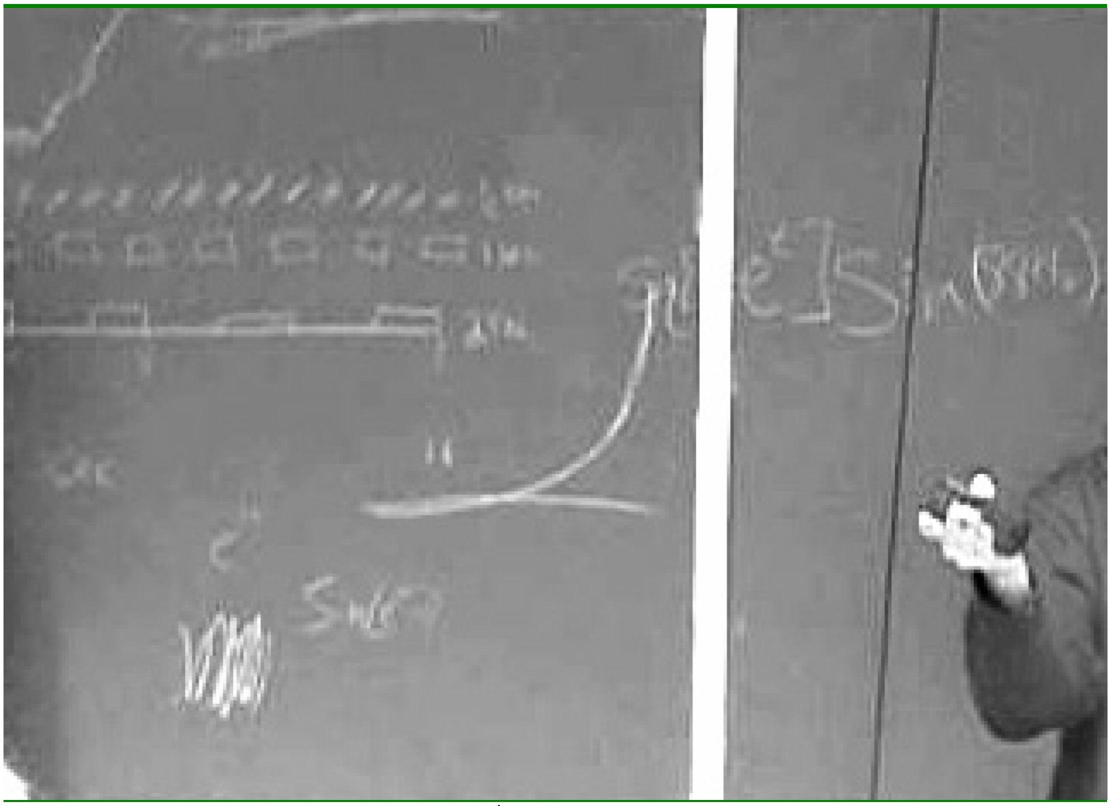

Figure 7.3. Charlie's e^t sketch of his music homework.

Charlie:
Does anyone want to hear it?
<everyone says yes!>

Charlie:
I hope you can hear my phone.
Beatrice:
We can all get close to it.

Charlie plays his composition for the class, holding up his cell phone (Figure 7.4), which has a very interesting electronic sound. No one takes Beatrice' suggestion to move close to his cell phone, in fact, her comment seems again to go unnoticed. Charlie holds his cell phone out towards the class, and the sound is perfectly audible;

the class remains seated. On the recording, somebody says, *That's great*, and there is general laughter.

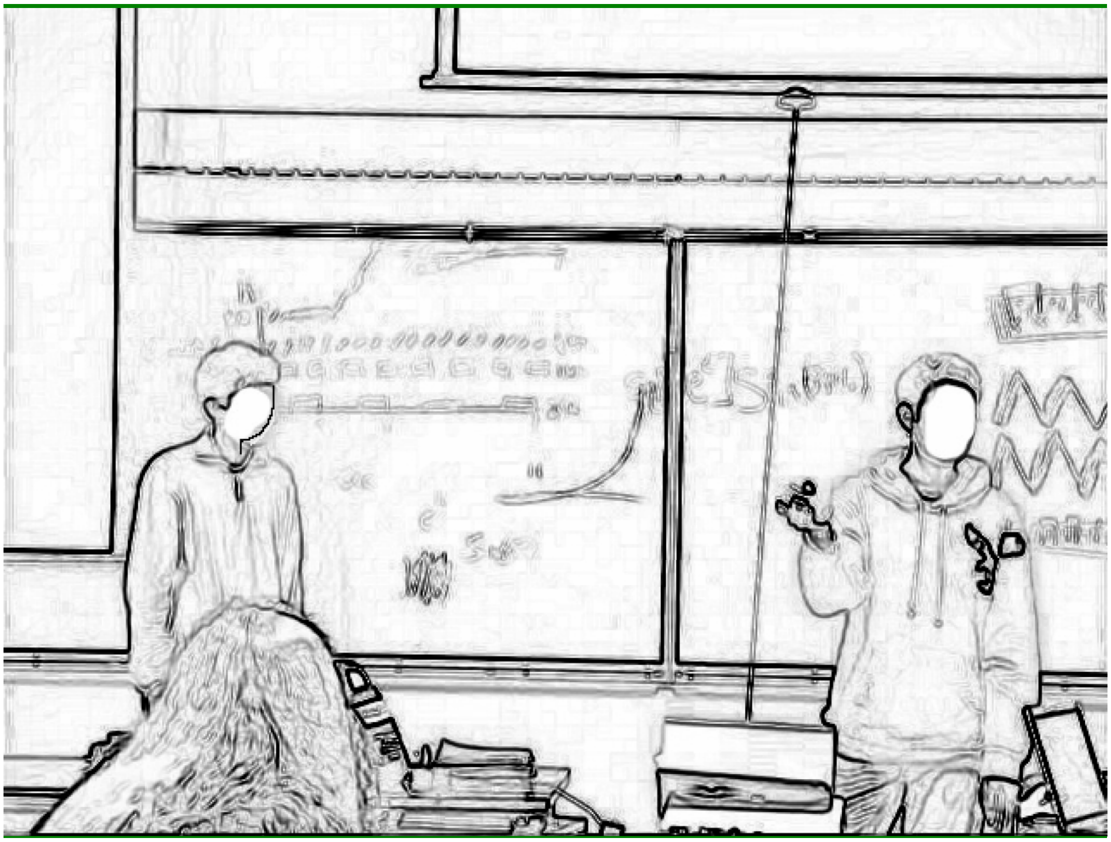

Figure 7.4. Charlie plays his cell phone for the class.

Al presented his composition next.

Al:
We did another thing, too, um
I kind of picked up on, ah,
I think Pythagoras said that,
the planets have sound to them,
And ah

Beatrice:
I LIKE the planets…

Al:
Planets have like, their own sound, each of them,
and, the way I did it was, …
I found numbers for – you know,
the time it takes for a planet to go around
ah, the Sun,
and I used that frequency to like,
the thing is, like,
that the Earth goes around in 365 days, and, ah,
and like, Uranus goes around, like…
ten times that much, or whatever,
So I had to scale it, and uh
I basically played it all as one single sound,
so all the planets together,
This might be what their group wave might sound like,
if - to a, to a human-like ear.

<Al plays this sound, which sounds like a buzzing of many electronic saws>

After Al and Charlie finished, and before we continued with the rest of the presentations, there are approximately twenty seconds on the recording in which the camera was on the group of Al, Charlie, Beatrice, Juno, and SS. The audio was not picked up by the microphone (which was on me), but on the video it appears as though Al and Charlie are explaining their work to Beatrice, Juno, and SS (Figure 7.5). Juno is seen to make a circular motion as if indicating a planetary orbit, and Al is seen to talk animatedly, although we cannot hear what is being said. Then my voice is heard off camera, asking how they scaled the frequencies of the planets so that they were all audible, to which Al replied that he used logarithmic scaling. Some discussion continues about the range of human hearing and logarithmic scaling between myself and Al, during which time Beatrice and Juno appear to be talking, although the microphone did not pick them up, nor did Al or Charlie appear to take notice.

Then the rest of the presentations followed, with Frank's presentation of his complicated Fibonacci meter, Sam's presentation of his syncopated salsa rhythm, and Manny's presentation on his computer of his rhythm, which he likened to a fractal which he made by removing a portion of each beat. Everyone followed my suggestion to gather around Manny's laptop (Figure 7.6). After the last presentation, which was Manny's, there was some open discussion between Sam, Manny, Al, and Charlie about how one might go about creating fractal music. Sam asked whether, if one continually reduced the duration of a note on a computer, it would increase the frequency of the note so that it would eventually exceed the human audible range. I mostly listened, and eventually recaptured the lead with the comment that in the Allosphere at UCSB they are actually experimenting with creating chaotic and fractal music, and that we would have a talk by the director of that organization. I then returned to my intended progression, which was to use the rhythms to lead into a discussion of discrete symmetry operations.

