Symmetry: Culture and Science
Vol. 24, Nos. 1-4, 463-484, 2013

SYMMETRY AS A THEMATIC APPROACH TO PHYSICS EDUCATION

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Fields of interest: Interdisciplinary Education, Visualization & Sonification in Science Education

Relevant Publications:

van der Veen, J. (2012). Draw your physics homework? Art as a path to understanding in Physics Teaching. American Educational Research Journal, April 2012, Vol. 49, No. 2, pp. 356–407. DOI: 10.3102/000283 1211435521.

van der Veen, J. (2007). Symmetry and Aesthetics in Introductory Physics: An Experiment in Interdisciplinary Physics and Fine Arts Education, Ph.D. Dissertation, September, 2007.

Exhibitions:

April 27-30, 2012: Symmetry and Aesthetics in Contemporary Physics: A Physics Art Show. Exhibition of Student Work, College of Creative Studies, University of California, Santa Barbara

March 15-22, 2013: Symmetry and Curved Spacetime: A Physics Art Show. Exhibition of Student Work, College of Creative Studies, University of California, Santa Barbara

Funding for this research has been provided by the Planck Mission Collaboration, Jet Propulsion Laboratory, Pasadena, California and the College of Creative Studies at the University of California, Santa Barbara

Abstract: *The persistent fear of physics motivated the author to explore a new paradigm for introductory college physics that starts with symmetry and the contemporary views of spacetime, and incorporates learning strategies from the arts. Symmetry is the thematic foundation of the course, as the mathematical foundation of physics and the conceptual link between physics and the arts. I describe the curriculum, the use of arts-based teaching strategies and student-generated representations in promoting concept development in physics. Results collected over six years suggest that this curriculum is effective in developing conceptual understanding, and highly appealing for non-physics students as well as physics majors*

Keywords: symmetry, physics education, aesthetic education

1. SYMMETRY AND AESTHETICS IN CONTEMPORARY PHYSICS: A NEW APPROACH TO PHYSICS EDUCATION

1.1 Motivation for Symmetry as a new curricular paradigm

In spite of government initiatives to attract a more diverse population of learners into science and technology, results of a number of studies in the United States (Hazari, et al., 2010; Blickenstaff, 2005, e.g.) and Europe (Sjøberg & Schreiner, 2007, e.g.) suggest that the standard introductory physics curriculum – the gateway course to science and technology - may be a deterrent for many students, particularly females. Indeed, negative popular opinions of physics appear to have been woven into western culture for some time. In an article in the journal Physics Education in 1976, physicist Victor Weisskopf wrote, "*Why is physics as a science considered 'inhuman' by so many people, including some of the students we teach?*" (Weisskopf, 1976, p. 75). Nearly forty years later, one of my own students echoed a similar opinion in an interview I recorded:

> 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 (van der Veen, 2007).

A number of previous studies have offered suggestions as to what can be done to improve the appeal of introductory physics. Osborne (1990) suggested that the complete overrepresentation of Newtonian physics at the expense of contemporary theories presents a distorted view of the world, which fails to address what should be the goals of contemporary physics education: ontology— the nature of reality and how the universe came to be; and epistemology—how we know that which we claim to know. Schreiner and Sjøberg (2005) suggest that the standard school science curriculum, particularly in physics and technology, may be incompatible with youth culture values in western industrialized countries. Studies conducted in Europe as part of the Relevance of Science Education (ROSE) project reveal that students in Western European countries and Japan report that school science neither increased their appreciation for nature nor sparked their curiosity (Sjøberg & Schreiner, 2010, p.11), but "space" and "wonder" are of equally high interest to both male and female adolescents most countries (ibid., p. 21). Levrini (1999) suggests that introducing contemporary ideas about space and time from Special and General Relativity into physics education early on can provide a powerful means of drawing learners into the study of physics. Hill and Lederman (2000) suggest that redisigning the introductory physics curriculum so as to start with Symmetry as the underlying conceptual motivation for the Laws of Physics would be one way of making physics more meaningful, interesting, relevant, and less intimidating for beginning students, as symmetry is a conceptual link between physics and many other domains, including the arts. I took this as a challenge to develop a symmetry-based introductory physics curriculum that utilizes concepts and instructional methods from the arts, along with mathematics, to increase access to physics for all learners.

Thus, three initial questions formed the basis for developing Symmetry and Aesthetics in Contemporary Physics as a new model for the introductory physics curriculum:

1. How can we improve access to physics for all learners by re-inventing the introductory curriculum so as to be interesting, relevant and meaningful in young people's lives?

2. What teaching strategies can we develop that allow students to utilize their full capacities of creativity, imagination, and inquiry so as to make physics appealing and accessible to a more diverse population of learners?