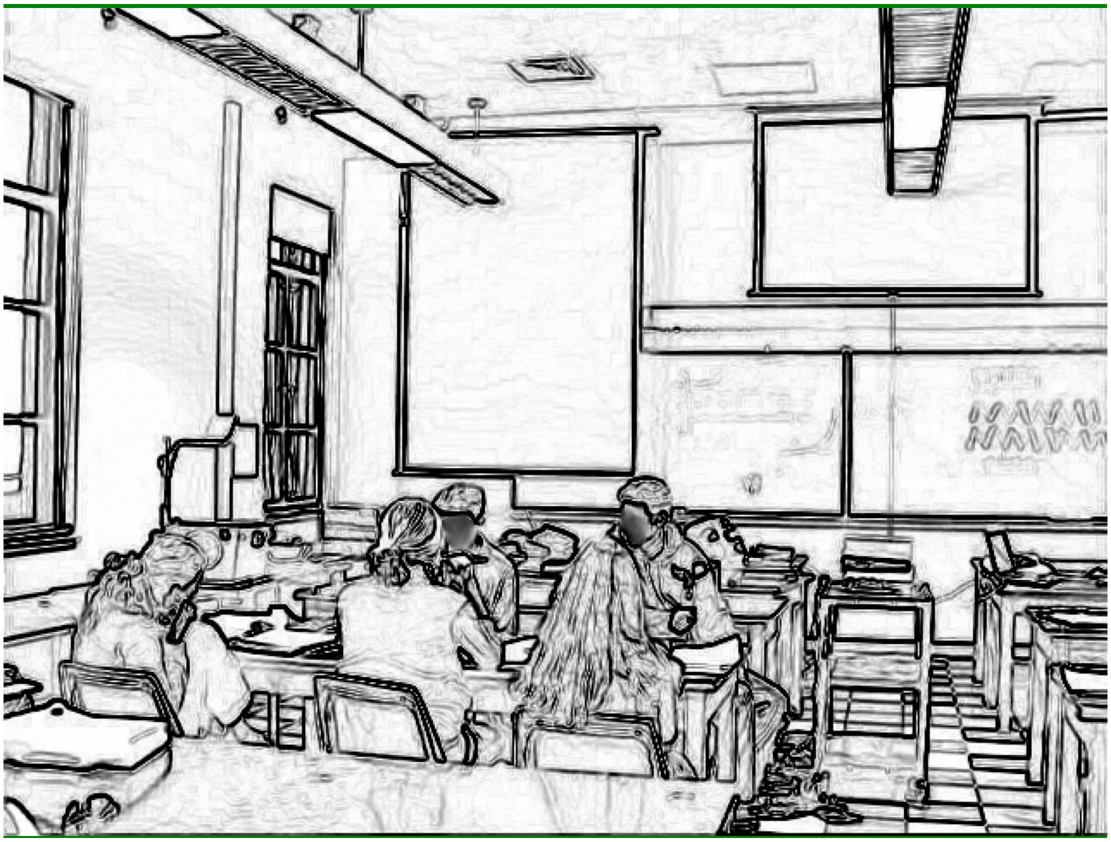

Figure 7.5. Beatrice gets an explanation from Al and Charlie


Figure 7.6. The class gathers around Manny's laptop

7.2.2. What "No Music Homework" Might Really Mean

During the class I had not noticed the comments made by Beatrice during the presentations by Charlie and Al. The class was rather noisy and exuberant, and I had migrated to a position at one of the desks on the right side of the room in front, facing the presenters, and Beatrice was sitting on the left side, towards the back, in the position shown in Figure 7.3. Her comments must have been sufficiently above the rest of the background noise that, although I did not notice at the time, the microphone picked up her voice above the others, so that I was able to hear her on the audio. Perhaps Al and Charlie did not hear her either when she asked what a square wave was, or offered that we could all move closer to Charlie's cell phone, and Al was not seen on the video to react to her comment that she liked the planets. Perhaps in this inaudible twenty seconds of video, she was getting the explanations to her questions that she had not gotten during their presentations, and what she really desired was to understand math, music, and the connections between them. Although earlier it may have seemed as though she was resistant to my trying to connect music and mathematics, it seemed that she was nevertheless quite interested in participating in the class activity which linked the two. Thus her statement to me that this assignment "did not work" for her was possibly more a condemnation of my insensitivity, rather than an excuse for her not having completed the assignment.

In what sense can this claim be credible? In an investigation of minority children's miscommunication with teachers who are usually members of the dominant majority social class, McDermott and Gospodinoff (1979) proposed that what may seem to be "misbehavior" may actually make sense in a given classroom situation. They proposed that children often manage to negotiate attention from their teacher by behaving in ways that may seem to indicate a lack of understanding of socially acceptable behavior, when in fact both students and teacher quite possibly do understand each other's behavior, manipulating it to their mutual advantages.

In a college physics class, it is unheard of for a student to tell a professor, "This assignment doesn't work for me." Students might not complete all the assignments in a course, and might still get good grades in the class, however informing a professor that an assignment did not work for them would be considered inappropriate behavior in most college physics classes. In this situation, however, rather than being construed as inappropriate, Beatrice's statement may be understood as a means of calling my attention to another matter: that the traditional expectations for teaching and learning mathematics need to be revised if "we" (the dominant cultural group of physics teachers) are to be able to reach students like her – members of the minority group of artists.

In this sense, Beatrice's behavior worked perfectly. I did not condemn her statement, but instead asked a question which showed concern for her position ("Was this a totally weird thing to be asked to do?"). More importantly, perhaps, her interactions with the dominant group of students, the physics majors, served her purpose of getting their attention and participating in their interactions. Thus, not-doing her music homework, which at first seemed to prevent her from participating in the general group activity, in the end enabled her to negotiate a way into acceptance by both the dominant "cultural" group of students (the top group of physics students) as well as gain attention from the instructor.

Taken in context with Juno's description of how math and physics were communicated to her ("don't worry about this …math IS hard, and physics IS awful, and it's supposed to make you feel miserable*"),* an even stronger parallel with McDermott and Gospodinoff's analysis of classroom reading behavior may be apparent. They assert that students who enter school deficient in the language and reading skills of the dominant cultural group tend to get caught in almost a self-fulfilling prophecy in school, which, over time, causes them to fall increasingly far behind. Eventually, teachers believe "they" can't read, and these students believe this about themselves. The situation with math that was evident in the early interactions in CCS-120 may be reminiscent of the literacy situation in elementary schools. Students who arrive at university behind in math may tend to have this image of their math deficiency reinforced. Thus, if one of the goals of the American education system is to improve mathematics and science literacy, an interdisciplinary environment such as CCS-120, in which physics and arts students can learn from each other, may have potential to reduce the discrepancy in the areas of math and science. The following statement by one of the art majors on the end-of-course evaluations supports this suggestion:

> I found this course to be wonderfully exciting. The instructor and the students were wonderful and passionate, which made the class a pleasure. I had to overcome and grapple with a lot of struggles with math and understanding the language of science. I wish that this class would continue and I could continue to study the math and science in such an integrated way.

7.3. Symmetry Groups, Group Interactions, and a Final Challenge

In the next portion of this class period, I presented a short lecture on discrete symmetry operations, and demonstrated the first group activity, which was to derive the table of unitary operations for the symmetry group of the equilateral triangle. I asked students to position themselves into mixed-major groups, to sit with people with whom they have not worked before. The groupings are shown in Figure 7.2.5, a composite image of the classroom. For this group activity, Beatrice positioned herself in the top physics group, with Al and Charlie, the two fourth-year physics majors (left side of the room in Figure 7.7).

Figure 7.7. Mixed major collaborative groups

The distribution of students into mixed major groups was as follows:

Beatrice + Al + Charlie = 1 art + 2 physics;

Juno + SS + Sam = 1 art + 1 physics + 1 geophysics;

MKS + Frank + Manny = 1 art + 2 physics;

AT + Victor Eremita = 1 art + 1 physics.

It is difficult to discern any of the group conversations on the recording, as I walked around the room, however one small piece of interaction between Beatrice, Al, and Charlie is audible, towards the end of this activity, which supports my analysis given at the end of Section 7.2.

The other groups seem to be finished, and on the recording, appear to be talking about other topics. I had become distracted by AT, who had finished the activity and was asking me if I would send some information to his high school A.P. Physics teacher. Sensing that it was now appropriate to gather the class together again, I approached the table with Beatrice, Al, and Charlie to see if they were ready to move onto the next phase.

Al:
So, um.. d’ you know what a set is?

Beatrice:
No.

Al:
So, a set is just….elements, so …

Jatila:
<approaching the group>
Can we go on?

Beatrice:
No.

Jatila:
Not yet?

Beatrice:
Not yet.

Jatila:
Ok.

The rest of the audio is impossible to decipher, as there are too many voices talking at once, but clearly Beatrice is enjoying the learning experience. From her initial stance with me of not-doing her homework and saying she does not see the world mathematically, she is now getting tutored by some of the most mathematically advanced students in the class. A short time later, I was successful in regrouping the class, and explaining the next activity: to create a table of binary operations of reflections and rotations of the group “equilateral triangle,” and demonstrate that the group is closed under all possible such operations. In the second part of this activity Al, Charlie, and Beatrice were joined by SS and Juno, who sat around one table in a group of five. On the other side of the room, Sam was working on his own; Manny and Frank were still working with MKS, and AT and Victor Eremita were still working together. I am seen on the recording to walk around the room, observing and helping when asked.

There is overlapping talk on the recording, as it appears that Charlie is helping Juno and SS, while Al is helping Beatrice. On the recording it is difficult to decipher which turns at talk belong to which conversation, as all the groups are busy working on this project.

Al:
So, you're rotating it "one twenty"
and then you're doing it two more times –

Beatrice: says or does something in response, which must have been correct, because Al says:

Al:
Exactly, so then you just get *I* [the identity element].

Then Beatrice asked me a question which I could not answer: "Why are we even doing this?" It seems that the others in the group did not notice, as no one else steps in to either question me or answer her.

Beatrice:
I was asking them why we're even bothering ↑
I don't even understand how one comes up with
a preoccupation of certain things,
such as, exploring symmetry.

Jatila:
You don’t understand why we’re doing that?
<floored, at a loss for words>
Because –

Beatrice:
Yeah, like what motivates that explanation?

Jatila:
To learn physics,
as a way of learning physics,
as a way of learning about the physical universe.
Because it’s more fundamental then simply studying –

Beatrice:
But what’s the, what’s the relevance t’ symmetry?

Jatila:
What’s the relevance of what to symmetry,
of physics to symmetry?

Beatrice:
Yeah.

Jatila:
Symmetry IS the language in which we can describe
a much wider range of phenomena.
For example, if you’re –
the way physics is normally taught,
you start with Newtonian mechanics,
‘cause – Galileo came first,
and then came Newton, and so we do that,
and then we kinda do a progression,
and we do all these disjoint topics,
and students end up coming out without any sort of –

Beatrice:

<overlapping>- Well, I haven't learned any physics at all,
so this is my first physics class EVER

Jatila:
Ever, so then

Beatrice:
so then t' say, Hey, let's study symmetry,
what would we-
what's the relationship to physics?