3. How can we bring the values 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 conceptual rigor which is necessary for proper understanding of the practice of physics?

1.2 Previous results of Symmetry and Aesthetics in Contemporary Physics

The course Symmetry and Aesthetics in Contemporary Physics is an experimental course for college students that I developed as part my doctoral dissertation in Education, and first taught in the winter quarter, 2007, in the College of Creative Studies at the University of California, Santa Barbara. It is an interdisciplinary course, designed to introduce students to the ways of thinking about and interpreting physics in the 21st Century. The pedagogical strategies emphasize reading and analyzing works by theoretical physicists and drawing for understanding over the more traditional problem-solving approach in physics education. Results of the first year the course was offered were published as a detailed ethnography of the class (van der Veen, 2007, Ph.D.

dissertation). I found that the inherent hegemony between physics and the arts, which was initially apparent in my physics and art students, parallels the hegemonic stratification of society in terms of dominant culture and subordinate minority cultures. I suggested that arts-based teaching strategies infused into physics education may have the potential to break down cultural barriers to physics by opening up the languages of physics and mathematics to a wider population of learners.

After four years of teaching the course, I discovered a pattern that emerged in the types of drawings students made, that reflects students' preferred learning modalities. I found that students' drawings tend to fall loosely into six categories: abstract-representational, direct-symbolic, metaphoric-analogical, allegorical-creative, flow chart, and hybrid, which are suggestive of the learning styles of engineering students described by Felder and Silverman (1988) and Felder (1993). I find that students' drawings are not only powerful indicators of whether or not they understand a concept, but also reveal their attitudes towards physics as well as their learning styles. Such information is important for the instructor in designing effective teaching strategies for the widest possible range of learners. Detailed analyis of using students' drawing styles to understand their learning styles is discussed in van der Veen (2012).

After six years of teaching this course I reported on the use of students' self-generated representations in promoting conceptual development and meta-representational competence in Special and General Relativity (van der Veen, 2013). I suggest that instructors can utilize students' creative representations to assess their understanding of abstract concepts, and that almost 'at a glance' an instructor can tell whether a student's representation is correct, or contains a fundamental misconception.

In this study I report on the most recent results (winter quarter, 2013) of teaching this curriculum, after six years of modifying and refining the teaching strategies and assignments. I give a brief overview of the curriculum and theoretical frameworks upon which it is based, and focus first on students' representations of symmetry as a general concept, and then on their representations of the symmetries that underlie Special and General Relativity. I show how students demonstrate their understanding of the concepts through their creative representations. Based on students' very positive reactions to the course over six years, I suggest that the dual approach of starting with symmetry and contemporary physics, *and* using arts-based teaching strategies, may be effective in making physics accessible to a wider population of learners.

In Section 2 I briefly describe the curriculum and theoretical frameworks that underlie the pedagogical methods. In Section 3 I present samples of students' art work and commentaries. In Section 4 I present students' reactions, and in Section 5 conclude with a summary and suggestions for wider application of the curriculum and methods.

2. DESCRIPTION OF THE CURRICULUM AND THEORETICAL FRAMEWORKS

Symmetry in physics refers to the concept of 'sameness within change,' and is the basis of all the known laws of physics. Any symmetry is defined by the set of rules that describe the invariance of a system under rotations, reflections, and translations. Historically, when physicists have confronted an apparent paradox, it has been resolved by finding the symmetry which explains away the paradox by a change of perspective. Thus, the search for deeper symmetries in Nature motivates advancements in contemporary physics. Symmetry is also an important concept in human perception, biology, evolution, neuroscience, and chemistry. Symmetry and asymmetry are central to our aesthetic experiences in the arts, and thus provide a natural foundation for an interdisciplinary physics course that incorporates arts-based teaching strategies. Teaching beginning students about Relativity and curved spacetime brings them face to face with some of the ontological questions that motivate contemporary physics at the largest scales. Moreover, teaching about Relativity in its historic context provides the iconic example of how symmetry has come to play a fundamental role in the development of contemporary physics. It also brings to the fore Professor Emmy Noether, whose theorems have played a seminal, yet little known, role in the development of new physical theories. Noether's example provides the opportunity to bring to the fore the discrimination that women in physics have faced historically, and continue to face.

The course, Symmetry and Aesthetics in Contemporary Physics, emphasizes math and the arts as interdependent semiotic systems for making sense out of and interacting with the physical universe. The course is an elective, offered through the Interdisciplinary Studies program of the College of Creative Studies (CCS) at the University of California, Santa Barbara (UCSB). CCS is the smallest of the colleges in the university, in which class sizes are capped at twelve to fifteen students. Interdisciplinary, experimental approaches are encouraged. The course is open to all students in the university, but most who enroll are CCS students. My enrollment has ranged from a minimum of eight to a maximum of twelve, so that after six years a total of 65 students have completed the course.