Jatila:
<overlaps>- Ok, if you walked into a regular physics class,
they would start out telling you,
Ok, you have to know powers of ten,
and this is a vector --

I tried to explain why we were starting with symmetry by comparing this class to a regular physics class, but she never allowed me to finish my explanation, telling me that my comparing this class with a regular physics class makes no sense to her, because she has never even seen a regular physics class. I cannot justify my approach by comparing it to something she does not know, and she has not yet accepted my first explanation that symmetry is the most fundamental concept underlying physics.

Beatrice:
<interrupts> - But I would ask them,
Why do I need to know that?
It doesn't make any sense to me.
Jatila:
And they'd say, why?
Because you have to know math to study physics.

Beatrice:
But I would ask,
Why is *that* math important t' learning physics.

Jatila:
Because it's a way that we can describe and interact with
the physical world.
Make predictions, make models, and…
describe what's going on.

Beatrice:
…I don't think I'm explaining what I'm meaning…
I'll keep working on the language.

Jatila:
Ok.

> [I don't want her to walk away frustrated, so I keep on trying even after she's given up on me.]

'Cause, basically, if you wanna do physics,   y' have t' do math -

Beatrice:
<jumps in> Right –

Jatila:
If you wanna really -

Beatrice:
-Right, but how do you know
which math is important –
is the correct math to be using –

Jatila:
ah, you as the student,
you have to trust the instructor,
who has more experience, how do you know?

Beatrice:
<overlaps> - but there must be a REASON,
there must be a reason that that math is chosen –

Jatila:
Ok, the REASON that I'm choosing symmetry
is it's the underlying conception that links all the topics in physics.
And, the way physics is normally taught,
they just take …
um…it's like, if you wanted t' teach art –

Beatrice:
<interrupts again> -You're stating, what you're telling me,
is that all of our world is based in symmetry.

Jatila:
If you – Yes.

Beatrice:
-Ok.

Jatila:
I'm telling you that-

Beatrice:
<overlaps> - Then that makes sense.

Jatila:
If you want to understand,
if you want to be able to …do physics,
this is what you need t' understand.
Beatrice:
But physics, with the idea that
everything is on the basis of symmetries.
So then, by understanding the simplest symmetry,
I'll be able t' develop my understanding
to more complex symmetry.

Jatila:
That is my premise, yes.
And that, compared to, the way it's normally taught,
which is simply a set of equations
that you manipulate to get an answer in 'this' context,
and we don't know how it transfers to another context,
that if you start with the basic math that connects all of them,
then you can use it in every topic.

Beatrice:
Yeah, I understand THAT,
but I didn't understand the importance of symmetry,
and I didn't understand
that physics was on the basis of symmetry.

This conversation between Beatrice and myself returns our attention to the initial premise of this chapter, as pointed out by Redish (1996), McDermott (1993, 2001) among others, that physics instructors are wrong to assume that students automatically accept the connection between mathematics and physics, when students may not understand this connection at all. In looking back at this conversation, I can see how we make the assumption that our connection of the physical world to math is logical, when for someone such as Beatrice, who has absolutely no connection with math, there is no reason why one mathematical technique should be preferred over any other.

Obviously, I did not understand her question. I had developed my class as an alternative to the traditional class, with the expected audience of beginning physics students, so I interpreted her question in the context of that assumption. Clearly, I was unprepared for her very legitimate challenge. My answer, which I kept trying to give her, was that I wanted to test this approach and compare it to the traditional approach, which was ultimately the reason why we were studying symmetry, but what she was really asking required an independent answer, grounded in Nature, not in opposition to traditional physics education, with which she had no experience.

In retrospect, I think I was so startled by the bold abruptness of her question, that I did not know how to begin to answer it. What I thought I had made clear in the first two lectures had apparently not been clear to Beatrice – and perhaps to the other art students, though she was the only one at that time who voiced the question.

Shirley Brice Heath's (1982) classic comparison of children in three different linguistic communities comes to mind. Children who grow up in communities where making sense out of books is a natural way of taking meaning from their environment, enter school with an orientation that is pre-aligned with the culture of school. Children who enter first grade without having had the prior linguistic orientation to books have difficulty interacting with the "mainstream" educational environment.

The orientation of the physics community is such that meaning is both taken from the physical universe, and given to the physical universe, via the language of mathematics. Thus, students who approach physics, regardless of their knowledge of mathematics content, are expected to orient to the idea of math a basis of communication about Nature. This math orientation feels so natural, that it is difficult to see how one could possibly take meaning out of the physical universe without the help of mathematics. It is *assumed* that by developing math skills, students will develop the ability to apply the skills in related contexts, however this presupposes that the students are already oriented towards math as a language. As was discussed in the first section of this chapter, even physics majors may not understand the connections between mathematics and the physical world, even if they are proficient at solving problems.

7.4. Reflecting, Assessing, and Looking Ahead

Ultimately, this interdisciplinary, aesthetic, symmetry-based, physics and fine arts course was successful, according to Maxine Greene's definition of aesthetic education which I quoted in the introduction: *new connections were made in experience, new patterns were formed, new vistas were opened*. In the final chapter I will summarize the results of this course, relate them again to the previously extant programs and research on interdisciplinary and aesthetic education, and make recommendations for implementing this curriculum in other venues.

Chapter 8. Looking Ahead towards Interdisciplinary Aesthetic Physics Education for All

> "The dazzling beauty of Nature revealed by our developing understanding should be presented with enthusiasm. The sense of wonder at the simplicity of the laws of Nature and the mystery of how mathematics seems to be embedded in these laws are important to convey. Hence, the science teacher can find common ground with teachers of art, music, and literature."
>
> -- Leon Lederman, in Science Education for the 21st Century (2003)

8.1. A Model of Interdisciplinary Aesthetic Physics Education

In conclusion, although the concept of interdisciplinary education which combines arts with math or engineering at the undergraduate level is not new, and interactive classroom techniques in introductory college physics were pioneered by Eric Mazur at Harvard beginning in the early 1990's (Mazur, 1997), this model for introductory college physics represents a new design concept in undergraduate physics education by combining interdisciplinary and interactive strategies with a new aesthetic physics curriculum.

I visualize this curriculum as a thick braid, consisting of three bundles of colored fibers: Symmetry, Interdisciplinary Strategies, and Aesthetic Ideology. Each of these bundles consists of a rich variety of colored strands from which an instructor can choose, so that the curriculum can be adapted to suit the needs of teacher and students. To be *aesthetic physics education*, however, each of the main bundles must be present, or the braid will unravel.

First of all, the physics content starts with symmetry and contemporary physics, or what I call the "*Noether before Newton*" approach, instead of concentrating heavily on the Newtonian world view. This approach is important because it starts from where students are *today*, and then looks back at Newtonian mechanics as a limiting case of our current understanding of spacetime, which is applicable to our viewpoint on Earth. Moreover, if an instructor starts by first discussing math *as a way of knowing about the world*, instead of *assuming* that students understand math, and immediately beginning by solving problems, access to physics may be opened up for a large population of students who often feel intimidated by physics. In addition, by foregrounding Emmy Noether, the woman whose mathematical insights provided the basis for the confirmation of Einstein's General Relativity Theory, the potential is there to begin to change the narrative of physics, which is almost exclusively androcentric. Changing the community narrative could provide one step towards changing the community identity (van der Veen, 2006a&b).

Second, I use a variety of interdisciplinary strategies, including assignments that incorporate physics literature, problem solving, drawing, and composing. By utilizing different ways of engaging with the physics content that include art, music, and literature, students have more opportunities to apprehend the *concepts* of physics than in traditional introductory courses which rely exclusively on problem solving as a way of understanding physics.

Third, the curriculum is underlain by the ideology of aesthetics. I use a liberal interpretation of Maxine Greene's definition of aesthetic education, grounded in the educational philosophy of Johann Heinrich Pestalozzi (1746-1827). Art and mathematics are both non-verbal ways of knowing and making meaning out of the physical universe. Einstein himself was trained in the method developed by Pestalozzi called the *Anschauung* (Miller, 1989), in which the visualization of a concept is integrally bound up with the understanding of the concept. Thus, art can help in visualizing concepts in physics which are also accessed mathematically.

The implementation of these design features is best accomplished in an interactive classroom atmosphere based on Eric Mazur's (1997) Peer Instruction model. The combination of these design features: *Starting with symmetry* and relativity, using *interdisciplinary* strategies, within the *ideology of aesthetic education*, conducted in an *interactive classroom* based on the Peer Instruction model, represents a new design concept in the teaching and learning of physics.

In Winter Quarter, 2007, I taught the first portion of what I envision as a full-year sequence, (shown in Figure 8.1), to a group of eleven students – seven physics majors and four art majors – in the College of Creative Studies at the University of California, Santa Barbara. The combination of starting with symmetry and relativity, using interdisciplinary strategies and Peer Instruction, underlain by the ideology of aesthetic education, was quite successful with this group of students. The enthusiastic response of both the art and physics students to this course was quite encouraging. Although CCS students are pre-selected for their talents in their chosen fields of study, and are thus not typical of college students in general, I believe that this model for introductory physics could be beneficial to a variety of student populations. For liberal arts majors, this model has the potential to offer access to physics for students who might otherwise avoid the subject. This model is ideally suited to the training of pre-service teachers, who typically have a fear of physics, due to the math. For students intending to major in physics, this approach of starting with symmetry has the potential to offer a deeper understanding of physics than the traditional introductory curriculum, especially if taken concurrently with, or prior to, a more traditional introductory course.

As discussed in Chapter Five, the physics majors in my class expressed that they appreciated learning about symmetry, as it clarified concepts such as conservation of energy and momentum, that had been given to them as rules in their regular physics class. Even physics majors may not have an opportunity to address symmetry and Noether's Theorems until graduate school, if at all; thus by introducing at least conceptual symmetry at the introductory level, physics majors may have access to the deeper layers of physics than they otherwise would.

Two of the art students expressed a desire to learn more physics and math *in this kind of interdisciplinary environment*, and all the art majors expressed an appreciation for physics which they never felt before. Juno reported that physics had previously been an unpleasant subject for her in her secondary school experience, growing up in Germany, but after her experience in this class she intended to "*stick around the physics department for ever.*" Victor Eremita expressed that now when he goes to the bookstore, he is excited about exploring the range of topics in the physics section, which he never did before. This positive change in attitude towards physics on the part of the art students who took the class suggests that indeed it is possible, with a course such as this, to change negative opinions about math and physics into positive ones. The positive results with these students suggest that it may be possible to achieve similar results with others.

The final projects, which were discussed in Chapter Six, indicated that both physics and art majors gained a greater understanding of each others' subject through the experience of this course, and through the creation of an original work of physics art. Three of the physics students (Frank, SS, and Manny) were already accomplished musicians before they enrolled in this course, however they demonstrated an understanding of the principles of symmetry in their music and in their written work which they did not have prior to this course. In their interviews they expressed that they also gained a deeper understanding of the connections between physics, and symmetry which they carried into their regular physics classes. Two of the physics students (Sam and AT) were already accomplished artists; they, too, demonstrated a deeper understanding of the principles of symmetry than they had before. Sam, who was exhibiting some of his paintings in a local gallery in the spring and summer of 2007, applied the knowledge of symmetry and groups that he gained as a result of this course to an analysis of his paintings, which he demonstrated to the class in his final presentation. Al and Charlie, fourth year physics students, demonstrated a new appreciation for art in their final projects. Basically, everybody gained in some personal and meaningful way from this course, and I believe this model could be exported to other campuses with equal success, with the participation of interested and motivated faculty.

The results of the Maryland Physics Expectation Survey (MPEX) which I discussed in Chapter Four, indicated that this course caused an improvement in the students' attitudes towards the process of doing physics, as well as an increase in their tendency to form opinions about physics, as compared with students in traditional introductory courses (Redish, Saul, and Steinberg, 1996).

One of the most encouraging results of this course was the growth in understanding of math as a way of knowing on the part of the art students, and art as an intellectual and rigorous subject on the part of those physics students who entered the course thinking that art was somehow “easy.”

I believe that the positive outcomes with the students who took this course can be replicated with a wider student population that includes physics majors, liberal arts majors, and future teachers. Practicing high school physics teachers could incorporate the interdisciplinary strategies and aesthetic ideology, even within the confines of state-controlled high school physics courses. There is even a symmetry-based text written at the level of high school physics by Leon Lederman and Christopher Hill, *Symmetry and the Beautiful Universe* (Lederman and Hill, 2003), for teachers who wish to incorporate symmetry into their high school classes.

8.1.1. Ten Strategies for Success

Ten strategies provided the framework around which to build this unique experience of aesthetic physics education: 1. Start by orienting to math as a language of nature; 2. Start with the modern perspective of Noether and Einstein before teaching the classical perspective of Newton; 3. Read literary works by theoretical physicists instead of a textbook; 4. Utilize a variety of visual, numeric, and descriptive types of assignments, instead of relying only on problem sets; 5. Relegate problem solving activities to class time for the first half of the course, until the art students feel sufficiently comfortable to solve problems on their own; 6. Utilize interactive classroom strategies; 7. Value both the scientific and the artistic ways of knowing; 8. Use a final project and not a final exam as a means of self-directed assessment; 9. Have students write anonymous comment cards each week, and adjust to their needs; 10. Co-teach, either by having guest speakers or by collaborating with a colleague throughout the course.

1) Orientation to math as a language of nature. Orientation to Math as a language of nature has the effect of humanizing mathematics, and connecting mathematics conceptually to the physical world. By having students discuss "the unreasonable power of mathematics" (Livio, 2002) before solving physics problems, all students – art students as well as physics majors – were provided with a deeper access to math as a language of physics than has been shown to be the case in traditional introductory physics courses (Redish, Saul, and Steinberg, 1996, McDermott, 2001; Hammer and Elby, 2002). Orienting to math as a language of nature <u>before</u> using math to solve problems allowed the students in CCS-120 to become aware of the important metacognitive questions which motivate physics: ontology – what do we know; and epistemology – how do we know that which we claim to know, and the important role of mathematics in shaping our contemporary understanding of Nature. Understanding math as a way of knowing about nature, instead of a set of disembodied equations, is a necessary first step towards reducing math anxiety in math-timid students (Ernest, 1992; Korey, 2002; Gellert, 2000), as well as an important first step in connecting mathematics to physics concepts for physics students (Hestenes, 1996, 1998; Redish, et al., 1996, among others).

One of the problems often discussed in physics education research is the failure of students to see the connection between equations and the reality they represent (Redish, et al., 1996; Hestenes, 1996, 1998; De Lozano and Cardenas, 2002). Studies of students' conceptual understanding have repeatedly shown that students who may be competent problem solvers, never the less cannot answer basic conceptual questions dealing with mechanics, electricity, or optics (McDermott, 1993, 2001; Mazur, 1997; Hobson, 2006; Hake, 2007). When attention is paid to epistemology – how students acquire knowledge, as well as how knowledge is acquired in physics, which includes mathematical reasoning - students' understanding of physics concepts, and the way math is used to model behavior in physical systems, has been shown to improve dramatically (Hestenes, 1996; May and Etkina, 2002; Hammer and Elby, 2002).

In CCS-120, I assigned readings and initiated class discussions which addressed open-ended questions such as, *Is the universe mathematical? Is mathematics a discovery, an invention, or both?* and *Are humans programmed to recognize mathematics?* These open ended discussions, for which there is not one single "correct" answer, helped create a safe space for learning math, as one art student said:

> I feel doubtful that I will ever “click” with the math. I’m just very glad that my not-understanding does not make me feel desperate, as this seems sort of a “safe environment” where it is good thinking that counts, which I am capable of.

2) Noether before Newton! Beginning the study of physics with the contemporary view of symmetry and the paradigm of dynamic spacetime has two major advantages over the traditional introductory curriculum, with its predominant adherence to the Newtonian paradigm. First, there is the advantage of modernizing the curriculum, as some of the topics which are currently called "modern physics" are now more than a century old. Whether the introductory course is to be a terminal course in physics, or the beginning of a physics major, it seems appropriate in the twenty-first century to introduce the study of physics with knowledge that was developed in the twentieth century. In addition, the devices which are part of the contemporary world, such as cell phones and satellite communication, utilize technology which is informed by contemporary physics. The goal of universal science literacy may not be achieved unless the public is conversant with the basic concepts which motivate physics today, such as symmetry, relativity, and quantum mechanics.

Second, contemporary physics lends itself far more naturally to aesthetic and interdisciplinary education because of its appeal to imagination and inquisitiveness. Levrini (1999, 2002) also suggested that the contemporary view of spacetime of Special and General Relativity are appealing to students of arts and history. I found this to be the case with the art students in CCS-120. A survey of high school physics students in 34 countries, conducted by the ROSE project in Europe, indicated that the topics in physics which were rated as most interesting to both girls and boys were contemporary issues, such as the mysteries of space, black holes, and fundamental physics (Sjøberg and Schreiner, 2007). This suggests that starting with contemporary physics, instead of Newtonian mechanics, may have the potential to interest more girls and young women in physics, starting at the introductory levels.

The results of teaching Noether before Newton with the students of CCS-120 cannot be used to address the gender issues, however we can say the following: the physics and art majors were divided almost perfectly along gender lines, with six out of seven physics majors being male, and three out of four art majors being female. The two (out of three) female art majors who granted me post-course interviews expressed that, as a result of *this course,* they wanted to learn more physics (Beatrice) and collaborate with the physics department on making art works (Juno). This result, taken with the results of the ROSE survey, suggest that this curriculum may offer a potential avenue towards increasing diversity in the physics community in the future. As SS, the one female physics major in CCS-120 said,

> I think the whole idea of relating physics to symmetry and aesthetics is an important idea to give to kids when they're really young, because …kids kind of grow up thinking that physics is this really dry boring thing, where you just go through the numbers, but if they have this perception of it maybe… we'll have different – we'll have a lot of different kinds of people becoming physics majors.

3) Reading literary works by theoretical physicists about physics content and physics in context, instead of a text book, had several beneficial effects with the students of CCS-120. First, it allowed students to interact, in a literary sense, with professional physicists who produce original work in physics. Text books, as Thomas Kuhn rightly said, do not give a sense of what the discipline of physics is really about (Kuhn, 1962). The literature I selected for this course consisted of the book *Fear of*

Physics by theoretical physicist Lawrence Krauss, and a course reader comprised of articles dealing with physics content as well as physics-in-context with art, music, literature, philosophy, and history. All but one of the articles in the original reader were written by theoretical physicists, including works by three Nobel Laureates (Einstein, Feynman, and Weinberg). A paper on Symmetry by Nobel Laureate David Gross (Gross, 1996) and a paper entitled "Symmetry and the Search for Beauty in Modern Physics" by theoretical physicist Anthony Zee (Zee, 1992) were added later, and will be included in future incarnations of my course reader.

Second, choosing a variety of authors instead of a single text allowed the students to learn from different perspectives. For example, it turned out that the physics students preferred Krauss' way of explaining, while the art students appeared to prefer the explanations of Mario Livio for the same concepts. In addition, by reading about Relativity from both Krauss and Feynman, it allowed Juno to discover a mistake in Krauss' book, which had not been detected (or at least, not reported) in the fifteen years that his book has been in print! This serendipitous discovery was quite exciting for Juno, who has since been acknowledged in the updated edition of the book, which is to appear later this year (Krauss, personal communication, March 20, 2007).

Third, reading literary works by a variety of physicists gave students the opportunity to see that physics is a human endeavor, instead of an encyclopedic collection of pre-determined facts, as it often seems. The students got to know our physicist-authors as individuals, some of whom they liked and others not as much, just as with any group of people. For example, Beatrice said of Nobel Laureate

Steven Weinberg, “I think from his writing that Weinberg is grumpy…. He has a demeaning tone in his writing but I also strongly agree with him on several points." MKS said of Mario Livio, that he was clearly "man with great insight.”