The curriculum was developed in consultation with several theoretical physicists who work in the field of symmetry in fundamental physics, notably Professors Lawrence Krauss (Arizona State University), Christopher Hill (Fermi National Accelerator Laboratory), and Anthony Zee and David Gross (Nobel Laureate, 2004), both at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. The arts-based teaching strategies are based on Professor Maxine Greene's model of Aesthetic Education (Greene, 2001), and the assessment strategies for evaluating students' creative representations are based on the work of Professor A.A. diSessa regarding student-generated representations and meta-representational competence (diSessa, 2004).

Professor Maxine Greene describes education as a ''process of enabling persons to become different'' by which ''the learner must break with the taken-for-granted, . . . and look through the lenses of various ways of knowing, seeing, and feeling in a conscious endeavor to impose different orders upon experience'' (Greene, 2001, p. 5). Although Greene's original model of Aesthetic Education focused on using arts to teach humanities, the enthusiastic reactions of my students, both via anonymous evaluations and direct communication, suggest that the arts provide a powerful means of bringing to life the objective, abstract world of physics and mathematics.

Drawing for understanding, or having students generate their own representations of abstract concepts, has been shown to help students advance their understanding of principles in science that are difficult to understand (Parnafes, 2009; Parnafes, Aderet-German, & Ward, 2012, e.g.). The term *meta-representational competence* (MRC) was invented by diSessa (2004) to describe students' abilities to go beyond understanding standard representations in science such as graphs, to be able to design and produce their own representations, explain their representations to others, and critique the effectiveness of new representations (p. 293). He further suggests that "learning may implicate developing one's own personally effective representations for dealing with a conceptual domain" (p. 299).

The course begins with interrogating the nature of science, and the nature of mathematics as the language of science. We then look at expressions of math in nature, such as Fibonacci numbers and fractals, then move on to Symmetry and elementary Group Theory as the conceptual/mathematical lens through which to understand contemporary physics. I then introduce the idea that new developments in physics proceed when a symmetry is broken and a deeper, more inclusive symmetry is sought and discovered. With this in mind, we progress from Galilean Symmetry to Lorentz

Invariance and Special Relativity, to general covariance and General Relativity, and finally to the contemporary ideas of cosmology and String Theory.

Readings are assigned from A. Zee's *Fearful Symmetry* (Zee, 2007) as well as articles by Richard Feynman, Albert Einstein, and Mario Livio. Each week students are required to submit critical responses (Reading Reflections) to the readings, which they share in class discussions. For most students, this is the first time they are asked to criticize literary works in physics, instead of simply reading for understanding and solving problems.

Students are exposed to practicing physicists and artists by visiting labs and galleries on campus, and I invite theoretical physicists and artists to visit the class. In my lecture-presentations I utilize examples of artists who have attempted to represent concepts in Relativity (most notably Picasso and Escher), as well as computer-generated visualizations and simulations.

The progression of arts-based assignments begins with students drawing their visualization of an article about the nature of science by Einstein. I use this assignment to introduce students to the idea of using drawing for understanding in physics, and to reflect on their own visualization strategies. Each art assignment is motivated by a drawing prompt, and is based on concepts that have been explored in the readings and class discussions. Students share their work in class first in small groups, then with the whole class, and are required to turn in a written explanation of their artistic representations. Assessment of their understanding is accomplished via dialog between the artist and the audience (consisting of other students plus the instructor), and written feedback from the instructor. I have been assigning four arts-based projects: the Einstein drawing, a demonstration of symmetry, an exploration of curved spacetime, and the final project. The final project is a *physics work of art* in which students are asked to choose a topic they wish to explore in greater depth, and produce a work in the medium of their choice that will be displayed in the art gallery of the College at the end of the quarter. By the time they get to the final project, students have had experience using arts to explore concepts in physics, and have observed physics-based art produced by professionals. The evaluative aspect of the final assignment is to see whether the students can use their art to explain their chosen physics concepts to visitors at a public reception.

3. THE DATA: STUDENTS' REPRESENTATIONS AND EXPLANATIONS OF SYMMETRY IN PHYSICS

The art works presented in this section were all selected from the most recent quarter, January through March, 2013. I selected samples from two assignments: the symmetry demonstration, in which the students are asked to design a representation that illustrates the concept of a symmetry group and explain it to the class; and students' final physics works of art in which they chose to further explore the concept of symmetry in general, and the specific symmetries of Special and General Relativity. The students whose art work is reproduced gave their permission, and all wanted to be credited publicly. They are: Mona Lua, first-year art major; Tai Rodrig, second-year computer science major; Gunnar Weibull, fourth-year computer science major from Sweden, who was spending the year at UCSB; and Ananda Das, third-year physics major. (Many excellent works are not represented here, which will be included in a forthcoming article.)