Even the classroom discourse about the readings served this purpose, as instead of assigning "Chapter X," I assigned "Krauss, chapter two," or "the Einstein article," and thus the students referred to the articles by their authors, as well. This opportunity to get to "know" physicists through their literary works contributed to the art students' change in perception of physicists from exclusive to more realistic human beings.

Finally, literary works about physics by theorists are more enjoyable to read than introductory text books, as they are meant to be appreciated as good literature. Even the physics students in CCS-120, who admitted to not having done all the reading assignments, said they looked forward to revisiting the articles in the course reader over the summer, and the reader was a resource they planned to keep. These responses suggest that using literary works by theoretical physicists, instead of a large encyclopedic text book, may have similar results in other educational settings, in terms of making physics appear more like a creative, human endeavor.

4) Utilizing as wide a variety as possible of assignments and activities, including writing reflections about authors' works, drawing as a way of becoming aware of how one understands, composing or choreographing, in addition to problem solving, made it possible for the art students to begin to access the content and process of physics in ways that were initially more familiar to them, while developing their parallel ways of knowing through mathematics. Visualization strategies, in addition to problem solving, allowed the physics students to access other ways of knowing. They reported that drawing their understanding came naturally and easily, although they had not been asked to draw their understanding of physics concepts before. The use of drawing in CCS-120 was discussed in Chapter Six.

For an interdisciplinary arts and physics course to accomplish the goals of aesthetic physics education, it is imperative that the instructor employ strategies that give the students multiple opportunities to develop their understanding of the content. In CCS-120, the art students came to the course to learn something about physics, and the physics students came to broaden their experience to include art, therefore it was important to help each group to develop the ways of sense-making that are appropriate to the *other* discipline, which they came to learn. This is the beauty of *interdisciplinary* instruction, which made this course important to the students in CCS-120, and which I believe is important for any instructor who wishes to teach with this model.

5) Relegate problem solving activities to class time for the first half of the course, until the art students feel sufficiently comfortable to do them on their own. As discussed in Chapter Seven, I made the mistake of assigning “discovery” problems for homework too early in the course, which was discouraging to the art students, who were less familiar with basic algebra than I had anticipated. By scaffolding the problem solving, creating opportunities to learn the techniques in mixed major peer groups of artists and physicists, the art students felt much more inclined to attempt problem solving later in the course. In their post-course interviews, both Beatrice and Juno expressed the feeling that, had I started with this approach first, they would have been more willing and able to attempt problem solving after a while. Both expressed a desire to continue to learn physics *in this type of setting,* meaning interdisciplinary, with physics major peers. These reactions lead me to make the suggestion that in an interdisciplinary classroom setting where grades are not a motivating factor and there is no competition for the better grades, mixed-major peer groups of physics majors and arts/humanities majors can facilitate learning of math and physics for students who may have previously been anxious about these subjects. The term "scaffolding," from the research of Russian psychologist Lev Vygotsky, has been used to describe this type of process, where students can accomplish more with the assistance of experts than they can alone (the "zone of proximal development"). After their confidence has been developed, students are ready to attempt to solve problems on their own.

6) Utilizing interactive, discussion-oriented teaching strategies such as Peer Instruction (Mazur, 1997), as well as meaningful explorations in small mixed-major peer groups, open ended discussions, and lectures that are "interruptible" created an atmosphere of interest and excitement that straight lectures cannot provide. Both art and physics students expressed their appreciation for the discussions with the "others." The art students appreciated the passion of the physics students, who in turn appreciated the direct way the artists had of questioning when they did not understand something. Six out of the eight students who granted me post-course interviews cited the discussions as their favorite aspect of the course. Only the one male art student was uncomfortable with the discussion format, reasons for which I attempted to analyze in Chapter Five. There is apparently a minority of students who do not like interactive methods (Zohar, 2006; Mazur, 2007, pers. Comm..), however in a mixed-major, interdisciplinary physics and fine arts course such as CCS-120, where collaboration and interdisciplinary dialog are important goals, there is really no other means of achieving these goals.

7) Valuing equally the scientific and artistic ways of knowing is vital for creating a classroom environment of trust. As was discussed in Chapters Five and Six, the scientific way of knowing has come to be more highly valued in our western society than the artistic (Eisner, 2002). This hegemonious outlook may be present in students, albeit subconsciously, but may emerge when probed, whether intentionally or not, through their comments or written work. The following example from a physics major's first homework essay that "The author’s comparison of art and science requiring similar levels of formal training is laughable to me," and "nobody can intuit something like the structure of DNA that took years to discover, while any artist could decide how to make a sculpture or compose a song without any training.," illustrates a perception of making work in art as a trivial pursuit, which is not true. This kind of sentiment is the counterpoint to the art students' feelings that physicists were exclusive. After the experience of this course, both physics and art students expressed greater appreciation for each others' discipline. A similar result was also noticed by faculty in the Dartmouth program (Korey, 2002). The camaraderie that was established between the physics and art students in the collaborative format of this class, suggests that a similar intellectual dialog between arts and science students can be developed in other settings.

Valuing the artistic way of knowing as equal to the scientific process is one of the most important steps towards achieving universal access to the knowledge of physics. Programs which attempt to reach into inner city schools, or target women as a population to recruit into physics, may be successful in bringing minority culture students to study physics, but if these students encounter hegemonious attitudes when they arrive at college, they will eventually turn away from physics (Ong, 2007). The devaluing of other ways of knowing as well, for example First Nations' or indigenous people's knowledge systems, is also a barrier to achieving equity and diversity in physics (Aikenhead, 1998, 2002, 2003; Emeagwali, 2003). Thus, by promoting dialog and appreciation of physics / mathematics and arts as valid ways of knowing, perhaps other hidden prejudices may also be addressed and overcome.

8) Having the final goal of the course be a performance-oriented or demonstrable project, rather than a final exam, made the course end on a high note, with students feeling that they learned something meaningful. According to Maxine Greene's Capacities for Aesthetic Learning, the final goal of reflecting and assessing which leads to further questioning, was achieved through their performance-oriented projects which were presented to their peers. Through their physics works of art, they each inspired admiration and also further thoughts, questions, and mental connections for themselves and their peers. As the instructor, it was gratifying for me to see how, after the presentations, the students were reluctant to leave each other, and expressed their desire for the course to continue. Physics major Frank expressed his positive response in his post-course interview:

> It hardly felt like an assignment at all, it was just something that I was doing that I enjoyed, and that I wanted to show to other people. … and that I hoped they would enjoy, too. So I got to learn something about math and physics and aesthetics and art all at once, and create something that I really liked.

9) Having students write weekly anonymous comments, allowed me to have constant feedback, which allowed me to make "course corrections" to adjust to their requests, regarding the content or process. Especially in an interdisciplinary format where students have very different backgrounds, it is important for the instructor to monitor the progress of the class. Moreover, if students feel that their opinions are valued by the instructor, they are more likely to be favorably disposed towards learning unfamiliar content.

10) Co-teaching with other experts, either inviting guest lecturers if possible, or collaborating with colleagues to team-teach, makes for a true interdisciplinary environment. In CCS-120 students commented that the guest lectures were some of the highlights of the course for them, as were the “arguments” between myself and Professor Lubin. As one student wrote on an exit card, February 23, 2007:

> Today’s class was awesome; 8 students and 2 cosmologists informally chatting about time travel, tachyon particles, higher dimensions, and black holes. ... what more could one ask for? Looking forward to the guest visits to come.

Similar comments were reported by the study team who evaluated the Dartmouth Math Across the Curriculum program (Korey, 2002). This suggests that it is useful for students to see the instructors model the attitude of interdisciplinary cooperation if the goal is to foster interdisciplinarity in their studies.

In the end, the success of this model was measured by the high evaluations the course received from the students on the end-of-course evaluations, excerpts of which are presented here:

> I learned so much from this course, and I have never taken physics before. Jatila encouraged us to think outside the box, and this definitely helped me to understand the importance of the subject matter.
>
> Overall, the course initiated a strong interest in physics – before I had always thought it was beyond me, but now I can't get enough of it for art inspiration, etc.
>
> I found this course to be wonderfully exciting. The instructor and the students were wonderful and passionate, which made the class a pleasure. I had to overcome and grapple with a lot of struggles with math and understanding the language of science. I wish that this class would continue and I could continue to study the maths and science in such an integrated way.
>
> Overall, this was an excellent class, and I hope it will be offered again for many others to experience.
>
> I got the sense that one must be passionate to produce meaningful work – not just as artist, but also as physicist! This course is a great jumping board to explore one's own passion and become someone who can and is inspired to make meaningful significant work.

> The amount of discussion was amazing. Along with the breadth of material. It has been great and enlightening (dare I say it).

Dr. Bruce Tiffney, Dean of the College of Creative Studies, invited me back to teach this course, and its sequel, in Winter and Spring, 2008, so that I will have the opportunity to develop in further. These positive results from both the students who were experienced in physics, and those who were not, suggest that this model can be adapted to benefit other populations.

8.1.2. Interdisciplinary Strategies and Aesthetic Ideology

As was described in Chapter Three, Svetlana Nikitina of Harvard's Project Zero has defined three approaches to interdisciplinary education, based on the primary type of inquiry strategy employed: contextualizing, conceptualizing, and problem solving (Nikitina, 2002). She outlined successes as well as limitations of each strategy, and recommended that for optimal success, an instructor should utilize a combination of interdisciplinary strategies.

My model of Symmetry and Aesthetics in Introductory Physics utilized all three interdisciplinary strategies defined by Nikitina. Symmetry was the underlying concept that linked physics and art. The context for the development of contemporary physics and art was the twentieth century post-modernist movement. Nikitina also discussed epistemology as a way of contextualizing, thus our readings and discussions regarding the epistemology of mathematics as a way of knowing about the physical world provided an additional component of contextualization. The final project, to create a physics work of art, utilized Nikitina's third strategy of problem solving to create a new product.