3.1 Students' representations of Symmetry

A system is said to possess symmetry if the following is true: When you make a change in the system (translation, rotation, reflection, or combinations thereof), OR if you make the same type of change in your viewpoint, the system looks the same (remains invariant). Objects and spaces (characterized by geometries) are classified by the transformations (symmetry operations) that leave them unchanged. After several readings and class discussions about symmetry, including an exploration of the symmetry group of the equilateral triangle and a simple proof that the length of a line is invariant under rotation of x-y axes, students are assigned to design and present a demonstration that illustrates the concept of symmetry as we have defined it, in any medium they choose. My goal for this assignment was to get students to understand the operational definition of symmetry as it is applied in physics, which goes beyond the non-scientific usage of the term 'symmetry' or 'symmetrical' to refer to objects that are bilaterally balanced.

3.1.1 Three-fold symmetry cut out

Figure 1 was created by Mona Lua, a first-year art major, as her symmetry demonstration. She described her piece thus:

> My "snowflake" has three-fold reflection symmetry and three rotational symmetries. It was made by folding a piece of paper in half, then into thirds to make a triangle. Therefore, there are six layers of paper to cut through when folded. Each cut produces three marks in the same relative place on the paper. The marks that are in the same place create the rotation symmetries 120, 240,

and 360^0. Because the paper is folded each cut also creates a mark opposite the fold. The three folds provide the three axes of reflection. I have chosen a theme of bones to highlight how symmetry is present in the very structure of our beings.

Her understanding of symmetry operations is evident in her correct use of rotational symmetries and axes of reflection. Her metaphoric use of the “theme of bones” (apparent in the three skull-like shapes that lie along the three axes of reflection) suggests that she understands the fundamental nature of symmetry.

Figure 1. Cut-out exhibiting three-fold symmetry (three rotation angles and three reflection planes). Artist: Mona Lua, 1st-year art major (female), 2013. Reproduced with permission.

3.1.2 Four-fold computer-generated drawing

Figure 2 was done by a Tai Rodrig, a second-year computer science major, as his symmetry demonstration. He generated his drawing via a computer algorithm that he wrote, and explained his piece thus:

> The picture I made contains several symmetries: You can rotate it by 90, 180, 270, or 360 degrees and it still looks exactly the same. You can reflect it across both the diagonals and it still looks exactly the same. You can reflect it across the vertical and horizontal bisections and it still looks exactly the same. Additionally, if you isolate each of the tessellating pieces they exhibit all of the symmetry operations.

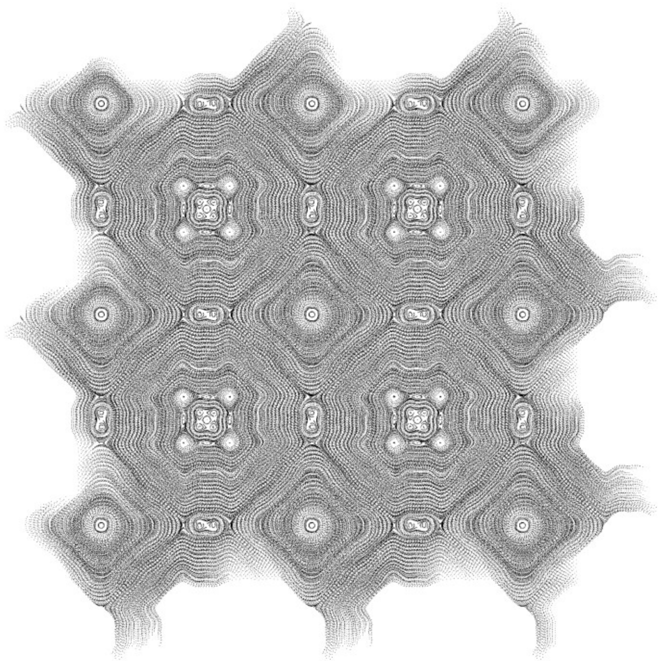

Figure 2. Computer-generated drawing exhibiting four-fold symmetry. Artist: Tai Rodrig, 2nd-year computer science major (male), 2013. Reproduced with permission.

From his execution of the drawing and his written explanation it is clear that he understands the operational definition of symmetry, as he explains the four rotation angles and symmetry axes in his piece as a whole and the individual components.

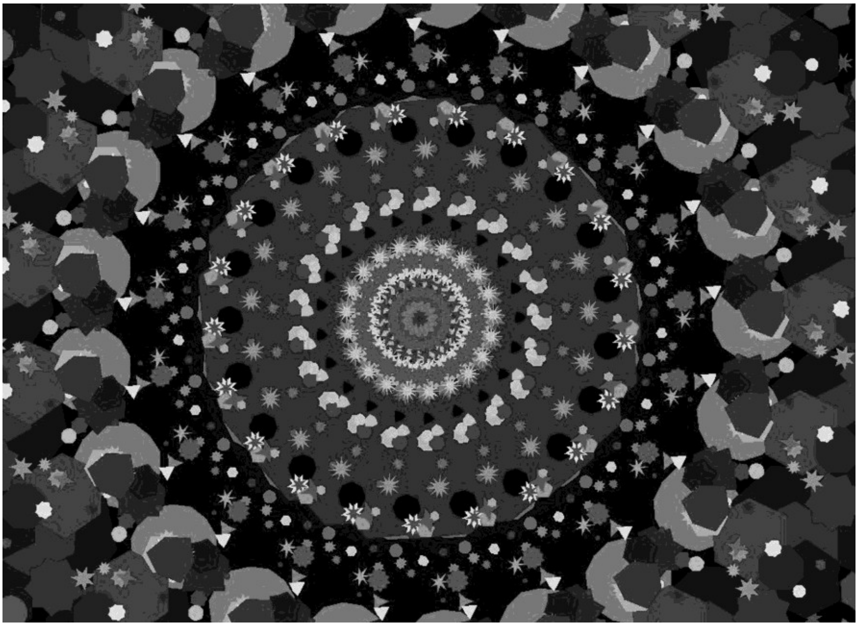

Figure 3. "Symmetry Sprinkles" Screen capture of interactive software written by Gunnar Weibull, 4th year computer science major (male) for his final project. Reproduced with permission.

3.1.3 Symmetry simulation and social commentary

For the final project students have complete freedom to explore any of the concepts we have covered in class, in the medium of their choice. The only requirement is that their artistic representation must illustrate their chosen concept sufficiently well so as to be able to teach the concept to an audience of non-specialists. Over the years a number of students have chosen the concept of symmetry as the theme of their final projects, represented through paintings, sculpture, dance, musical compositions, and computer simulations. Figure 3 is a screen capture of an interactive simulation entitled "Symmetry Sprinkles" by Gunnar Weibull, fourth-year computer science major, as part of his final project. To run the simulation, the user clicks and drags the mouse anywhere inside the screen, and the software generates random shapes that spiral outward in radially-symmetric patterns. His simulation was the centerpiece of a series of works that he created as his contribution to the gallery exhibition. He intended his collected works to be a commentary about physics, as well as his personal explorations of topics discussed in class, which he explained as follows:

> The different pieces explore slightly different concepts that have been discussed in the class. My aim is to get an interaction with the user, which is why I have made the art rather easy to access and humorous (so as not to scare away anyone). I try to convey my view of physics as a playful activity and expose how funky it can be (a fact sometimes well hidden beneath mountains of math and rivers of standardized tests).

One of his cartoon commentaries is shown in Figure 4. In the gallery the original work, drawn on two sides of one paper, was displayed across the gap between two floor-to-ceiling columns, so that the viewer could see it from both sides.

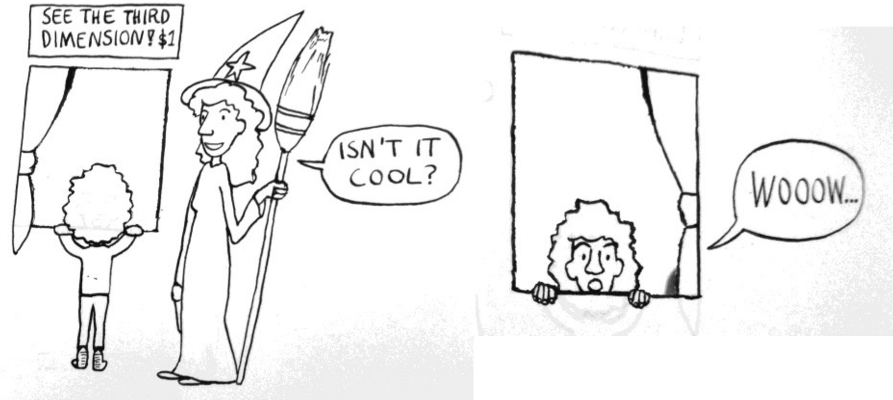

Figure 4. The Window of the Witch. Artist: Gunnar Weibull, 4th year computer science major, 2013. Left: view from 2D into 3D; Right: view from 3D into 2D. Reproduced with permission.

The explanation he wrote for this cartoon, which was hung next to it on the wall, said:

> This piece plays with the fact that a paper can be used to portray our 3D world in a 2D environment, and gives a hint of the wonders we would see if we suddenly got a chance to glance through a window to another dimension (at the quite bearable price of $1. Witches are not very fond of over prices).

I chose to present Gunnar's work (with his endorsement) because his symmetry simulation not only indicates his understanding of the concept, but he has chosen to present his work in the context of a social commentary on physics education. Unlike the traditional approach to physics which he describes as hiding concepts “beneath mountains of math and rivers of standardized tests,” he attempts to convey physics as a “playful activity” and generally accessible “at the quite bearable price of $1.” A major component of this assignment was to be able to explain a physics concept to the general public in an art gallery, and Gunnar chose to use humor to make physics accessible, “so as not to scare away anyone.”

3.2 Students’ representations of the symmetries of Special and General Relativity

Lorentz Invariance, the symmetry of Special Relativity, explains that, although observers moving relative to each other at a constant velocity (approaching the speed of light) will measure different units of length and time when they peer into each other’s reference frames, their measurements will always differ by the same amount. The symmetry rule that governs these measurements is called the Lorentz Transformation, and a ‘Lorentz boost’ to a moving reference frame is effectively a rotation of space and time axes. The radical break of Special Relativity with classical (Newtonian) physics is that space and time are now understood as not independent of each other; rather, space and time comprise a four-dimensional continuum, called *spacetime* by Hermann Minkowski (1907). General covariance[1] is the dynamical symmetry of General Relativity that allows observers in different reference frames to interpret the different physical realities they observe as being due to the presence of gravitational fields. Whereas Special Relativity describes physical reality in the absence of gravity, General Relativity describes the set of transformations that allow two observers in different gravitational fields to interpret the different physical realities they measure as being due to the same underlyng physical laws. The way that spacetime is deformed by gravitational fields is described by Einstein’s (tensor) field equations, the mathematics of which are beyond the scope of this course. However, through readings, discussions, and creating their own representations, students are able to gain a conceptual grasp of curved spacetime and general covariance. The next two pieces were done in fulfillment of the final project, and displayed in the art gallery of the College.

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[1] According to some, General Covariance is not a symmetry. For the purpose of this course I adopted the viewpoint of A. Zee that “the customary usage among physicsits” is to “refer to general covariance simply as a symmetry” (Zee, 2007, p. 83).

3.2.1 Intersecting light cones: Illustrating Lorentz Invariance

The sculpture shown in Figure 5 was created by Ananda Das, third-year physics major. He wanted to create a 3-dimensional representation of the intersecting light cones of two observers in relative motion at a constant velocity. He wrote a multi-page illustrated explanation, which he designed in the traditional physics way of posing a question, confronting an apparent paradox, and then removing the apparent contradiction with a change of reference frame in which the paradox vanishes. Like Gunnar (Figures 3 and 4), Ananda also felt that humor could make the physics concepts more accessible and less intimidating to a general audience.

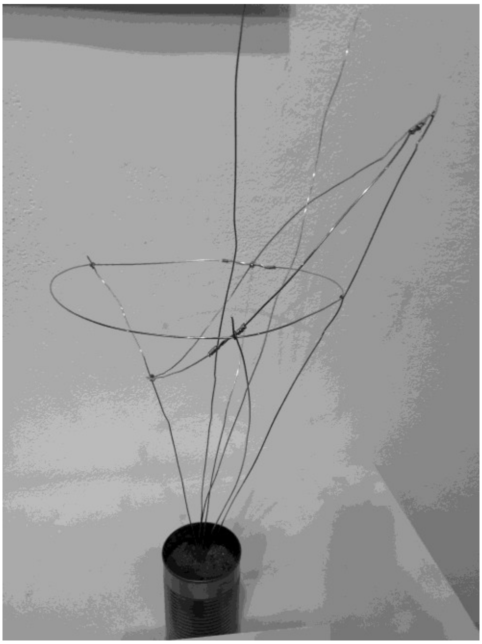

Figure 5. Wire sculpture depicting the intersection of the light cones of two observers in relative motion. Artist: Ananda Das, 3rd year physics major (male), 2013. Reproduced with permission.

In his written description, Ananda motivated his piece thus:

> If a person in the dark emits a flash of light, he perceives himself to be at the center of an expanding sphere of light, but another person running away from

the first will also perceive himself to be at the center of an expanding sphere of light. How can this be? The explanation is that motion can rotate your perception of space and time.

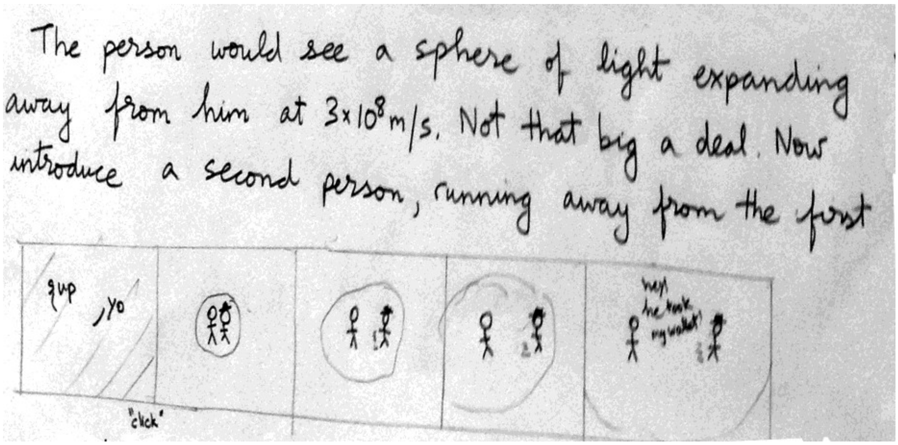

Figure 6. Portion of the explanation of the Light Cone shown in Figure 5. Drawn by Ananda Das, 3rd year physics major. Reproduced with permission. The figure without the hat exclaims, "Hey! he took my wallet!"

In a post-course interview he explained his motivation for creating his piece:

> My motivation behind creating this piece was that Special Relativity confuses everyone, even the physics majors, and I definitely needed to see it three or four times before I really grasped it. And so I wanted to come up with a way to easily demonstrate weird three dimensional, four dimensional concepts that they talk about. And in particular, a certain paradox that I've found interesting, and easy to illustrate as well. I would also include my write-up as part of the art project, because I enjoyed doing it, and I definitely think that humor and simplicity are very important in communicating a deep concept, because I definitely found a lot of people just switch their brains off when someone talks about their physics to them. And it's important to kind of trick them into learning something new.

3.2.2 Illustration of General Covariance

The piece shown in Figure 7 was created by Mona Lua, first-year art major, as a representation of the concept of General Covariance – the dynamical symmetry of General Relativity. In her description she wrote:

> This piece was inspired by the concept of general covariance. Nine drawings were drawn on nine unique grids. The image of the man and woman is distorted and layered one on top of the other. … Each drawing is warped, as spacetime will do, yet still preserves a system and basic foundation.

Figure 7. Booklet of transparencies illustrating the principle of General Covariance. Artist: Mona Lua, 1st year art major (female), 2013. Reprinted with permission.

Mona's representation demonstrates a solid conceptual understanding of the idea that General Covariance describes a set of rules that allow one to interpret the different physical realities observed in the presence of gravitational fields. Her grid of points was the visual / conceptual representation of a set of such rules, and her use of 'slices' across a volume of space shows that she understands the three-dimensional nature of the deformation (neglecting time).

Professor Andrea DiSessa (U.C. Berkeley) coined the term "*conceptual homomorphism*" to indicate "a structural description that, generally, is less detailed than the full structure, but preserves the relevant relationships" (2013, pers. comm.). Mona's piece is a correct conceptual homomorphism of general covariance, as she has conveyed the three-dimensional nature of the warping of space (without time), rather than a deformation of two dimensions *into* the third, as is often depicted in text books as a mass stretching space as if it were a two-dimensional rubber sheet.

4. DISCUSSION

This course began as an experiment to develop an alternative to the standard introductory curriculum that I hoped would make physics more appealing and accessible to a broad spectrum of learners, including students who might be curious about physics, but afraid of the traditional large introductory classes. The success of using symmetry as a thematic approach to teaching physics should be interpreted in the context of an interdisciplinary physics course in which emphasis is placed on drawing for understanding, literary criticism, and other student-generated representations. Mathematical representations and explorations are utilized in class, but not assigned for homework for two reasons: The physics majors are already doing such homework in their other classes, and see this class as a break from their regular routine; and the non-physics majors have not the mathematical skills to be successful at such problems on their own. However, mathematical explorations done in class, in which physics majors and other students work together in groups, seem to be quite successful in promoting understanding among the non-physics majors of the way we use math in physics, without the fear of being responsible for solving problems on their own.

Over the six years I have taught the course, I have continued to refine the curriculum and improve my own understanding of how to use what I have called *arts-based teaching strategies* both to help students visualize abstract concepts, as well as to assess students' understanding of concepts from their creative representations. Overall, students' reactions to the curriculum and methodology have been quite positive in all years, as indicated by their final evaluations. For the instructor, teaching this curriculum is highly rewarding because one can see the excitement students have in learning physics and their satisfaction in creating their own artistic interpretations. Not only do students develop representational competence in physics, but they gain a sense of empowerment and ownership of the concepts. In addition, having students' create their own representations, as opposed to simply having them solve problems and interpret graphs, allows an instructor to identify hidden talent and creativity that may not be apparent through traditional instructional methods. I find that this course has continued to attract a range of students, many of whom otherwise would not have chosen to study any physics in college, and that the students leave with a sense of the wonder of physics, rather than a sense of frustration (noted by Mazur, 1997, p. 3).

4.1 Discovering hidden talents

Anthropologist Sheila Tobias, who has researched social interactions in science in the United States, commented that it is important for science teachers to recognize "talent that is differently packaged from the norm" (Tobias, 2006, p. 10). I find that much of my students' art work is reminiscent of the drawings of highly creative students reported in a famous study by Getzels and Jackson (1962), in which they compared high-IQ and highly creative adolescents in a secondary school in the American midwest. They characterized the highly creative students as having "the ability to play spontaneously with ideas, colors, shapes, and relationships" from which "there arises the hunch, the creative seeing of life in a new and significant way" (p. 53). I suggest that having students design their own representations of concepts allows instructors to identify and encourage highly creative students whose talent may not be apparent through traditional problem-solving methods.

4.2 Developing meta-representational competence

The term meta-representational competence, coined by diSessa (2004), is described succinctly by Heggarty (2011) as "the ability to choose the optimal external representation for a task, use novel external representations productively, and invent new representations as necessary" (p. 1240). DiSessa (2004) suggests that "learning may implicate developing one's own personally effective representations for dealing with a conceptual domain" (p. 299), while Heggarty recommends that "more attention should be paid to teaching people to use, design, and critique external spatial representations, in addition to training their internal visualization abilities" (p. 1241). The data presented in this study are examples of novel representations developed by students. The progression of assignments through the course was designed to have students first understand their personal visualization styles, and then to use their visualization strategies to develop effective ways of communicating their understanding of concepts to others. Through their art projects, and especially the presentation to the public of their final physics works of art, my students demonstrate their meta-representational competence in a range of media and visualization modalities. Other media, not reproduced here, include musical representations, dance, sculpture, and film.

4.3 Empowering students by encouraging creativity

I find that the the art assignments, culminating in the final project, empower students to take ownership of the concepts. They enjoy the art assignments, and in many of the anonymous feedback comments that I solicit each week, students express a desire for more art assignments. Students reflect on their final project in post-course interviews:

> ***Art major, 2013:*** It [the final project] was definitely a new perspective to take, in kind of, um, abstracting the concept to make a work of art.
>
> ***Computer science major, 2013:*** When I was creating it [the final project], I had to … really think about what I was doing. I wasn't just …like… blindly going through it, I had to think what it meant to me, and then take that concept and apply it to…an…artistic aspect.
>
> ***Physics major, 2007:*** My favorite assignment was definitely the final project, because there was just so much freedom in what we could do, that 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.
>
> ***Art major, 2007:*** 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.

5. CONCLUSIONS

Results of the ongoing study of this course suggest that it is indeed meeting the goals of both improving access to physics for non-physics/non-science students, as well as providing a fresh approach for physics majors. Students' ratings of the course continue to be high, averaging 1.2 out of 5 (with 1 being the best and 5 the worst) each year. While I cannot claim to have 'converted' college students to become physics majors, students' comments strongly suggest that Symmetry as a thematic approach to teaching physics, along with the use of arts-based teaching strategies, in an interdisciplinary setting, is appealing to students from a wide range of backgrounds, and thus has the potential to address the problems of lack of appeal and lack of diversity I discussed in the introduction.

> I found this course to be wonderfully exciting. I wish that this class would continue and I could continue to study the math and science in such an integrated way (anonymous final evaluation, 2007).

> Thank you so much for teaching this class. I don't think I've ever been quite so stimulated by a class here as much as your class has done for me. I thought the material was awesome and the readings were great, although difficult at times. Thank you for opening up my mind more! (anonymous final evaluation, 2011).

> I'm really glad that I got to take this class & that classes like this exist. I feel like I learned a lot & that I will retain it because I enjoyed learning it (anonymous final evaluation, 2012).

> This was a really awesome course, truly interdisciplinary. I think using an artistic perspective to learn/interpret physics is really beneficial, and I learned and was way more driven than I would be in a regular physics or art course. The course is more than a sum of its parts. Keep it up! (anonymous final evaluation, 2013).

> The implications of the cross-field connections in this class have been some of the most fascinating I have ever learned about. I have thought about many things I never thought I would think about (anonymous final evaluation, 2013).

> Probably one of the most inspirational classes I have taken. I hope that you keep doing it for many more years (anonymous final evaluation, 2013).

Physics majors appreciate this approach as well, as told to me in a post-course interview by one of the physics majors this year:

> I think I was kind of disillusioned from my other physics classes, and I'm glad I had this class to take, and remind me that physics is cool, and that there's lots of broad concepts out there that we should get excited about. To me, if you add physics and creativity to it, that's the part of physics that I love … instead of "Oh, I can solve an integral which is really hard. 'Yay!'" <laughs>.

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