Symmetry and Aesthetics in Introductory Physics also embodied the ideology of aesthetic education as defined by Maxine Greene, which I quoted in Chapters One and Three. A particularly gratifying outcome of the course beyond the final projects is the planned collaboration between several of the students from CCS-120 with students and professors in the UCSB Dance Department, to produce a choreography to some of the algorithmic music and poetry that my students created for their physics works of art. This collaboration is set to begin in Fall, 2007, with the goal of a performance of the modern ballet, “Fibonacci’s Dream” for the Spring, 2008 student concert. The students from CCS-120 also have been invited to perform their algorithmic music pieces for the Kavli Institute of Theoretical Physics!

As has been discussed in Chapter Six, the final projects of the students all demonstrated that principles of symmetry, contemporary physics, and math as a language, were correctly utilized and applied, and expressed according to each student's individual experiences. In the future, this course could easily be accompanied by a separate laboratory course which could combine experiences with computer-generated music, imaging, Relativity simulations, and movement experiences. In addition, this design concept could provide the conceptual foundation for an interdisciplinary program in arts and engineering, such as those at Connecticut College, MIT, or even at UCSB, where the Media Arts and Technology program exists as a separate graduate program within the Engineering College.

The outcomes of aesthetic education are purposefully not concrete, and cannot be judged in isolation from their connections to the rest of a student's experience. The outcomes of aesthetic education are best described by the Capacities for Aesthetic

Learning, developed by Maxine Greene and members of the Lincoln Center Institute: Noticing Deeply, Embodying, Questioning, Identifying patterns, Making connections, Exhibiting empathy, Creating meaning, Taking action, and Reflecting/Assessing which, rather than the endpoint, is meant to be the beginning of another inquiry (Holzer, 2005). The final projects and written work of my students indicate that they did indeed develop many of these capacities. The success of the curriculum with these students suggests that it is possible to develop many of these capacities for aesthetic learning in students elsewhere.

8.2. Recommendations for Extending this Model to Other Levels

The course as it stands represents the first quarter of what should be a one or two year course. After investigating the contemporary views of spacetime, the course should look back at Newtonian mechanics from the viewpoint of symmetry, progress through electricity and magnetism and the birth of modern physics, finally returning to symmetry as it applies to quantum mechanics and the Standard Model of Particles and Interactions. A schematic prospectus is shown in Figure 8.1.

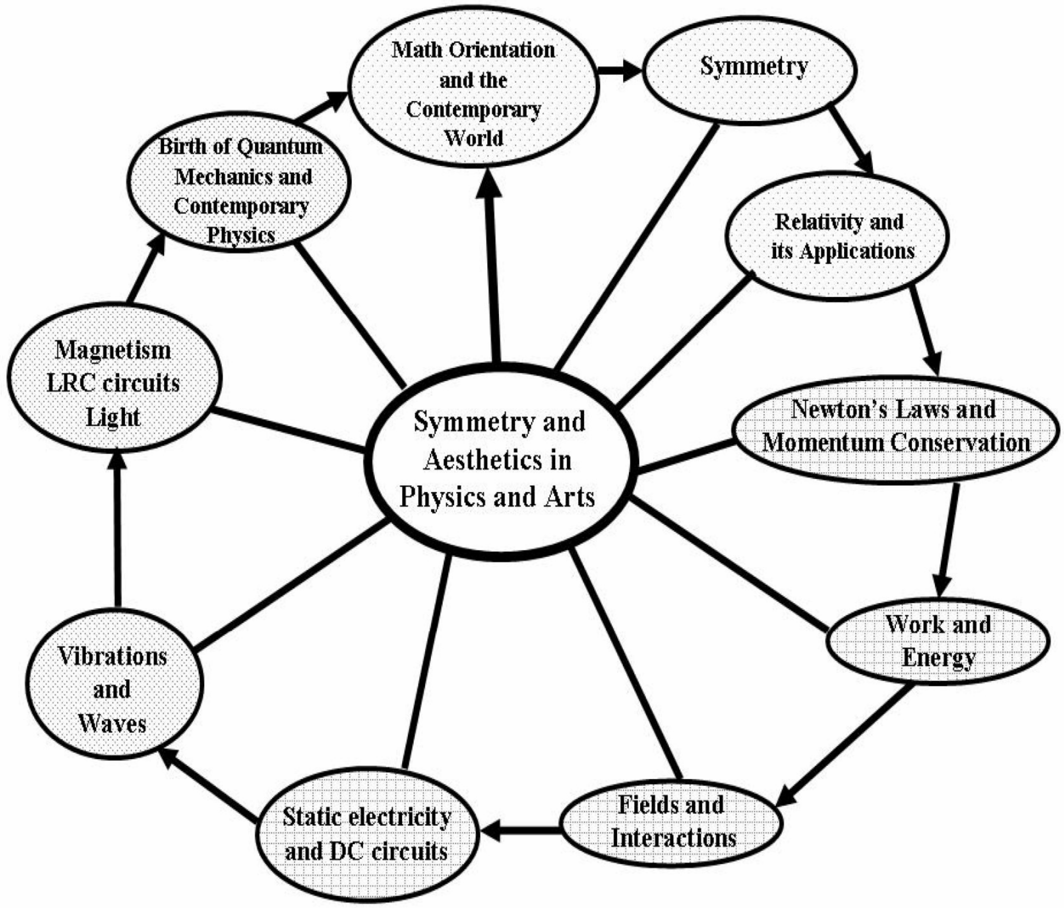

Figure 8.1. Prospectus for full year course

Once completed, this model for introductory physics – starting with symmetry and contemporary physics, utilizing interdisciplinary strategies which incorporate art, music, literature, history, and dance, with the ideological outlook of aesthetic education, can be adapted to serve a range of populations. Initially, I envisioned this model as a curricular paradigm for undergraduate education, with three main uses: as a physics sequence for students majoring in fields other than physics, as an introduction to physics for physics majors, and as a physics course for education majors, who aspire to become teachers. I now believe that this model could serve as an appropriate foundational course for an interdisciplinary Media Arts and Science program, such as exists at Connecticut College, and even the Media Arts and Technology program at UCSB. In addition, I believe that this model for teaching physics could be adapted to a series of workshops for in-service teachers at the pre-college level. These branches are shown in Figure 8.2.

As an introduction to physics for physics majors, the design concept of Symmetry and Aesthetics in Introductory Physics could serve as an entry point to the great ideas that are part of the contemporary world, and could provide a humanist context for the traditional two-year introductory physics and calculus sequence. Rather than having to wait until graduate school to learn about symmetry and the important contributions of Emmy Noether, physics majors should be exposed to these ideas early in their training. Foregrounding Noether – a woman – may also have positive effects of tacitly informing young women that physics is not only for men. As a physics sequence for non-majors, the design concept of Symmetry and Aesthetics in Introductory Physics is, I suggest, more appropriate than the current paradigm, which is heavily oriented towards engineering and classical physics. In the traditional courses, students for whom the introductory sequence is a terminal course in physics are hardly introduced to the concepts of physics that revolutionized the field a century ago, as more than half of the year is spent on mechanical systems.

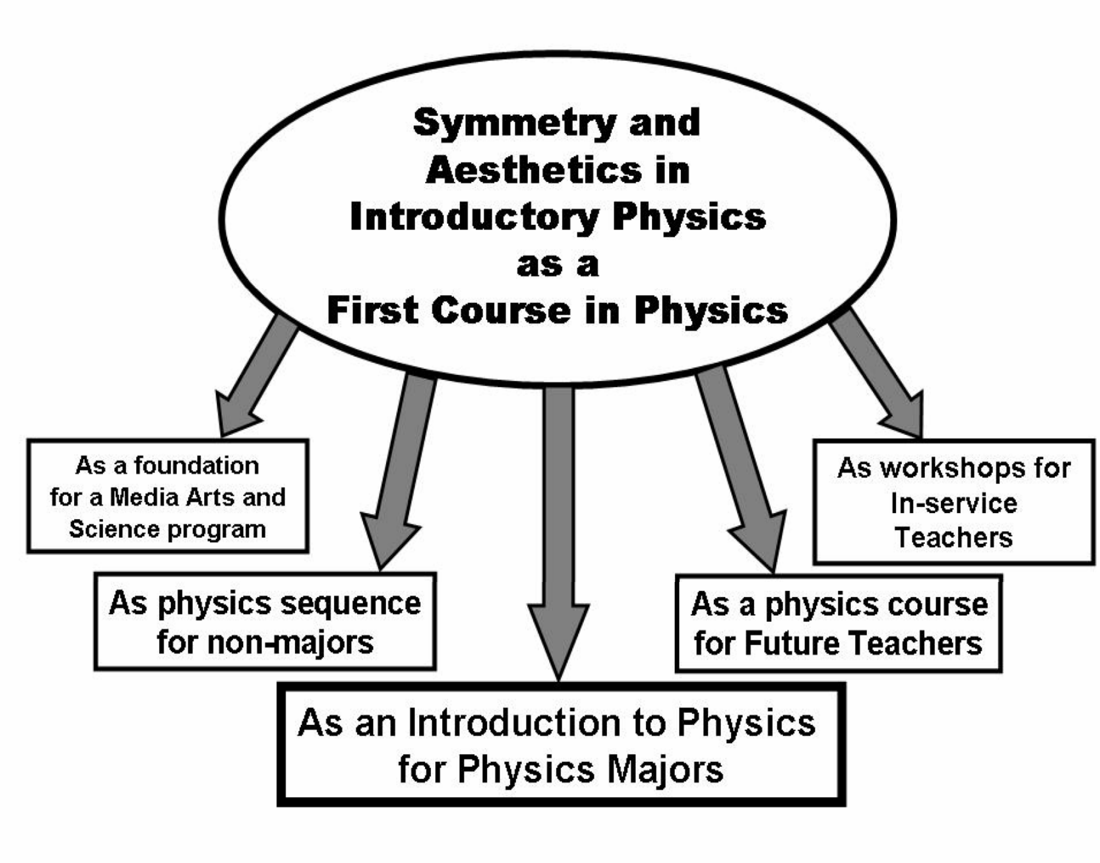

Figure 8.2. Potential target audiences

The questions and applications which occupied the minds of seventeenth century physicists should not be taught *to the exclusion of* the questions and applications which occupy the physics community today (Hobson, 2006). The design concept which I propose removes the overwhelming emphasis on the classical perspective of static space and universal time, placing it in its historical context, and begins instead with the contemporary perspective of dynamic space and the non-absolute nature of time, as well as contextualizing physics with arts, history, and literature.

The question asked by the late Victor Weisskopf, which I quoted in Chapter One: “Why is physics as a science considered ‘inhuman’ by so many people, including some of the students we teach”? (Weisskopf, 1976) was answered in Chapter Two. To many, physics is considered “an extreme culture of objectivity; a culture of no culture” (Traweek, 1988), separated from the rest of society by its specialized discourse (Bazerman, 2000). The positive comments of the students in my class suggest that the design concept of Symmetry and Aesthetics in Introductory Physics has the potential to humanize the study of physics, and thus make it accessible to a wider population.

A group for whom access to physics is particularly important consists of future elementary school teachers, who traditionally have a fear of math and physics, but who are called upon to teach these subjects to children. This model of aesthetic physics education may have the positive effect of providing access to the knowledge and processes of physics to this important population.

8.2.1. As a Physics Course for Future Teachers

Tseitlin and Galili (2004) noted that the introductory physics curriculum is almost universally oriented towards engineering. They proposed that a different physics curriculum should be offered to those who would become teachers, which should be more oriented towards fundamental physics. Physics teachers, they proposed, should command a much deeper knowledge of the subject matter than working engineers. Unfortunately, many elementary school teachers never take a single course in physics, and if they do take the currently available one-year survey course, they will most likely not learn about contemporary physics. This model curriculum could be ideal for future teachers, as it begins with fundamental ideas that unify all of physics. In addition, this curriculum models interdisciplinary strategies and aesthetic ideology which are applicable to elementary education.

Richard Hake, one of the leading authorities in Physics Education Research, proposed that colleges and universities make a stronger effort not to neglect students who will become future pre-college educators:

> Many faculty in Science, Mathematics, Engineering, & Technology (SME&T) at the postsecondary level continue to blame the schools for sending under prepared students to them. But, increasingly the higher education community has come to recognize the fact that teachers and principals in the K-12 system are all people who have been educated at the undergraduate level, mostly in situations in which SME&T programs have not taken seriously enough their vital part of the responsibility for the quality of America's teachers (Hake, 2007).

In addition, regarding the preparation of pre-college teachers, there are now state and national standards not only for science and math education at every grade level, but for dance, art, and music as well. An interdisciplinary physics and fine arts program such as I am proposing could benefit future teachers by giving them content knowledge and strategies in science, math, and the arts in an interdisciplinary format which they could use in the classroom. Also, as Gardner (1985) suggested, logical/mathematical reasoning may develop out of spatial/kinesthetic intelligence, therefore especially for primary grades, both of these types of reasoning should be developed simultaneously. As has been discussed in Chapter Three, dance and music relate to both spatial/kinesthetic and logical/mathematical reasoning. Thus, for those college students who desire to be teachers, this aesthetic physics curriculum model could provide an ideal one-year physics course.

8.2.2. As Workshops for In-Service Teachers

This curriculum of Symmetry and Aesthetics in Introductory Physics could be adapted to a series of workshops for in-service teachers. Elementary school teachers who did not have a physics course in college, but who must teach science and math, could benefit from such workshops. Middle school teachers, such as the dance and physical science teachers I met at Millikan Magnet School in Los Angeles, who are attempting to incorporate elements from each other's class into their own, would similarly benefit. High school teachers who wish to incorporate symmetry and topics from contemporary physics in their classes could also benefit. Topics in Symmetry and Relativity could be easily adapted as a suitable finale to an Advanced Placement Physics course, after the national examination in May, but when there are still four or six weeks remaining in the school year.

8.2.3. As a Foundation for a Media Arts and Science Program

Media Arts and Sciences programs have begun at a number of campuses around the country. Besides the two programs which I described in Chapter Three, there is a growing graduate program of Media Arts and Technology at UCSB. Symmetry and Aesthetics in Introductory Physics could serve as a foundation for the content and philosophy of interdisciplinary arts and sciences research.

8.3. Implications for Balancing the Gender Bias in Physics

The following quote is part of a speech by condensed matter theorist Susan Coppersmith, which was recorded in October, 2004 at the Future of Physics Conference at the KITP, which I transcribed from the proceedings of the conference on line:

> I wanted to say something exTREmely controversial,
> just SO y' wouldn't be bored. And THAT,-
> and again, you can sorta shoot me at dinner,
> and that is, <…> soft condensed matter physics
> I believe is one of the SUBfields where there ARE more WOmen,
> BUT ah, I don't have the perCEPtion
> that ah, women are making a lot of progress in the FIELD.
> And in terms of the FUture,
> I think it's something that IS part of the future of physics,
> is wondering what the sociology is gonna be like.
> Now I don't wanna FOcus on this,in, in this FIELD
> but I think that it's something that,
> at least in the time that I've BEEN here
> that no body has brought UP,
> and I think it is important to the future of our FIELD
> that it be representative of society at large.

(transcribed from http://online.itp.ucsb.edu/online/kitp25/, December, 2004).

The quote from Susan Coppersmith, prominent condensed matter theorist, at a *Future of Physics* conference is indicative of two aspects of the "gender question" in physics: First, that there is still a question as to why women remain under represented in physics, according to their proportions in society at large; and second, that the hesitancy she demonstrated indicates that the gender question is one which is forbidden to bring up, at least not officially, at professional physics conferences. The implication of her orthogonal offer, *" you can sorta shoot me at dinner,"* indicates that she knew she was taking a risk by bringing up the gender question at a Future of Physics conference.

The public perception that it is now important to bring the genders into balance in physics, math, and engineering is evidenced by incentives from the National Science Foundation, such as the current Research on Gender in Science and Engineering initiative (NSF 07-578). However, at the highest levels of the profession, gender is not an official topic of investigation. It is therefore suggested that the task of attracting a more balanced student population from which the professional physicists will emerge naturally falls to those who teach introductory physics.

The design concept of Symmetry and Aesthetics in Introductory Physics, which connects physics with art, music, history, and literature, represents what has been called "connected ways of knowing" (Zohar, 2006, among others). Connected ways of knowing have been called feminist epistemology (ibid.), although I suggest perhaps a more appropriate term would be *humanist* epistemology. As I discussed in Chapter Two, contemporary physics represents connected knowing, both at microscopic scales of fundamental particles and interactions, and at the largest scales of gravitational interactions in the universe. The view by feminist scholars that physics represents masculine ways of knowing (Traweek, 1998; Zuga, 1999; Tobias, 2003; Zohar, 2006, e.g.) may be due to the public perception that equates physics with engineering, and the emphasis of school science on the Newtonian paradigm. The implicit separation of observer and observed which is fundamental to the Newtonian paradigm, and which is equated with an androcentric way of knowing, is eschewed in the contemporary paradigm. From the smallest scales which are governed by Heisenberg's Uncertainty Principle, where the mere presence of an observer influences the outcome of the experiment, to the largest scales which are governed by General Relativity, in which the presence of mass deforms spacetime, there is no concept of an absolute inertial observer. Thus we may say that contemporary physics, as the embodiment of a connected way of knowing about the physical universe, is feminist – or humanist - at its conceptual core. Therefore, the suggestion is that by starting with contemporary physics instead of the mechanistic viewpoint of engineering physics, the subject may become appealing to a more diverse population, including women.

After nearly two decades of reform in physics teaching strategies, the percentage of women earning Ph.D.'s in physics has not kept pace with the increases in women's participation in other fields. The number of women earning Ph.D.'s in physics increased from approximately 8% in 1990 to 17% in 2003, according to figures from the American Institute of Physics (Ivy and Ray, 2005, p. 1), however during this same time the percentage of Ph.D.s awarded to women in all fields increased from approximately 36% in 1990 to 45% in 2003 (ibid., p. 6). Perhaps the introductory curriculum, with its emphasis on contexts that are naturally more appealing to the (heteronormal) male viewpoint, contributes to the stubborn resistance to women in physics.

Another gender-balancing influence may be found in Emmy Noether herself, the discoverer of the symmetries that underlie all the conservation laws of physics. In my study, "Physicists and Firewalkers**:** The Co-construction of Community Identity through Narratives in Ritual Performances" (van der Veen, 2006) I discussed the importance of narratives in the co-construction of community identity. In physics, the stories which are most often told belong to Isaac Newton, Albert Einstein, Stephen Hawking, and other men. The image of Einstein is commonly associated with the public perception of the canonical physicist, and hardly anyone outside the physics community, as well as many physicists and physics educators, has ever heard of Noether, although her work was actually quite important for the final proof of Einstein's General Relativity (Byers, 1998). Her theorems, summarized as "For every continuous symmetry in nature, there is a conserved quantity in physics" are the foundation of all our current understanding in physics. The existence of Newton's Laws is a consequence of Noether's theorems, as was discussed in Chapter One: Perhaps if Noether's Principles were taught before Newton's Laws, and Noether's narrative added to the anecdotes of physics, it could have a long-term effect towards gender balancing the physics community, as well as simply providing a firmer foundation of physics for all students.

Finally, as the ROSE study in Europe has indicated, contemporary issues in physics are equally interesting to both girls and boys, but to study contemporary issues, such as black holes, requires at least a conceptual knowledge of General Relativity. Thus, changing the design of the introductory physics curriculum so as to start with contemporary physics, as well as utilizing interdisciplinary strategies and the ideology of aesthetics, may naturally diversify the community. The desire to see physics and art taught this way to children was expressed by all the CCS-120 students whom I interviewed, as discussed in Chapter Five, Section 3.5, and summed up in the statement by SS:

> I think the whole idea of relating physics to symmetry and aesthetics is an important idea to give to kids when they're really young, because kids kind of grow up thinking that physics is this, … really dry boring thing, where you just go through the numbers, but if they have this perception of it maybe – we'll have a lot of different kinds of people becoming physics majors.

8.4. Concluding Remarks, and the Next Steps…

The introductory physics curriculum that is in place in 2007 is basically the same as the curriculum that was designed in 1957 to train more American engineers to compete with the Soviet launch of the Sputnik satellite. The imperatives of global warming, dark energy and the accelerating universe, fundamental physics that may be revealed by the Large Hadron Collider, nanotechnology and the need for alternative fuel sources, are different in 2007 than the concerns which motivated the development of the introductory curriculum half a century ago. Thus, it is time for a new introductory curriculum, which will support the need to train a new type of physicist who can think in broader terms. To use an analogy, we need to refertilize our soil to grow a more diverse crop for the future.

The next step I envision in the development of this model for interdisciplinary aesthetic introductory physics education is to develop and teach the second quarter of this model curriculum. The second quarter should begin where the first left off: with the introduction of the principle of stationary action as the invariant quantity. As Professor Eric Mazur has said, the three pillars of physics are symmetry, conservation laws, and mechanics; assume any two, and the third follows (Mazur, 2007, pers. comm.) Thus, I began with symmetry and introduced the conservation laws in the first quarter, and the second quarter will start with the conservation laws (the principle of stationary action) and lead into mechanics. This will motivate Newtonian mechanics from the viewpoint of symmetry and conservation of momentum.

On the artistic side, the rich context of the Enlightenment and the political situation between Western Europe and the Ottoman Empire provide an abundance of historic material from which to draw. Many of the mathematical foundations of the work of Galileo, Kepler, and later Newton, came from the Islamic scholars of Baghdad, and DaVinci was both artist and inventor. Dance is ideally suited as a medium for conveying concepts of conservation of momentum, center of mass, friction, rotation, balance and equilibrium, forces and accelerations, momentum, and gravity.

A third quarter should include electricity and magnetism, light and waves, and return again to the modern era, ending with a look at quantum mechanics and a return to symmetry, and the beginnings of contemporary physics, which is where the course began. The time period in which these discoveries were made spans the nineteenth and early twentieth centuries, and thus the rise of industrialism and colonialism in the west, and the art, literature, and music of the time offer rich interdisciplinary contexts from which to draw. Of course, every topic is connected by the underlying principles of symmetry which motivate the laws of physics, and which provide a sense of aesthetics in art, music, and dance.

This general sequence represents my idea for a year-long version of the course, Symmetry and Aesthetics in Introductory Physics. I also envision developing a laboratory component to accompany this sequence, which would encompass the aspects of observation and experimentation with mechanical and electrical devices, but also incorporate aspects of digital art and music, and various dance experiences which would support and enhance the understanding of each topic.

This introductory sequence does not attempt to include in one year all the topics which are present in a traditional encyclopedic introductory physics text book. For example, I have not addressed thermodynamics, however this topic can be attended to in a subsequent course. The historic context of the Industrial Revolution, and the current problem of global warming, as well as the current research questions of the energy balance of the universe, provide rich textures with which to thread an aesthetic approach to thermodynamics in context.

Combining interdisciplinary strategies and the ideology of aesthetics, and starting with symmetry as the foundation and the linking concept between physics and art, offers an exciting prospect for a new paradigm in introductory physics education. I conclude with a quote from the German philosopher Friedrich Nietzsche. I first encountered this quote on the website entitled "The Preposterous Universe," (http://preposterousuniverse.blogspot.com), which belongs to theoretical physicist Sean Carroll, although Sean seems to have removed it as of this writing. It seems to me to fit the spirit of this project as, ultimately, physics and art are expressions of the same human desire to make sense out of the universe.

> We, however, want to become those who we are --- human beings who are new, unique, incomparable, who give themselves laws, who create themselves. To that end we must become the best learners and discoverers of everything that is lawful and necessary in the world: we

must become physicists in order to be able to be creators in this sense --- while hitherto all valuations and ideals have been based on ignorance of physics or were constructed so as to contradict it. Therefore: long live physics! And even more so that which compels us to turn to physics --- our honesty!

--- Friedrich Nietzsche (1882), ***The Gay Science***, Aphorism 335.

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Appendix A. Reader Table of Contents

Symmetry and Aesthetics in Introductory Physics

Winter Quarter, 2007, CCS 120, Section 5 Fridays, 1 – 4 PM, Physical Sciences South, 2712 Instructor : Jatila van der Veen

Outline and Schedule

1. Campbell, Peter (2004). Seeing and seeing: visual perception in art and science, *Physics Education* 39(6) p. 473-479, Nov. 2004, taken from www.iop.org/journals/physed
2. Einstein, Albert (1936). Physics & reality. Reprinted with permission in *Deadalus, Fall 2005*, American Academy of Arts & Sciences, p. 22-25
3. Livio, Mario (2002). Prelude to a Number, chapter 1 of *The Golden Ratio*, p. 1-10, Broadway Books, New York
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8. Livio, Mario (2005). The Supreme Art of Abstraction, p. 179-188 *(ibid.)*
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10. Taylor, Richard P. (2002). Order in Pollock's Chaos, *Scientific American*,p. 111-121, December, 2002
11. Weinberg, Steven (2005). Physics & History, *Deadalus*, Fall 2005, American Academy of Arts & Sciences, p. 31-39
12. Feynman, Richard (1963). Curved Space, chapter 42 of *The Feynman Lectures on Physics, Vol. 1*, p.42-1 – 42-1413.
13. Baez, John, and Bunn, Emory (2004). The meaning of Einstein's equation, *American Journal of Physics*, (73)7, July 2005 p. 644-652
14. Krauss, Lawrence (2006). Revisions for Chapter 5, Fear of Physics pre-print directly from the author himself! 3 pages
15. Livio, Mario (2002). The Unreasonable Power of Mathematics, final chapter of *The Golden Ratio*, p. 237-253

Appendix B. Post-Course Interview Questions

1) Please state the name by which you would like to be known in my research:

2) Please state your major and year in college:

3) What math and physics did you have prior to taking this course?

4) Were you taking other courses in math and/or physics concurrently with this course?

5) Why did you enroll in this course?

6) If you were also taking other physics courses concurrently, did you feel that this course complemented your studies in the other courses, or would you say it was completely orthogonal? or tangential?

7) What about this course did you like most? least? What changes would you suggest?

10) What assignments did you like most? Were there any that you did not do, or did but did not like? Why?

12) Do you think your attitude toward the *process of doing physics* has changed as a result of this course?

13) Did this course change the way you see yourself using physics or math, in your life in the future?

14) Did this course change the way you see yourself using art or music in your life in the future?

15) Would you recommend this course to other students, and if so, what age range and what majors?

Appendix C. Dance and Physics Questionnaire

Dear Participant:

I appreciate your willingness to participate in this survey. All answers will be kept strictly confidential and anonymous. Please feel free to add additional comments, or to omit any questions which you do not wish to answer.

You can email your responses to me at jatila@physics.ucsb.edu,

1. Ethnographic Data:

a) What is your present approximate age? Please circle one category.

16-25 26-35 36-45 46-55 >55

b) What is your gender? Female Male

c) What is your primary cultural heritage group or groups, that you most I dentify with?

d) Where did you mostly "grow up"?

Part I: Dance

2. How old were you when you first started dancing?

3. How did you first get interested in dance?

4. How would you describe your current involvement with dance? Please select all that apply.

Completely recreational, no performing or teaching

Primarily recreational, occasionally performing and / or teaching

Primarily as a professional, performing and / or teaching, occasionally attending recreational events

Completely as a professional, no recreational dance Other? Please describe:

5. If you teach dance, how would you describe yourself? Please select all that apply.

Primarily a teacher for recreational dance groups

Primarily a teacher for serious students and professional dancers

Director of an ensemble Choreographer Other?

Please describe:

6. What genres of dance are you currently most involved with?

7. Would you describe yourself as “passionate” about dance (i.e., “gotta dance!”) ? Or is it just something that is “fun” but not imperative for you?

8. How many times / week, on average, would you say that you dance, including classes, rehearsals, recreational groups, and performances?

9. About how many hours/week, on average, would you say you spend dancing?

10. How do you earn your living? Please select one, and fill in the blanks, if appropriate.

Completely from dancing

Primarily from dancing, somewhat from _________________

About half dance, half ____________________

Primarily from _______________, somewhat from dancing

Completely from _____________, I dance for fun

11. Is there a person, or people, who first inspired you to dance? If so, who is this person, and what is/was your relationship to him/her/them? Please describe this person, and how this person (these people) inspired you to want to dance.

Part II: Physics

12. What is your non-dance field? Please select all that apply.

Physics	Engineering	Mathematics
Astronomy	Geophysics	Biology
Medicine	Computer Science	

Other please describe):

13. How did you first get interested in physics (or other science), and at what age?

14. What inspired you to want to "do" physics (in some capacity) for a living? Was there a moment of realization or inspiration that you can recall? Please describe.

15. Is there a person whom you would say is a role model, or hero/heroine for you in physics? Please describe this person, and your relationship to him/her.

Part III: Dance and Physics

16. Please describe how you approach a new problem in your research in physics (or other science) – how you become “inspired” to work on something, and how you proceed. Please feel free to include anything that is relevant to you.

17. If you choreograph, can you describe how you approach a new choreography? What inspires you, how do you proceed, and what motivates your work?

18. Would you say there are similarities in the way you approach a research problem in science and a new work in dance or music?

19. Is there anything that you feel is common to the way you experience dance and physics (or math) in your life that attracted you to both? Or would you say that you were attracted to each for completely different reasons?

20. Were there experiences / influences in the environment in which you spent your early childhood (before age 12) that inspired you in dance or physics, or both?

21. Do you have a website of your own that you would not mind if I have a look at? If so, what is the url? This is strictly confidential information, and I will never reveal it in the context of my research on attitudes toward dance and physics.

Thank you kindly for your answers!

~Jatila

Feel free to add any additional comments: