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Draw Your Physics Homework? Art as a Path to Understanding in Physics Teaching

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The persistent fear of physics by learners motivated the author to take action to increase all students' interest in the subject via a new curriculum for introductory college physics that applies Greene's model of Aesthetic Education to the study of contemporary physics, utilizing symmetry as the mathematical foundation of physics as well as the conceptual link between physics and the arts. The author describes the curriculum and suggests how students' drawings and written commentaries can provide insights into students' preferred learning modalities, promote understanding of abstract concepts through visualization, and reveal students' preexisting attitudes toward science. Outcomes align with the goals of improving students' attitudes toward physics, indicated by their comments, written work, and results of the Maryland Physics Expectations Survey.

Keywords: physics education, aesthetic education, interdisciplinary education, arts-integration, symmetry, contemporary physics

In spite of government initiatives to attract a more diverse population of students into science and technology, research conducted by the American Institute of Physics (AIP) suggests that although the percentages are up from the 0% to 3% range in 1958 (the first year that such data were collected), there is still a dearth of women and minorities in physics and engineering in the United States (AIP Statistical Research Center, n.d.-a, n.d.-b; Ivy & Ray, 2005). In 2008, 17% of all physics PhDs in the United

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States were awarded to women while 83% went to men (AIP Statistical Research Center, n.d.-b). When the numbers of PhDs in physics in the United States in 2008 are broken down by race and ethnicity, only 1% were awarded to Hispanic Americans, 1% to African Americans, while 41% went to White Americans and 54% to foreign nationals (AIP Statistical Research Center, n.d.-a). Hazari, Sonnert, Sadler, and Shanahan (2010) cite recent studies that show that physics lags behind biology and other sciences in awarding bachelor's degrees to women, so that the relative number of female students graduating with degrees in physics has actually declined in proportion to the number of women in other sciences. In addition to the persistent lack of female and minority students, they also note a decline in the total number of degrees (to men and women) awarded in physics between 1983 and 2005 relative to other sciences, indicating general lack of interest in studying physics among all students. It behooves us to ask: Why should this be so?

Negative popular opinions of physics appear to have been woven into our 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). A generation later, a quote from an interview with a female sculpture major at a California university indicates that students' perceptions of physics may have not changed much over the years:

> 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. (van der Veen, 2007)

The Possible Role of the Introductory Physics Sequence in Maintaining the Status Quo

The standard introductory physics course begins with Newtonian mechanics, in a curriculum that was established in the 1950s in response to the Western world's race for space (Brekke, 1995; Stuver, 2001). Osborne (1990) suggested that although Newton's contributions were certainly revolutionary for his time, they represent a world view that is "relentlessly deterministic, linear and remote from human action or influence." He further suggested that the complete overrepresentation 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 contemporary physics education: ontology—what is the nature of reality and how did the universe come to be?; and epistemology—how do we know that which we claim to know? Recent studies suggest that the way physics is taught to beginning students may play a nontrivial role in both the persistent gender bias as well as the declining interest in studying physics among college students. Blickenstaff (2005) examined 30 years of research on the gender imbalance in physics in the United States and concluded that the very nature of science may be a significant contributor to what has been called the "leaky pipeline," whereby women have greater attrition rates than men in physics. In a study of nearly 4,000 students from 34 randomly selected American colleges and universities, a lack of self-identification with physics was one of the most potent deterrents to studying physics, particularly for girls (Hazari et al., 2010).

The ongoing Relevance of Science Education (ROSE) project in Europe finds similarly negative attitudes toward school science among 15-year-old pupils in Northern Europe and the United Kingdom (Sjøberg & Schreiner, 2010), and towards physics in particular (Kessels, Rau, & Hannover, 2006). After surveying adolescents in this age group in 34 countries in Europe, Africa, and the Pacific Islands about their attitudes toward science and technology, Schreiner and Sjøberg (2005) suggest that the perception of science as taught in schools may not be compatible with youth culture identity in contemporary Western societies and that perhaps young people perceive the identity of an engineer or a physicist as "incongruent with their own" (p. 13). Their survey also suggested that boys prefer topics such as explosives and machines, which figure prominently in the introductory physics curriculum with its heavy emphasis on Newtonian mechanics, while girls prefer topics relating to biology, health, ethical, aesthetic, and "New Age" concerns (Sjøberg & Schreiner, 2007).

In a preliminary study (not yet published) I interviewed second graders in a public school in Santa Barbara, California, after they attended a physics demonstration show put on by students from the local university. I found that girls and boys were equally interested in the demonstrations, but when asked what they want to be when they grow up, the majority of boys responded with occupations that deal with adventure and high risk (e.g., swat team, fire fighter, super hero), while the girls responded with a wide range of occupations that included medicine, education, entertainment, and the arts. Introductory physics, with its emphasis on Newtonian mechanics, relies heavily on scenarios involving projectiles, collisions, explosions, sports, machines, and military applications, which correlate with the adventure and high-risk occupations chosen by the boys I interviewed.

Recent research suggests that topics from contemporary physics are equally of interest to girls and boys and thus may provide a more gender-neutral entry point for introductory physics. Sjøberg and Schreiner (2007) noted that both girls and boys reported equally high interest in studying topics from contemporary physics, including black holes, space science, unsolved mysteries in outer space, philosophical issues, and phenomena that scientists still cannot explain. Angell, Guttersrud, Henriksen, and Isnes (2004) reported that unlike the topics from standard school science, adolescents have the sense that topics from contemporary physics relate to their own interests and personal lives.

These findings lead me to suggest that it is time to change the way in which we introduce physics to beginning students if we are truly interested in promoting at least a more equitable gender balance in the physics community in future generations.

Aesthetic Physics Education: A New Approach to Introductory College Physics

> They said, "You have a blue guitar,
>
> You do not play things as they are."
>
> —Wallace Stevens (1982) as quoted by Greene (2001)

In an editorial in 2006 in *Physics Today*, the monthly news-and-opinion publication of the American Institute of Physics, anthropologist Sheila Tobias suggests that equal access to physics may be achieved through a new pedagogical paradigm, within which teachers can recognize a talent for physics that is "differently packaged from the norm" (p. 10). In another editorial in the same journal, physicist Kent Eschenberg (2006), quoting a 1985 study of scientists and artists by psychologist Robert Root-Bernstein, correlates the "ability to imagine new realities," which is the basis for new discoveries in science, with "what are traditionally thought to be nonscientific skills . . . usually associated with the arts, music, and literature" (p. 10). With these comments in mind, and the sense that physics—a profoundly creative endeavor—is still perceived as inaccessible by so many, the following question motivated this study: 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 that 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, without losing the qualities of honesty, objectivity, and repeatability, expressed through the language of mathematics, that define physics as a way of knowing and seeing?

Maxine Greene's Aesthetic Education provides the philosophical framework for a new pedagogical paradigm for introductory college physics that, I suggest, has the potential to attract students who are "differently packaged from the norm." In *Variations on a Blue Guitar*, Greene (2001) defines *aesthetics* as "the way in which a work of art can become an object of experience, and the effect it then has in altering perspectives on nature, human beings, and moment-to moment existence" (p. 5). She 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" (p. 5). For Greene, education should be "an initiation into new ways of seeing, hearing, feeling, moving" and should "nurture a special kind of reflectiveness and expressiveness, a reaching out for meanings, a learning to learn" (p. 7). Unfortunately, for many students, their experience with introductory college physics leaves a permanent sense of frustration (Mazur, 1997).

Greene (2001) proposed a set of Capacities for Aesthetic Learning as the desired outcomes of Aesthetic Education: Noticing Deeply, Embodying, Questioning, Identifying Patterns, Making Connections, Exhibiting Empathy, Creating Meaning, Taking Action, Reflecting and Assessing (Holzer, 2005). I suggest that the first five Capacities (Noticing Deeply, Embodying, Questioning, Identifying Patterns, and Making Connections) are, in essence, nondifferent from the goals of any introductory physics course, since physics represents a new way of seeing the world and requires students to develop a new vocabulary with which to interpret experience. I suggest that the next four Capacities (Exhibiting Empathy, Creating Meaning, Taking Action, and Reflecting and Assessing), goals of contemporary education that seeks to promote a sense of social justice, should also be goals of contemporary physics education if we as a community of physics educators are to redress the problems of equity, diversity, and the sense that physics is "scary" and "inhuman."

Aesthetics is not part of the lexicon of physics education, yet physics as it is practiced by professionals does seem to be motivated by a certain sense of aesthetics. Nobel Laureate Steven Weinberg (1992) asserts:

> 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 for 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. (p. 130)

I suggest that an introductory college course that incorporates learning strategies from the arts into the teaching of physics, and which *begins* with the 20th-century world view and *later* addresses Newtonian mechanics, may be effective in attracting a more diverse population of students than the present curriculum.

About This Study

This article reports on the preliminary results of teaching an experimental college-level curriculum in Aesthetic Physics Education. This study began as a dissertation project in the fall of 2006. The initial experiment was conducted during the winter quarter (January through March) of 2007 at the University of California Santa Barbara (UCSB), a public university in California, and reported in van der Veen (2007). I had the enthusiastic cooperation of the dean of the College of Creative Studies (CCS), a small honors college within the larger university, to experiment on his students, as CCS encourages faculty to develop interdisciplinary, experimental courses. My course, Symmetry and Aesthetics in Contemporary Physics, which I first taught in 2007, received such high evaluations from the students that I have been invited to teach it each year. I have taught it again in 2008, 2010, and 2011, with a hiatus in 2009 while I was teaching out of state. In the second section I briefly describe the rationale for a symmetry-based physics curriculum and the theoretical frameworks that support the idea that Aesthetic Physics Education has the potential to promote greater access to physics and cite previous studies that support the use of arts in promoting access to physics, math, and engineering education. In the third section, I briefly describe the curriculum and the demographics of the students. In the fourth section, I discuss an application of drawing for understanding in physics and how students' drawings, in conjunction with their written work, can give insight into their preferred learning modalities, their attitudes toward physics and physicists, as well as their understanding of a reading assignment. I follow several students' progressions through the course, as demonstrated by some of their other writings and physics-art projects, which indicate their various transformations in attitudes and conceptual understanding. In the fifth section, I suggest further research that would build on these preliminary results and discuss possible implications of Aesthetic Physics Education for increasing diversity in physics.

Theoretical Frameworks

The conceptual framework for a symmetry-based introductory physics curriculum was primarily inspired by Lawrence Krauss's (1993/2007) book *Fear of Physics* and by Anthony Zee's (1999/2007) *Fearful Symmetry*. Lengthy discussions with Professors Krauss and Zee (both theoretical physicists), as well as e-mail conversations with Professor Christopher Hill of the Fermi National Accelerator Laboratory (Fermilab), helped clarify some of the teaching strategies. Critical discussions with Professor David Gross, Nobel Laureate and director of the Kavli Institute for Theoretical Physics (KITP) at the University of California Santa Barbara, provided additional strategies for tying together topics in physics with the thread of symmetry.

The pedagogical model that informed the design of this curriculum is Greene's (2001) model of Aesthetic Education, as discussed in the previous section. Support for Aesthetic Education as an educational paradigm that has the potential to increase access to physics can be found by combining the following models: Multiple Worlds Theory (Phelan, Davidson, & Yu, 1993), which illuminates the difficulties that minority students face when attempting to navigate the boundaries and borders that separate their home worlds from the world of the dominant culture in public schools; sociolinguistic theories of language and power (Bourdieu, 1977); studies that suggest that the discourse of physics, which includes the language of mathematics, serves to set physicists apart from everyday interactions (Bazerman, 2000, among others); and the historic importance of visualization in discoveries in physics (Holton, 1996; John-Steiner, 1997; Miller, 1989).

Aesthetic Education as a Means of Reducing the Barriers Presented by the Discourse of Physics

I suggest that incorporating teaching strategies from Aesthetic Education in introductory college physics can assist students in overcoming some of the difficulties of entry into physics that are associated with the way physicists use language. The discourse of science presents borders that separate science, particularly physics, as a speech community (Gumperz, 1968) by virtue of its specialized language. The discourse of physics, which includes the language of mathematics, sets physicists apart as a privileged group (Traweek, 1988), which often leads to a general mistrust of physicists (Bazerman, 2000), yet, in order to understand physics, students must first learn to use language in the way physicists do (Hestenes, 1998; May & Etkina, 2002). This language barrier can be especially problematic for minority culture students (Aikenhead, 2002; Brown, Kloser, & Henderson, 2010; Lee, 2003; Phelan et al., 1993).

According to the Multiple Worlds Theory of Phelan et al. (1993), students from minority culture home worlds must make a transition to the dominant culture of the school world, with language being one of the barriers. Corson (2001) discussed the use of "high status vocabulary" as being problematic for minority culture students in dominant culture schools and recommended that managing discourses in school can be a powerful means of ameliorating inequalities. I suggest that the dominant position of sciences over arts in education resembles the hegemonic positioning of majority and minority culture students as described by Phelan et al.

Eisner (2002) describes the origins of the cultural dominance of science over the arts as arising from the Enlightenment period in Western society, which was heavily influenced by the emergence of Newtonian physics:

> 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)

I have observed, over the 4 years I have been teaching this course in an interdisciplinary setting, that even in a culturally homogeneous group of academically high status students, the same difficulties with language exist for arts-oriented students relative to physics as exist for minority culture students in a majority culture school relative to dominant culture discourse (van der Veen, 2007). I suggest that incorporating arts-based learning strategies of Aesthetic Education can help reduce barriers presented by language. As one of the art students in the course, a White female, said in a post-course interview:

> [At first] 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 an issue for me. Taking the class has opened the way I perceive my world . . . because my perception of my existence and of the world is different. (Female art major, 2007)

Aesthetic Education as a Means of Facilitating the Language of Math

I suggest that the incorporation of cognitive strategies and ways of knowing from the arts in concept development in physics can help students learn how to visualize the relationships that are described by the unfamiliar language of mathematics. Hickman and Huckstep (2003) compared math to a language, in that once taught the rules of grammar, a student should be able to extract meaning from symbolic sentences (equations) and construct his or her own syntactically correct sentences, follow logical arguments, and apply descriptors to new situations. Mathematics in physics education can be compared to Bourdieu's *langue* in the sense that facility with math-as-a-language represents not only linguistic competence in physics but also represents the symbolic capital that defines a student's position within the social hierarchy of a physics class. According to Bourdieu (1977), "All particular linguistic transactions depend on the structure of the linguistic field, which is itself a particular expression of the structure of the power relations between the groups possessing the corresponding competences" (p. 4). The hegemony of math-speakers and non–math-speakers emerged in some of the remarks of my students in their essays:

> Physics major (male): 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.
>
> Art major (female): 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.
>
> Art major (female): Not knowing how the other half lives makes physics seem inaccessible to the commoner, which is not necessarily true.

The potential of incorporating learning strategies from Aesthetic Education for changing these attitudes is suggested by some of the final comments of the students. The art major quoted previously commented in her final essay:

> 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.

Equations represent rich and sophisticated schema that a student can recall to give almost instantaneous access to a complex concept. A schema, defined as "a cognitive construct that permits us to treat multiple elements of information as a single element, categorized according to the manner in which it will be used" (Sweller, 1999, p. 10), can be anything from an apple to Faraday's electric field lines to Einstein's field equations. Thus, the languages of the arts can provide a means of helping students visualize the relationships in the physical world that are described by mathematics. As one art major (White female, third year) wrote in one of her weekly reading reflections,

> Perhaps anyone who is interested in physics should first undergo a basic math training so that equations make sense, and also a "language course." In this course, students would be taught metaphors with which they can understand and remember what terms like "a volt" or "symmetry" actually mean. But it is not a description that is memorized for each term, but a picture.

The Importance of Visualization in Physics Education

Physics addresses phenomena that span a range of 40 orders of magnitude in scale, only a tiny fraction of which are directly accessible to our sensory perception. The rest must be imagined through symbolic representations: equations, images, and specialized language. Visualization has been seminal in the development of Western science, and mathematics provides a powerful nonverbal language that allows us to visualize phenomena in the physical universe that we cannot experience directly. Bruno Latour's (2002) 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" is certainly applicable to the way physics is practiced today.

A useful concept in physics teaching, which was first developed by 19th-century Swiss educator Johann Heinrich Pestalozzi (1746–1827), is *Anschauung*: mental imagery developed by abstraction from phenomena that have been directly experienced (Miller, 1989; Pestalozzi, 1805/1894). 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, 1805/1894, p. 85). In other words, knowledge evolves from confusion to definiteness, from definiteness to plainness, and from plainness to clarity (Pestalozzi, 1805/1894). Pestalozzi advocated a threefold 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 (Pestalozzi, 1805/1894). Einstein himself was trained in this method of *Anschauung* in high school at the Kantonsschule at Arrau (Miller, 1989), and Pestalozzi's influence is evident in his description of the nature of science in his 1936 (2003) essay "Physics and Reality," which I have students read and draw for the first homework assignment.

Drawing as a Means of Concept Development in Physics

Drawing is a means by which a learner (artist) can get in touch with and express her or his own inner language, and is thus a way to connect students' internal translations of external experiences through symbolic representations. Although most of the research on the use of drawing for understanding has focused on primary education, I suggest that the use of drawing for understanding is entirely appropriate for introductory college students, who may harbor completely naïve interpretations of concepts in physics based on prior assumptions, misunderstanding of texts, or simply a lack of previous exposure to physics.

Several studies reported by Rinne, Gregory, Yarmolinskaya, and Hardiman (2011) suggest that the use of arts as a teaching methodology leverages a number of factors that promote comprehension and long-term memory. Edens and Potter (2003) demonstrate that students who were given the opportunity to draw their understanding of concepts related to the principle of Conservation of Energy, concurrently with verbal descriptions, performed better on tests than students who were given only verbal descriptions. Based on the results of their study and others, they suggest that "visual-based instructional strategies may be particularly useful for concepts associated with non-observable scientific concepts" (p. 142).

Brooks (2009) discusses drawing in teaching science to young children as a means of assisting them to move from linking concepts to objects at a basic, recitative level to a more metacognitive understanding that promotes higher level thinking. Drawing on the methodology of Vygotsky, Brooks uses young children's drawings of concepts in science to better understand the way children think about science. She suggests that drawing can help children bridge the gap between naïve thinking and scientific thinking, between understanding that is bound to sensory experience and more abstract, symbolic thinking. In the fourth section, I will demonstrate how art-making in a college class has been useful in both understanding how older students think about science, as well as in development of abstract concepts.

Kendrick and McKay (2002) suggest that children's drawings reveal a great deal about the literacy narratives they bring with them to school. Peterson (2005) reported on a study of 250 elementary students and 70 graduate students in which a combination of students' drawings about topics dealing with science and talking with students about their drawings yielded valuable information about how the students process and retain information, as well as their attitudes toward science. Chambers's (1983) fascinating study of more than 4,800 elementary students in the United States and Canada suggested that as students grow up, from lower to upper elementary school, their perceptions of a scientist increasingly approach the 20th-century "standard" image of the man in the white lab coat. The same result—that students' perceptions of who is a scientist and what constitutes the domain of science—was obtained by She (1995) in a study of 289 elementary and middle school students in Taiwan. She concluded that one of the greatest influences on how young students perceive science and scientists comes from the images and topics discussed in their school text books, which is not surprising, as text books tend to reproduce the cultural norm (Gosling, 2004).

In a study of an elementary classroom, Crafton, Silvers, and Brennan (2009) suggest that students' drawings, used in conjunction with reading, writing, and talk, serve to mediate new understandings of self and the world in young children. Lemke (2000) advocated the importance of developing multimodal representations, or "multi-literacies," in science education that include verbal, mathematical, visual, musical, and choreographic.

The success of interdisciplinary, multimodal instructional methods at the college level in making physics accessible to a broader population of students has been reported in several previous studies. Dartmouth's Math Across the Curriculum (MATC) program was successful in attracting a diverse population of students, averaging more females than males over the 5 years the program was offered (Korey, 2000). The MATC evaluation team reported that based on surveys and individual interviews, the courses in the program were successful in expanding students' understanding, awareness, and appreciation for math as it relates to art, music, literature, and society in general (Korey, 2000). An important realization reported by the Dartmouth faculty who taught in the MATC program 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 that facilitated their feeling more confident about their math abilities (Korey, 2000).

Faculty who teach in the Interdisciplinary Center for Arts and Technology at Connecticut College report similar results with the students from arts and computer science who enroll in their program (Izmirli & Baird, 2002). Students who enter the program from arts backgrounds are initially uncomfortable in a technology-based environment but report greater self-confidence regarding math and technology after taking computer science courses; similarly, students who enter the program from computer science backgrounds report a greater appreciation for the arts after working in the interdisciplinary arts-sciences environment (Izmirli & Baird, 2002).

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. The students who have taken my interdisciplinary physics course over the 4 years I have taught it report similar changes regarding their attitudes, in that arts and humanities students report a greater appreciation for physics and math and the human side of physics. Similarly, physics students report a greater appreciation for the arts and the rigor involved in making art. Based on previous studies, as well as analysis of my own students, I suggest that the methods of Aesthetic Education applied to physics teaching can have a potentially transformative effect in changing students' perceptions of science and their attitudes toward science and scientists.

The Experiment

A Brief Description of the Students

UCSB is a public university situated in central coastal California, with a total undergraduate enrollment of more than 18,000. According to the UCSB website (http://bap.ucsb.edu/IR/UCSB_Portrait.pdf), 95% of the undergraduates come from California, with 4% out of state and 1% from other countries; 53% are female, and 47% are male. Of the undergraduates, 51% identify as White, 17% as Asian or Pacific Islander, 21% as Hispanic, and 3% as African American, with 7% "unknown" and 1% foreign.

I teach in the Interdisciplinary Studies program of the College of Creative Studies, the smallest of three undergraduate colleges within the university. All CCS classes are intentionally kept small, with a maximum of 25 and an average enrollment between 10 and 12 students per class. Although my course, Symmetry and Aesthetics in Contemporary Physics (hereafter referred to as Symmetry), is open to all undergraduates, the majority of students who have enrolled in the course have been from CCS, which has fewer requirements and more flexible grading options than the other colleges. I have taught Symmetry during the winter quarter (one quarter is equal to 10 weeks of instruction) in 2007, 2008, 2010, and 2011, and it is planned again for 2012. (During 2009 I was out of state, teaching at another university.) Symmetry is an elective, outside the regular physics department; thus, the students who enroll are fulfilling a curiosity rather than a requirement. In order to publicize the course, I post flyers around campus and also send announcements to the undergraduate advisors of the various departments, which they then send out to their students.

A total of 44 students (25 male, 19 female) have taken Symmetry over the 4 years it has been offered. Table 1 shows the distribution of students by gender, year in school, major, ethnicity, and home college. The average class size was 11 students. Of the 44 students who have taken Symmetry in 2007, 2008, 2010, and 2011, 57% were male and 43% were female, with the greatest number of females in 2011. In addition, 84% of the students who elected to take Symmetry have been White, 9% Latino, and 7% Asian. At this time I have no explanation as to why the demographics of Symmetry do not more closely reflect the demographics of the student body as a whole. Because the course is an elective, the title naturally attracts a self-selected sample of students with both an interest in the subject ("high task value") and an expectation that they will succeed in the course (Duschl, Schweingruber, & Shouse, 2007, p. 198). The question of why such a course title and description should attract a student sample that is "more White" than the general student body is reserved for a separate line of inquiry.

A Brief Description of the Course

Symmetry and Aesthetics in Contemporary Physics is an interdisciplinary, introductory college course, designed to introduce students to the ways of thinking about, interacting with, and interpreting nature that are important for the practice of physics in the 21st century.

Why symmetry? The reason for beginning with the concept of symmetry is that symmetry and asymmetry are motivating principles that are common to both physics and the arts and thus provide a basis for opening the dialog between the scientific/mathematical and artistic/humanist approaches to learning. In addition, beginning with symmetry as the mathematical basis for all the Laws of Physics provides an opportunity to foreground Professor Emmy Noether, little-known contemporary of Einstein, whose mathematical theorems provided the proof that General Relativity was

Table 1
Demographics of Students Who Took the Course Over 4 Years

Gender	2007	2008	2010	2011
Males	7	9	6	3
Females	4	3	4	8
Year in college				
First year	5	2	0	1
Second year	0	8	5	3
Third year	2	1	4	2
Fourth year	4	1	1	5
Major				
Physics	6	2	5	1
Geology	1			
Biology		2	2	1
Art	3	3	1	1
Math		3	1	1
Computer science		1		
Psychology, biopsychology		1		4
Music				1
Humanities	1		1	2
Ethnicity				
Euro/American	11	7	8	11
Latino		2	2	
Asian		3	0	
Home college				
Creative Studies	10	10	9	3
Letters and Sciences	1	2	1	7

consistent with the principle of Conservation of Energy (Byers, 1996). Noether suffered discrimination both as a female and because she was Jewish, and left Germany in the 1930s for America. Thus, bringing Noether into the narrative of physics at the introductory level is also important in potentially changing the perception of women in physics.

The course begins with the contemporary view of spacetime, motion, and gravity, rather than starting with the Newtonian mechanistic view. Levrini (1999) suggests that introducing the contemporary ideas about space and time into physics education early on can provide a powerful means of drawing learners into the study of physics because it interrogates "pre-scientific" concepts of space and time that have historically been at the center of cultural debates, and thus of general human interest. More importantly, space and time are historically of concern to other disciplines such as art, literature, and philosophy and thus can be a powerful bridge to other subjects, allowing for a comparison of the physics ways of looking at space with other points of view (Levrini, 1999).

The instructional methods and classroom activities incorporate strategies from art, music, literature, mathematical derivations and physics demonstrations, guest lecturers and field trips, and student-led collaborative projects and presentations. Overall, the course emphasizes both math and the arts as interdependent semiotic systems for making sense out of and interacting with the phenomenological universe. Throughout the course I incorporate various ways in which artists have explored math and physics in their work. The first guest lecture, usually in the second class meeting, is presented by the Artist in Residence at the Kavli Institute for Theoretical Physics on campus, who demonstrates his methods of creating algorithmic art. This presentation introduces students to the idea that art can be an expression of mathematics. During the first part of the course, I explore various expressions of math in nature, such as the Golden Ratio, Fibonacci series, and fractals. In the second part of the course, we analyze paintings by the 20th-century artists Pablo Picasso and M. C. Escher in which these artists attempted to represent concepts from Relativity Theory on canvas. In particular, when discussing Einstein's proof that there is no simultaneity of events for observers in relative motion, we analyze in detail Picasso's *Les Demoiselles d'Avignon*, and in discussing the way that gravity is represented in General Relativity, we analyze some of the paintings of M. C. Escher that deal with this topic. Analyzing the way in which artists have attempted to express mathematical ideas gets students to realize that making art for the purpose of exploring a concept in physics is just as valid as drawing a diagram and that the artist is not bound to a literal representation. For most, this is a new concept.

The assignments include: weekly readings and written reflections on those readings, which are discussed in class; three drawing (or alternate form of representation) assignments based on the readings; a symmetry demonstration in any medium (art, music, movement); and a final project in which students are asked to create a "physics work of art" that explores and expresses one topic that most interested them during the quarter, in any medium they choose, and present it to the class. The classroom activities include student-led discussions in small groups, instructor-led discussions involving the class as a whole, instructor-led lecture-presentations, student presentations, and art-math projects done in small groups. To introduce students to professionals who are involved in art and physics research, in addition to inviting guest lecturers to class, I also organize several "field trips" around campus: a visit to the art gallery in the Institute for Theoretical Physics with a tour led by the Artist in Residence; a visit to the lecture-demonstration room behind the main physics lecture hall, with a presentation of relevant demonstrations by the department's lecture-demonstration expert; and a visit to the Media Arts Technology center, with a demonstration in the UCSB AlloSphere, an immersive laboratory designed for multimodal representation of multidimensional data, to demonstrate artistic expression of mathematical physics through media arts technology in a 3D immersive space.

At the end of each class I ask the students to write anonymous "exit-card comments," in which I ask them to give me feedback, ask questions, or make requests. This feedback allows me to make adjustments in the course in response to their needs, and gives the students a sense of agency in their own learning.

Visualizing the Process of Science: Einstein's 1936 (2003) Essay "Physics and Reality"

Each year that I have taught this course, I use the first homework assignment to introduce the idea that one can use drawing as a means of understanding in a physics class. At this point the students have had one introductory lecture that included a discussion of the nature of physics as an attempt to make sense out of the universe and ways in which abstract ideas in math that, once discovered, "appear" in Nature, such as the Golden Ratio, Fibonacci series, and fractals. For the first homework assignment, I ask students to read Einstein's (1936/2003) essay "Physics and Reality," draw the way they visualize Einstein's description of the process of science, and write an explanation in their own words. I chose this article because Einstein gives an explanation of the nature of science from a physicist's point of view, using richly descriptive language that lends itself to being drawn. In addition, reading Einstein's own words provides a glimpse into the way he thought in images. In a letter to mathematician Jacques Hadamard in 1945, Einstein wrote:

> 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 images which can be voluntarily reproduced or combined. (Hadamard, 1945, p. 142)

At the time this drawing assignment is given, we have not yet analyzed famous works of art in which the artist attempted to express concepts in physics. I want the students to get in touch with their own internal visual language and work directly from Einstein's rich description to express the way in which they see what he is trying to say and then share their vision with the class.

Einstein (1936/2003) starts with the premise that to understand the process of science, one must first understand the nature of thinking, as "the whole of science is nothing more than a refinement of every-day thinking." He then asserts that what we call "reality" is nothing more than the agreed-upon existence of a “real external world,” which is postulated by means of the symbols we develop to express, codify, and unify our sensory experiences of it. Rather than postulating an absolute external reality, Einstein says that it is impossible to separate with certainty the real external world from our internalized conception of it, at the same time remarking on the mystery that through human thought, we can comprehend the universe.

> 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, 1936/2003)

He goes on to describe the process of making sense out of the totality of sensory experiences by connecting them through layers of conceptual relationships:

> The aim of science is, on the one hand, 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, 1936/2003)

In Einstein’s (1936/2003) view, primary concepts are connected directly to sensory experiences but lack in “logical unity.” They are then connected to each other through a secondary level of concepts, which has a higher degree of logical unity, but is removed from direct sensory experience, and which is connected through a still higher layer.

> Further striving for logical unity brings us to a tertiary system, still poorer in concepts and relations, for the deduction of the concepts and relations of the secondary (and so indirectly of the primary) layer. Thus the story goes on until we have arrived at a system of the greatest conceivable unity, and of the greatest poverty of concepts of the logical foundations, which is still compatible with the observations made by our senses. . . . While wrestling with the problems, however, one will never give up hope that this greatest of all aims can really be attained to a very high degree.

Einstein’s (1936/2003) writing is full of analogies and visual metaphors. For example, he describes the connection between sensory experiences and logical concepts not as a vague abstraction, but as a direct connection:

> The relation is not analogous to that of soup to beef but rather of check number to overcoat.

His writing thus lends itself to being interpreted visually and is reminiscent of Pestalozzi’s (1805/1894) description of the process of learning as making sense of the “sea of confused sense impressions, flowing one into the other.”

Moreover, in spite of the dated language (which, admittedly, some students find tedious to wade through), his conclusion is relevant to the true nature of physics, namely, that the practice of physics may be messy, full of false starts and inconsistencies, but physics as a way of knowing is held in high esteem by virtue of its theoretical validity, even as it is constantly evolving.

> We have to deal, however, with the science of today, in which these strata represent problematic partial successes which support one another but which also threaten one another, because today's system of concepts contains deep-seated incongruities. (Einstein, 1936/2003)

The intention of this assignment is twofold: to set the tone for the study of symmetry as the mathematical and conceptual foundation of the study of physics, as symmetry principles represent that highest level of abstraction Einstein describes, and to establish the validity of using drawing and visualization in understanding concepts in physics. Most students report that this assignment represents the first time they have been asked to draw their understanding of an article, especially in a science class. Some report that it was difficult to get started, but once they did, the drawing flowed easily. Some report that they visualize concepts and equations naturally, so that although they had not been asked to draw their understanding in previous courses, the assignment felt quite natural. Others took this opportunity to express not only their visualization of Einstein's article, but their disdain for conventional science teaching. In addition, over the 4 years that I have given this assignment, I have observed that there are certain categories into which students' drawings tend to group, which are suggestive of learning preferences, and that individual students' drawing styles remain fairly consistent throughout the course. Thus, I suggest that students' drawings not only reveal whether or not they understand an article or a concept, but that students' drawings offer a glimpse into the way they process information.

Students' Drawings of Einstein's Article "Physics and Reality" and Learning Preferences

In this introductory assignment, before delving into the actual physics content of the course, it is possible to get a peek into the way that students think and process information. The topic itself—the nature of the scientific process—does not depend on prior physics or math knowledge, thus students' preexisting attitudes toward science and scientists, as well as the modalities by which they receive, process, and internalize information, may be apparent. This kind of information about students can be highly beneficial for the instructor in designing teaching strategies and organizing students into cooperative groups, as well as beneficial for students to understand what types of learners they are.

Felder (1993) and Felder and Silverman (1988) describe learning preferences among undergraduate engineering students as combinations five types of opposite traits, in varying proportions: sensory versus intuitive, visual versus verbal, inductive versus deductive, active versus reflective, and sequential versus global. They described the characteristics of each type of learner as follows: Sensory learners tend to favor information that comes in through their senses, while intuitive learners favor information that arises internally through memory, reflection, and imagination. Visual learners tend to learn best from visual images (e.g., pictures, demonstrations), while verbal learners favor verbal material (written and spoken words and mathematical formulas). Inductive learners prefer to learn by seeing specific examples first and then working up to general principles and theories by inference, whereas deductive learners prefer to begin with a theory and deduce its consequences and applications. Active learners tend to learn best by active experimentation, bouncing ideas off others, and are comfortable working in groups; reflective learners prefer introspective processing of ideas on their own, prefer to think things through before trying them out, and prefer to work alone or in pairs. Sequential learners acquire understanding of material in a linear fashion, whereas global learners take in information in seemingly unconnected fragments and achieve understanding in large leaps. Global learners may appear slow and do poorly on homework and tests until they grasp the total picture, but once they have it they can often see connections to other subjects that escape sequential learners (Felder, 1993; Felder and Silverman, 1988).

Over the 4 years I have taught Symmetry, I find that students' drawings have tended to fall into general categories that suggest combinations of the learning preferences described by Felder and Silverman (1988). I have labeled these categories *abstract-representational*, *direct-symbolic*, *metaphoric-analogical*, *allegorical-creative*, *flow chart*, *hybrid*, and *incomplete understanding*.

I considered drawings to be correct interpretations of Einstein's article as long as they represented the process of science as including three basic elements, which they also explain verbally: first, that they indicate that science starts with some form of sensory input or experience; second, that they indicate some way of interpreting experience; and third, that they indicate some means of coming to a unified interpretation. Drawings that did not include these elements, at least by inference, I considered to represent incomplete understanding, or perhaps an incomplete reading of the article. The students' written descriptions that accompanied their drawings were also used to interpret students' understanding of the article.

Member checking. Effectively, member checking was done through a combination of in-class discussion and students' written explanations. On the day the assignment was due, each student presented his or her drawing to the class, first in mixed-major groups of two or three students and second in front of the class as a whole. During the students' presentations, I and the other students had the opportunity to comment and ask clarifying questions. Each artist explained the aspects of the article he or she was attempting to draw and what the symbols in his or her drawing represented. The combination of the in-class presentation and discussion and the students' written explanations, which were turned in as part of the assignment, informed my analysis and evaluation of the work.

Coding the drawings. I coded the students' drawings based on general characteristics, rather than the presence or absence of specific iconic elements, such as moustache, lab coat, baldness, or glasses, that have been used in previous studies such as the "Draw a Scientist Test" (Chambers, 1983). The general characteristics that I looked for are:

1. the type of symbols used: abstract, geometric, or pictorial;
2. the type of representation: direct mapping of concept in the article to symbol in the picture or representation of concepts in the article by a pictorial analogy or metaphor;
3. the representation of some sort of temporal progression;
4. the representation of the article as a whole with an allegory or "what if" scenario.

Abstract-representational drawings use abstract symbols with a one-to-one correspondence between the symbol and the concept being represented. Direct-symbolic drawings utilize recognizable objects to represent concepts in a one-to-one mapping of symbol to concept, using arrows to indicate correspondences or placing labels directly on the drawing. Metaphoric-analogical drawings represent the concepts discussed in the article with an analogy or metaphoric representation. Allegorical-creative drawings represent the article as a whole with a pictorial story that builds on the idea of science as making sense of a myriad of sense impressions, perhaps going off on a "what if" tangent. Flow charts incorporate some element of temporal progression to indicate the development of concepts, and hybrid drawings include elements of two or more categories. Drawings that indicate incomplete understanding of the article are of two general types: The drawing lacks one or more of the basic elements of the process of science, or the drawing does not address the article at all. Drawings of the second type include a caricature of Einstein and representations of a general question along the lines of, "What is the meaning of life?" Table 2 gives a list of these categories, a summary of the markers I used to categorize the drawings, and the characteristics of Felder and Silverman's (1988) learning styles that are suggested by the types of drawings when considered along with other information such as students' written assignments, interviews, and in-class discussions. Of the 44 students who completed the course, 34 turned in drawings for this assignment. The distribution of drawings is shown in Table 3.

Table 2
Types of Drawings With Description of the Elements That Define Each Type

Drawing Style	Defining Markers	Felder and Silverman (1988) Characteristics
Abstract-representational	Student uses abstract symbols with a one-to-one correspondence between the symbol and the concept being represented.	Intuitive, visual, deductive, reflective, sequential
Direct-symbolic	Student uses pictures of recognizable objects to represent concepts in the article in a one-to-one mapping.	Sensory, visual, inductive, active, sequential
Metaphorical-analogical	Student represents the layers of scientific reasoning with a metaphor or analogy of how a scientist may derive a set of inferences from direct observations.	Sensory or intuitive, visual, deductive, reflective, global
Allegorical-creative	Student represents the intention of the article with a pictorial story or takes off from the article by drawing a "what-if" scenario.	Sensory, visual, inductive, reflective, global
Flow chart	Student uses elements of temporal progression to indicate the development of concepts in the article.	Sensory, visual or verbal, inductive, reflective, sequential
Hybrid	Student's drawing shows qualities of several categories.	Various combinations
Incomplete understanding	Student's drawing and verbal description indicate a lack of understanding or incomplete reading of the article.	Can't determine from this assignment

Examples of Students' Drawings and Commentaries

Direct-symbolic drawings. The greatest number of students (9) drew direct-symbolic representations of the process of science, in which they used recognizable images or symbols and incorporated textual labels on their drawings. The unifying feature of the drawings in the direct-symbolic category is the one-to-one mapping of symbol in the drawing to concept in the article, often with labels written directly on the drawing, suggesting

Table 3
Numbers of Drawings in Each Category

Drawing type	Number
Direct-symbolic	9
Abstract-representational	5
Metaphoric-analogical	5
Incomplete understanding	6
Hybrid	4
Allegorical-creative	2
Flow chart	2

that students who drew this type of representation are literal thinkers. Examples of direct-symbolic drawings are shown in Figures 1, 2, and 3. I chose these examples because they represent a range of literal pictorial interpretations of the article, from geometric shapes (Figure 1) to shapes that suggest mountain ranges (Figure 2) to a drawing of a person with an exposed brain (Figure 3). From their drawings and written descriptions, I suggest that these students exhibit learning preferences for sensory, visual, inductive, active, and sequential modes. Their preexisting attitudes toward science, with which they approached this course, are also apparent in their drawings and essays.

Figure 1 was drawn by a first-year female literature major in 2007. Although she has not written the label *sensory perceptions* on her diagram, it seems apparent from her description that sensory perceptions would be at the base of the pyramid:

> In this essay, Einstein discusses the limits of human knowledge. He 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. . . . The way Einstein sees it is that as long as there appears to be a method to the madness, or the apparent "chaos" of sense perception, it is worth attempting to establish a pattern between these perceptions.

She has clearly understood the description of the process of deriving a hierarchy of logical deductions from sensory impressions, but her description of the process as a "method to the madness" suggests a certain skepticism toward physics. In a subsequent essay she describes her way of understanding as an active process, which she visualizes taking place inside her body:

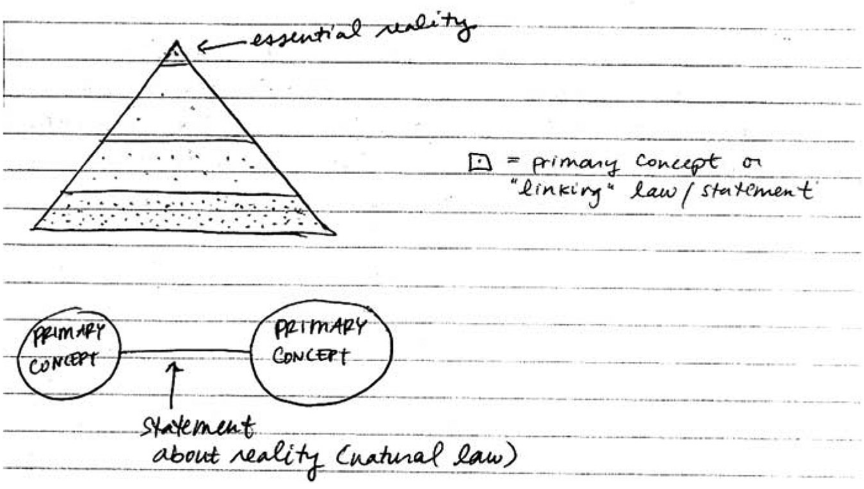

Figure 1. **Direct-symbolic drawing, literature major (female, first year), 2007. Used with permission.**

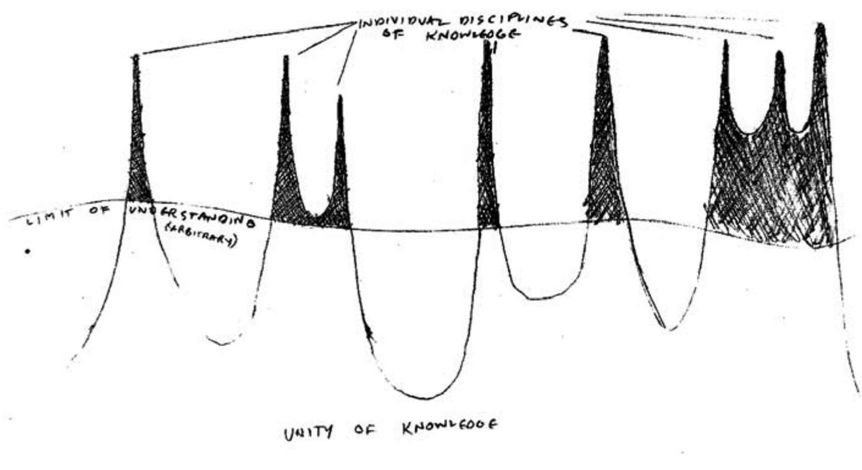

Figure 2. **Direct-symbolic drawing, geophysics major (male, fourth year), 2007. Used with permission.**

> For me personally, understanding something new is at once visceral and mentally systematic, if such a combination of seemingly incongruous experiences is indeed possible. I feel the piece of knowledge in question becomes assimilated into the network of neural pathways

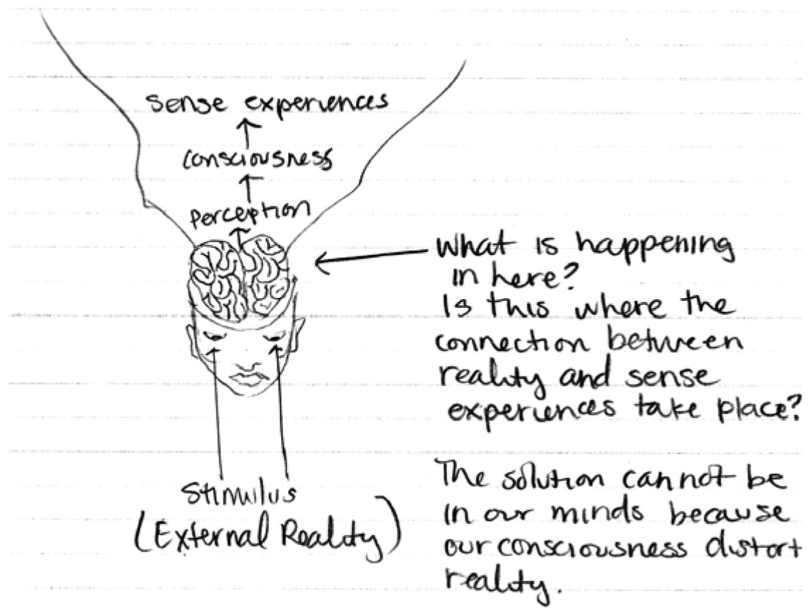

Figure 3. **Direct-symbolic drawing, biopsychology major (female, fourth year), 2011. Used with permission.**

> which constitute my higher mind, and the sensation is almost physical.

The drawing shown in Figure 2 was made by a fourth-year male geophysics major, in 2007, who was also double-majoring in Southeast Asian Studies. His drawing shows Einstein's layers of observation, interpretation, and unifying theoretical framework as "Individual disciplines of knowledge," "Limit of Understanding," and "Unity of Knowledge." It is interesting that his second layer, Limit of Understanding, is shown as a wavy line, and he has labeled it "arbitrary."

In his essay, he wrote:

> 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 has understood Einstein's point that through thinking we can understand the external world. As a geophysics major, he has a positive attitude toward science, unlike the skepticism of the literature major. In another essay he wrote about the importance of art in developing his interest in studying science:

> Art has been absolutely vital to my current comprehension of any and all areas of science; one of the first books I remember looking at is "Powers of Ten" in which scales from near the Planck length to near the breadth of the universe are represented by an artist. Books like this and others all served to pique my interest in the sciences from an early age, and would not have done so if artists had not created these images of the world and physical processes around me.

The third drawing was done by a fourth-year female biopsychology major. Her drawing contains the elements of sensory experience and interpretation, but perhaps due to her training in psychology, she appears to disagree with Einstein's premise. She claims that "The solution cannot be in our minds because our consciousness distorts reality" and equates "stimulus" with "external reality." This interpretation is opposite to the process of science that Einstein describes, in which sensory experiences cannot be taken as "reality," but an understanding of a "real external world" can only be developed through thinking. In her essay she wrote, "It was very hard to wrap my head around Einstein's words, so translating it was hard to do visually and verbally."

Although she stated on several occasions how she really enjoyed physics in high school, and was fascinated with the idea of String Theory, in a subsequent reading reflection, in response to an article on the way physicists use numbers to represent concepts, she felt inspired to compare scientists who use arguments that invoke Occam's Razor to atheists who "hold themselves with such offensive arrogance, as if Atheism is some kind of intellectual rite of passage." However, at the end of the course she wrote the following evaluation, signing her name, although the evaluations were supposed to be anonymous:

> 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! (Signed with her name)

Interestingly, over the four times that this assignment has been given, a total of five of the eight students who drew direct-symbolic drawings included eyes and/or brains. All were drawn by females: one literature major (2008), one political science major (2011), one biology major (2008), and one psychology major (2011), in addition to the example shown in Figure 3. The literature major and political science major in this category dropped out of the class after 3 weeks.

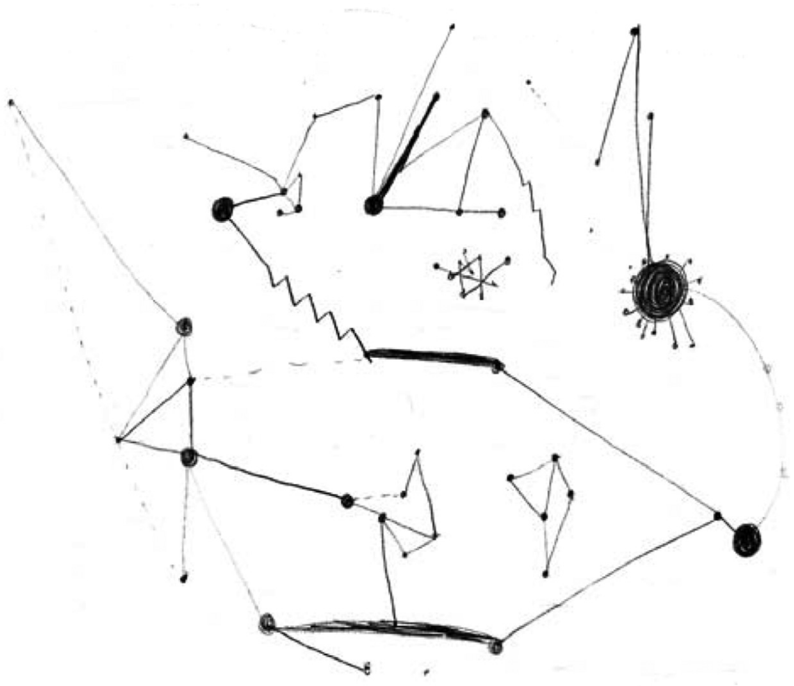

Figure 4. **Abstract-representational drawing, physics major (female, first year), 2007. Used with permission.**

Abstract-representational. Five students drew abstract representations of the article. The unifying feature of the drawings in this category is the use of completely abstract designs to represent the description in the article, yet from the students' verbal explanations, it is clear that they symbolically represented the elements of sensory observation, interpretation, and unifying theory. Students who drew abstract-representational drawings also showed characteristics suggestive of learners who are sensory, visual, inductive, active, and sequential.

Figure 4 was drawn by a first-year female physics major in 2007. She correctly summarized the article:

> In formulating our scientific views, we want as complete a connection as possible between sense experiences. However, we want to be able to formulate scientific views based on the minimum amount of connections possible, since each connection has a certain level of uncertainty. Einstein hopes that, given the success of science so far, we will be able to approach a more and more unified system of science.

She described the meaning of 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.

Two other examples of abstract-representational drawings are shown in Figure 5. I do not have written descriptions, but in each case I determined that each student understood the article by means of verbal explanation. Figure 5a was drawn by a first-year math major, female, in 2010. She explained the meaning of her drawing as representing Einstein's layers from sensory input (shaded ball at the bottom), to secondary layer of concepts, represented by the two open circles, and finally up to the third level, which explains everything below with a unified theory. The dashes surrounding the perimeter, she told me, represent the limit of our present knowledge. Figure 5b was drawn by a third-year male math major. He explained that the brick-like objects in the foreground are sensory perceptions, and the shaded portion in the center of the drawing, which appears behind the bricks, is the theoretical explanation which unifies all the experiences.

Metaphoric-analogical. Five students chose a pictorial metaphor or analogy by means of which to represent Einstein's progression from sensory perception, through increasing levels of abstraction, to a simplified theoretical framework. The unifying feature of the drawings in this category is the use of a pictorial metaphor or an analogy to represent the elements of sensory observation, interpretation, and unifying theory that Einstein described. Students who drew abstract-representational drawings seem to show characteristics suggestive of learners who are visual, reflective, and global thinkers, in that they represent the article as a whole, rather than a direct mapping of symbol to concept. I chose to reproduce four examples from students with different backgrounds (physics, math, biology, and art). Their essays suggest that the physics and math majors favor intuitive modes of learning, while the biology and art majors favor sensory learning.

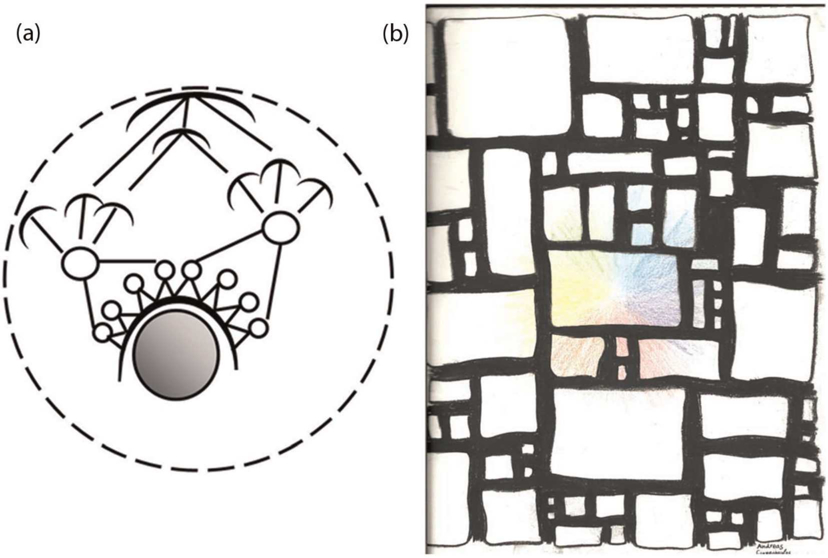

Figure 5. **Abstract-representational drawings. 5a (left): female math major, first year; 5b (right): male math major, third year. Used with permission.**

Figure 6 was drawn by a first-year male, who was double-majoring in physics and math. His written explanation indicates that he understood the intent of the article:

> 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.

In response to the question of how he felt about being asked to draw his understanding of an article in physics, he wrote:

> 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.

Figure 6. **Metaphoric drawing, first year male, physics major, 2007. Used with permission.**

From his description of his own thinking/visualization process, it would seem that this physics major shows similarities with the creative thinkers in science and mathematics described by John-Steiner (1997).

The "Reptile of Science" (Figure 7) was drawn by a first-year male math major. He explained his drawing thus:

> At the top, you see a fairly detailed, intricate picture of something that looks intimidating, but as the viewer's eyes progress down, the shape is simplified and simplified until it becomes an innocent, almost stick-figure-esque drawing. This symbolizes how our sense impressions of the real world, a powerful experience, is abstracted by science until it becomes something simpler and more friendly to use.

In several of his subsequent essays, this student alluded to his feeling of satisfaction when a given explanation from the reading allowed him to make sense of the world in simple, user-friendly terms.

A second-year female art major chose to represent Einstein's description of the process of science by using the analogy of understanding the intentions of her pet rabbit by observing the animal's body language (Figure 8).

She wrote:

> In his essay, [Einstein] described how the pursuit of science was dominated by sense impressions and its relationship to concepts. These

Figure 7. **"The Reptile of Science," metaphoric-analogical drawing by first year male math major, 2008. Used with permission.**

> impressions were related to concepts based on a set of rules and it was by this method that the scientist would work his way to a conclusion. In this way, a person could figure out what a pet wants based on sense impressions, brought upon by examinations, and knowledge of pre-set concepts that are related to what is examined.

This art student has revealed a subtle perception that was not apparent in any of the other students' essays, namely, that scientists are male. The gender referencing of scientists as male, as compared to "people" and "pets" is apparent in her statements, "the scientist would work his way to a conclusion" and "a person could figure out what a pet wants." In Chambers' (1983) "Draw a Scientist Test," out of the 4,800 students who were tested, 99.5% represented scientists as male, although 49% of the students tested were girls. This art student's preexisting view of scientists was apparently aligned with the cultural stereotype. Whether her view of scientists as male was reversed as a result of this course is not possible to say; however, her final essay suggests that her attitude toward physics did change as a result of the course:

> [Before] I thought of physics as existing in numbers and equations found by others while I regarded Art to be a result purely from the artist's mind. To tell the truth, I placed Art in a much higher respect than Physics because I never thought of the beautiful process that

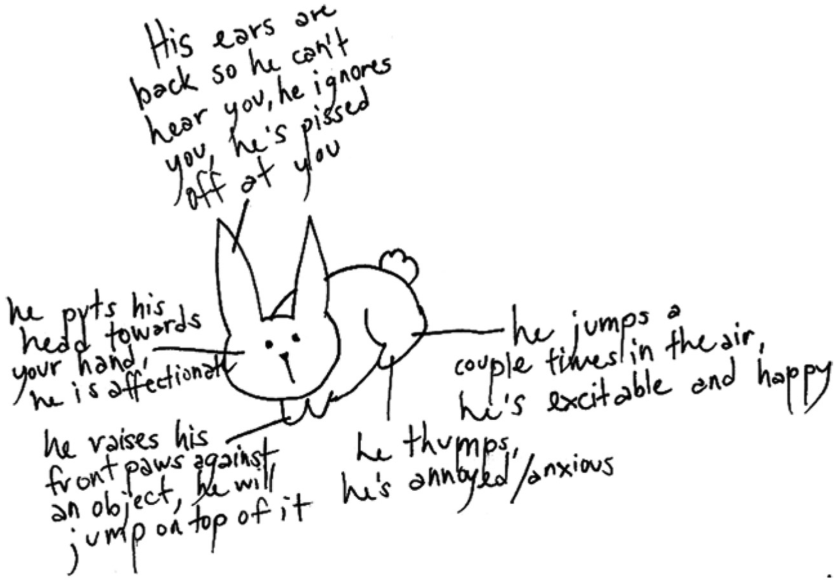

Figure 8. **Drawing by second-year female art major, 2008, using the analogy of interpreting the intentions of her pet rabbit by observing his gestures and body language. Used with permission.**

> led to equations and the relation to Nature that Physics possessed. . . . I think what changed most for me was my concept of Physics now that I have seen it outside of the textbooks. I found that the pursuit of figuring it out was as important and creative as the work of expressing Nature through Art.

A fourth-year male marine biology major (2010) was the only student who created a 3D representation for this assignment, instead of a drawing (Figure 9). He explained his sculpture as follows:

> When Einstein is referring to the constraints on a physicist's thoughts being restricted by "fundamental concepts and fundamental laws, which are so well established that waves of doubt cannot reach them" it rang true to the struggles I have felt in science. I think it is a misrepresentation of science when textbooks are not portrayed as theory, but instead as bibles of the natural world. In my piece I tried to capture the weight of theory that you must subvert with waves of doubt in the "S" shaped stand creeping under a heavy stone.
>
> Einstein also discusses how preconceived rules may get in our way when we try and use them to explain new problems. . . . To try

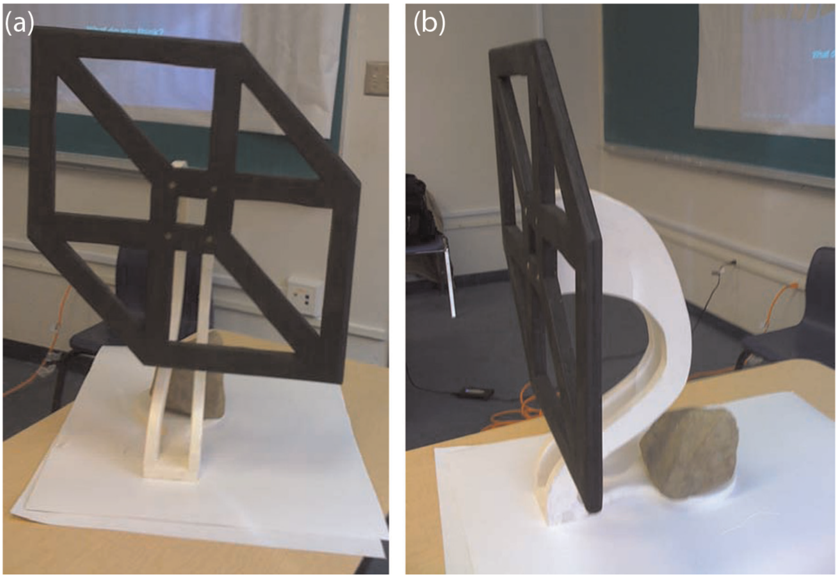

Figure 9. **Metaphoric representation of Einstein's article by a fourth-year male marine biology major, 2010. 9a (left): Frontal view; 9b (right): side view, revealing the illusion. Used with permission.**

> and show how we naturally force ourselves to see things in the context we have seen them before, I created a simple optical illusion. When you look at this 2D wooden box image you will suddenly start to see it as a 3D cube with one box in front and the other off in the distance behind, then it will suddenly switch and the other box will jump to the foreground. This chaotic flip-flopping is a hilariously confused attempt by your mind to turn this pseudo familiar image into something you recognize, when in fact it is simply 12 straight lines.

Like the art student in the previous example, he is expressing his attitude toward science, although with deliberate intention.

Allegorical-creative. Two students represented their understanding of Einstein's description of the process of science with allegorical drawings that extended the concepts of the article into a pictorial narrative, building upon the ideas presented. Figure 10, "Plato's Cave," was done by first-year male physics major in 2010, and Figure 11, "A World Without Eyes," was drawn by a second-year female political science major in 2011. Both drawings contain the elements that indicate a correct understanding of the article: a reference to sensory experiences that are interpreted and from which a theoretical explanation of the "real external world' can be derived,

Figure 10. **"Plato's Cave," first-year male physics major, 2010. Used with permission.**

but these students have taken the assignment to another level in applying the process of observation and interpretation to a new scenario.

The student who drew Figure 10 explained that Einstein's description of developing a theoretical model to explain sensory observations reminded him of Plato's Allegory of the Cave. He explained that the figure with his hand over his eyes is looking toward the light, not at the shadows on the wall like the others, wondering what he would find if he were to climb the stairs and follow the light.

The student who drew Figure 11 chose to extend Einstein's model by exploring how our models would be different if we lacked the sense of sight. She wrote on her drawing, "This is a lighted version of a world with no

Figure 11. **A world with no eyes, second-year female political science major, 2011. Used with permission.**

eyes." Above the picture she drew a sun with a circle around it, crossed by a diagonal slash, as if to indicate "No Sun allowed here." The fingers and toes of the beings in her picture have extended pads, indicating an enhanced sense of touch. She wrote:

> In a world with no sight priorities for necessities in a house would change. People would maybe [be] ultra-sensitive and appreciate things like music and fuzzy walls more. Here there would be less absolutes without visual aids. The idea that the blanket is warm and fluffy is stronger than the idea of the blanket itself.

She added a few notes at the bottom of her discussion: "6th sense: heat sensory? Privacy is not a term. Beauty changes."

Both students' drawings are suggestive of sensory, visual, inductive, reflective, global learners, but also reminiscent of the drawings of highly creative students discussed by Getzels and Jackson (1962) in their study of adolescents in a Midwest suburban high school. When given a drawing prompt, the students in their study who were identified as high-IQ tended to draw literal interpretations, whereas the drawings of students identified as highly creative tended to be freer and less rule-bound. For example, when asked to draw a picture of playing tag in the school yard, the students identified as high-IQ drew the school, the yard, the playground equipment, and children running, whereas those identified as high-creative drew liberal, sometimes whimsical, interpretations, including animals and aliens playing tag, and a map of the interior of the school with a note: "Note: It is ghosts who are playing tag" (Getzels & Jackson, 1962).

In characterizing the highly creative students, Getzels and Jackson (1962) described the following traits:

> the ability to play spontaneously with ideas, colors, shapes, relationships—to juggle elements into impossible juxtaposition, to shape wild hypotheses, to make the given problematic, to express the ridiculous, 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. (p. 53)

The use of drawing for understanding has the potential to reveal these kinds of highly creative students, such as the two who drew Figures 10 and 11, who might go unrecognized in a standard introductory physics class. The student who drew Figure 11 wrote the following in her final evaluation, which she signed:

> Thank you for one of the craziest (cool) classes I've taken my whole time being here. Not many classes care about what you think, but in your class I felt like my understanding was the whole point.

Flow charts. Flow charts are visual representations that indicate progressive relationships between concepts, often depicted with arrows or connecting lines. Four students drew interpretations of Einstein's description that incorporated elements of temporal progression. Only one student, a fourth-year male physics major, drew a pure flow chart, with words only and no pictures (Figure 12). He drew this same type of representation for all his drawing assignments, suggesting that his preferred learning modality may be intuitive, verbal, inductive, reflective, and sequential. On his drawing he wrote,

> It is fairly easy to draw this as there is something fundamentally simple going on: using logic to refine logic.

Hybrid drawings. Four students drew interpretations that embody characteristics of two categories, such as a flow chart or equation that utilizes metaphors, an abstract representation that tells a story, or an abstract representation with labels written directly on the drawing. Figure 13, drawn by

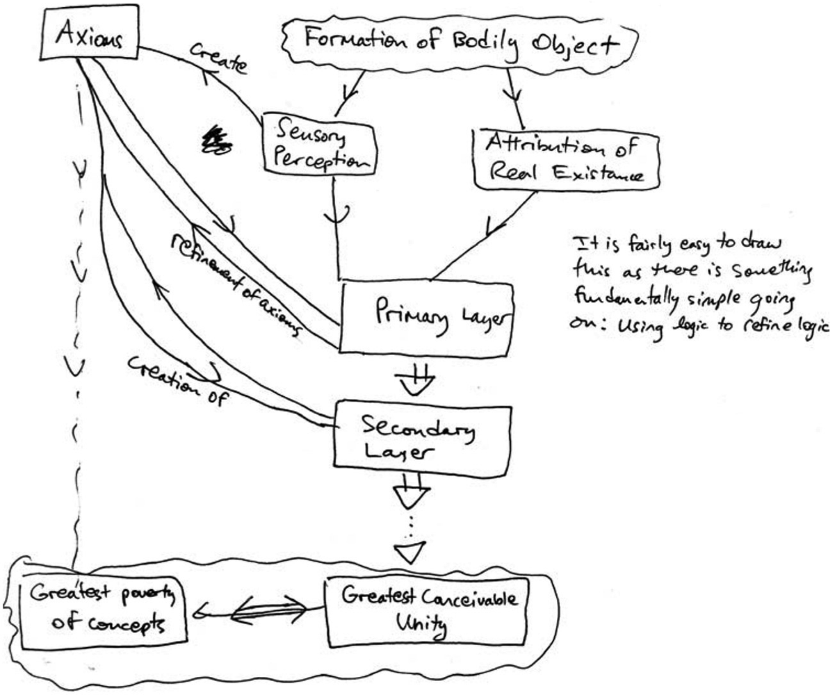

Figure 12. **Flow chart, fourth-year male physics major, 2007. Used with permission.**

a first-year male physics major, is a pictorial equation, which I consider a combination of a flow chart (representing temporal progression) and a metaphoric representation. His drawing also embodies a sense of sophisticated humor, reminiscent of the drawings of the highly creative students in Getzels and Jackson's (1962) study. He explained the meaning of his equation as "The sum, from i = 0 to all thinking (represented by a brain sitting atop the summation symbol, where the upper limit would normally be indicated) of all forms of existence adds up to an increasingly accurate picture of reality." The "Higher Order Terms" represent what we don't yet understand. Figure 14, drawn by a fourth-year male physics major, combines an abstract representation with a metaphor. He explained that his drawing is supposed to represent the Cantor Set, a fractal in which one third of a line segment is removed with each iteration, until one is left with "Cantor dust." He also displayed a sophisticated sense of humor: his caption reads, "You 'can't' always trust your intuition."

Figure 15, drawn by a third-year female art major, combines abstract representation with direct-symbolic representation, in that the scribbles cannot be

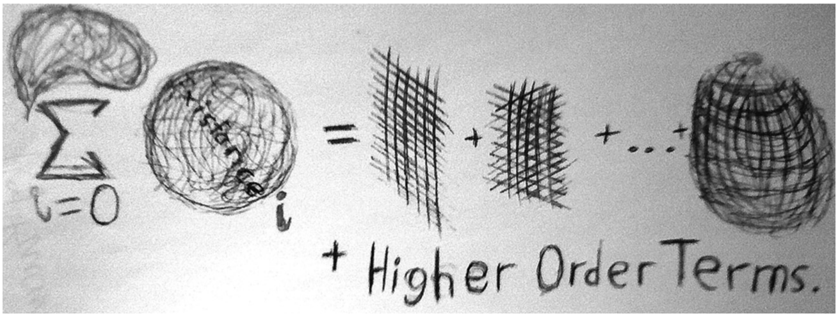

Figure 13. **Hybrid drawing: flow chart + metaphoric, male physics major, first year, 2010. Used with permission.**

said to truly resemble any recognizable objects, yet the labels written directly on the drawing are suggestive of the kinds of literal interpretations drawn by students who drew direct-symbolic representations. Her drawing follows the progression of science from "Our sensory experiences—touch, smell, sight, hearing, taste" through "perception," which she represents with a tangled web of lines; through "interpretation," which lies just outside of the web of perceptions; to arrive at the level of "thought or expectation." Throughout the course she commented on numerous occasions, in class discussion and in her homework essays, that she learns by sensory experiences, and for her, understanding must be grounded in a bodily experience. She had not taken math since 10th grade, and had never taken physics. She described her own process of understanding as relying on bodily experiences, exemplifying the type of sensory learner described by Felder and Silverman (1988).

> When determining how I "understand something" I perceive my understanding in my head that relates to by bodies experience or my perceived experience. One's gut feeling is an important place to start from when coming to an understanding. I myself must often visualize a situation which I then get about to imagine in my body or through a direct experience that I have already had.

In a subsequent essay, she wrote the following about herself:

> I . . . believe that the prospect of learning, understanding and imagining certain theories is daunting. They are challenging because often one has to imagine an experience that does not relate to our everyday experience or perception. I do believe however that it is possible to engage in this imagining process if one is trained to use their imagination in such a manner.

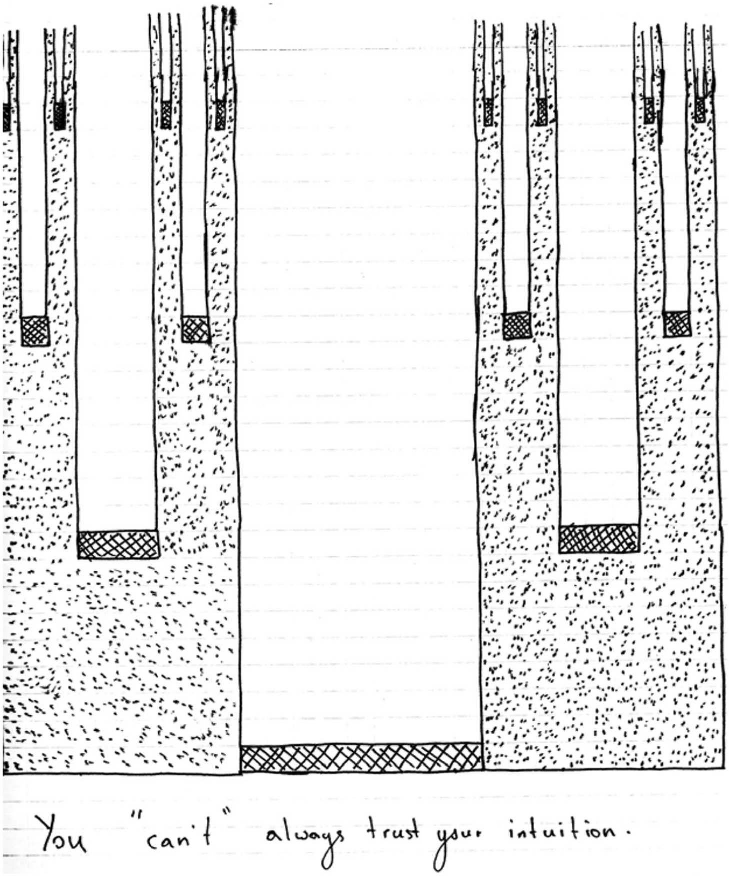

Figure 14. **Hybrid drawing: abstract + metaphoric, fourth-year male physics major, 2011. Used with permission.**

As the course progressed, she had difficulty coming to terms with concepts in physics which appeared to her to contradict her direct sensory experiences. She stated on several occasions that it was "not fair" of physicists to appropriate terms from daily language, which she understood, and assign to them alternate meanings. She stated in a homework essay that this practice caused her to mistrust physicists in general. She had particular difficulty coming to terms with abstract concepts from Relativity, for which we can have no direct experience, and expressed a deep mistrust of physicists for attempting to reinterpret experiences that she had come to accept as

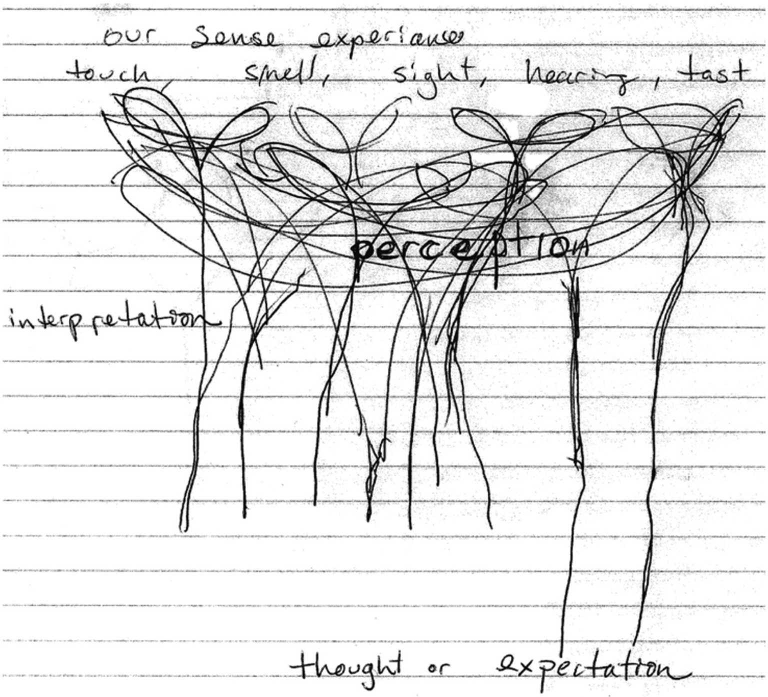

Figure 15. **Hybrid drawing, art major (female, White, third year), 2007. Used with permission.**

"reality," as she expressed in her critique of Feynman's description of the surface of a cylinder as representing flat space:

> 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. . . . When it comes to a cylinder whose space seems to be obviously curved we find it does not have curved space because Euclidian geometry holds. My first reaction is to say that the definition that Feynman gave in the beginning must be wrong.

Students who are concrete learners may need extra help in developing the ability to make the leap of faith from descriptive to hypothetical or theoretical understanding in science. Interdisciplinary multimodal teaching strategies that cross-pollinate between multiple ways of making meaning of the phenomenological world can provide the critical momentum necessary to help such students bridge the gap from concrete to imagined realities. This was clearly the case with this art major, as she demonstrated by the end of the course. In her final essay, 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.

In her final evaluation of the course, she wrote:

> I found this course to be wonderfully exciting. 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.

Incomplete understanding. I considered a drawing to represent incomplete understanding if one or more elements of Einstein's model (sensory experiences, intermediate layers of interpretation, higher level of unifying theoretical explanation) to be missing or if the drawing did not address the process of science, and the written explanation was either missing or did not match the article. Six drawings appear to represent incomplete understanding. Of these, three students (one male physics major, one male biology major, and one female art major) appear to have missed a key element, perhaps through misinterpretation or too quick of a reading. Two drawings, one by a male math major and the other a female religious studies major (who dropped the class after the second assignment) give the impression that the student may have tried to wade through the article, more or less got the idea of science being a process of making sense out of a myriad of sensory experiences, but gave up and drew a representation on the order of "What is the meaning of life?" Neither student turned in a written explanation. One student, a male art major, simply drew a caricature of Einstein (Figure 16). While an excellent drawing, it did not represent the process of doing science, and his brief written explanation did not indicate that he made it through the entire article, as he referenced only the first page.

Figure 17 was drawn by a fourth-year male physics major and resembles a diagram of atomic orbitals in the hydrogen atom. This drawing appears to be a direct symbolic representation, in that it contains recognizable symbols (atomic orbitals), and a description, or legend, is provided directly on the drawing. I consider it incomplete as there is no representation of sensory experience, in that electron orbitals cannot be directly observed, but represent a theoretical interpretation. On his drawing, he wrote:

> 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 fuzziness to signify the (word is lost in reproduction) of axioms.

Figure 16. **Caricature of Einstein, first-year male art major, 2008. Used with permission.**

In his summary of the article, he wrote:

> 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.

Compared with descriptions and drawings of the other physics majors in the same class (2007), shown in Figures 4, 6, and 12, this student surprisingly missed the point. Perhaps he just did not have time to read the article completely, due to other homework pressures as a fourth-year physics major. This student was initially skeptical that art and physics could have similar goals.

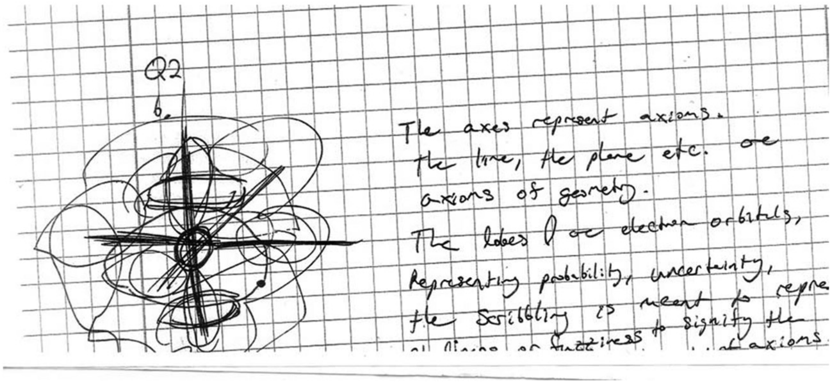

Figure 17. **Incomplete understanding, fourth-year male physics major, 2007. Used with permission.**

In his reflection on another article that was assigned for homework (Campbell, 2004), he wrote:

> The author's comparison of art and science requiring similar levels of formal training is laughable to me. . . . The difference is that 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.

Through the course, this student showed a transformation that is similar to those reported in the Dartmouth study (Korey, 2000). This transformation is apparent from his final paper, which accompanied his final 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.

Discussion and Implications for Physics Education Reform

This population of students is admittedly small and self-selected; however, some interesting patterns emerge from an analysis of their drawings.

Students' drawings reveal something about the type of learners they are, which can be described in a number of ways. I identified six types of drawings: abstract-representational, direct-symbolic, metaphoric-analogical, allegorical-creative, flow chart, and hybrids, which embody more than one style. The markers that I used to define these categories are listed in Table 2. I suggest that these categories of drawing are suggestive of combinations of learning styles identified by Felder and Silverman (1988) among undergraduate engineering majors. Understanding students' learning preferences and ways of meaning-making can be valuable for instructors in designing appropriate learning strategies, adjusting reading assignments, organizing collaborative groups, and providing a supportive learning environment.

Even in a more traditional physics course, drawing should be seen as a useful exercise for students as a means of organizing their thinking about difficult concepts as well as a potential learning strategy for effecting conceptual change. Particularly when conceptual change requires a restructuring of learners' fundamental ontological commitments, such as is required in transitioning from the Galilean notion of static space and universal time to the post-Einstein view of space and time as dynamic and interdependent, the process of expressing difficult concepts through artistic visualization can be a potentially transformative experience for the learner.

I suggest that student-generated drawings, together with written reflections, can support the recommendations for change in science pedagogy in the United States that have been proposed in the report of the National Research Council (NRC) Committee on Science Learning, Taking Science to School (Duschl et al., 2007). According to the NRC report, one of the most important considerations in designing appropriate and effective science instruction is for teachers to take into account students' ideas, prior experiences in science, and cultural experiences, which will help them make sense of scientific phenomena and practices. To do so, teachers must have access to students' ideas and employ a range of strategies to learn what students understand about a given topic (p. 279). Having students draw their understanding of an article or concept is a powerful means of accessing students' preexisting attitudes toward science, as in the case of the art major who indicated an initial association of scientist-as-male (Figure 8), or the marine biology major who protested the way science had been presented to him previously (Figure 9).

Drawing for understanding supports another recommendation of the NRC: the need for instructional strategies that encourage articulation and reflection as part of the scientific process. When students are asked to draw their understanding of a concept, they must first articulate their understanding in order to produce the drawing; when they present their drawing in class, they have the opportunity to reflect on their understanding, as well as reflect on how effectively their drawing, and their explanation of the drawing, communicates their understanding to others. Students' drawings can also provide a method of formative assessment for instructors in that drawings reveal whether or not a student understood a concept or reading (e.g., Figure 16), but even more importantly, drawings provide a window into students' preferred learning modalities. Understanding students' individual learning preferences can inform the way an instructor adjusts curricular materials and manages classroom interactions, for example in organizing cooperative learning groups. The NRC report strongly recommends that

> To support student sense-making in instruction, teachers need to know how students think, have strategies for eliciting their thinking as it develops, and use their own knowledge flexibly in order to interpret and respond strategically to student thinking. (Duschl et al., 2007, p. 312)

Students' drawings of their understanding provide powerful means of assessing how students think and process information. In addition, assessing students' understanding through drawing forces the instructor to continually use his or her own knowledge flexibly in order to interpret and respond to student thinking, as well as improve his or her own understanding of the concept by seeing how different students understand it.

The use of drawings throughout a course can also reveal changing attitudes and a maturing of students' perspectives regarding their relationship with the subject. Katz et al. (2011) used drawing as a means of assessing student teachers' changing self-perceptions of themselves as teachers and their students as learners as a result of their experiences in an informal science education program. The student teachers' drawings revealed significant changes in their perceptions before and after exposure to an informal science education program. Similarly, I suggest that instructors can have students revisit a concept that they drew early in the course with a follow-up drawing toward the end of the course, asking students to comment on any differences in understanding that their early and late drawings reveal. Although I did not have students revisit a subject that they had drawn earlier, their increasing ability to synthesize the Big Picture concepts as the course progressed was revealed in their written assignments, subsequent drawing projects, and their final physics works of art.

> 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. (Female art major, excerpt from final paper, 2007)

> I was really glad to make my final project. It helped me develop my view of the interconnectedness of things. (Female art major, signed exit card, 2011)

> My favorite [assignment] 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. (Male physics major, post-course interview, 2007)

Possible Implications for Addressing the Lack of Diversity in Physics and Engineering

In 2007, the first year that this course was taught, I administered the Maryland Physics Expectation Survey (MPEX) (Redish, Saul, & Steinberg, 1998). The MPEX was designed to measure changes in students' attitudes toward physics before and after they experienced 1 year of introductory college physics. In their benchmark study of 1,500 college students in six colleges and universities, Redish et al. (1998) demonstrated that students' attitudes toward physics decrease significantly after taking a standard introductory college physics course. Moreover, they demonstrated that when students adopted the behaviors that led to good grades in their introductory physics courses, their actual learning of physics concepts and understanding of the deeper connections between mathematics and physics decreased. Not surprisingly, the students in my class who took the MPEX as a matched-pair, pre- and posttest demonstrated significant gains in attitudes toward physics, and art students improved significantly in their sense of self-efficacy regarding their ability to learn physics (van der Veen, 2007).

Hanrahan (2002) noted that successful science teaching should take into account psychological, sociocultural, and cognitive factors that students bring with them to class. Important factors to consider in building an equal-access classroom are the development of trust among students, trust between students and teachers, whether students feel personally affirmed in the class, and the degree to which students have input as to what takes place in class (Hanrahan, 2002; van der Veen, 2007). Hazari et al. (2010) cite several classroom strategies by which minority culture students can establish a sense of their own identities within science. Such strategies include

> allowing students the opportunity to express their own voice through presentations, establishing a respectful/encouraging classroom atmosphere that minimizes the anxiety of public expression, positively acknowledging students' views, allowing students to see the "backstage" learning struggles (that even a teacher faces) rather than presenting the material from an elite transfer perspective, and, in general, creating hybrid spaces within classrooms. (Hazari et al., 2010, p. 19)

My research with students at a California public university suggests that the relative positioning of physics and arts students parallels the positioning of majority and minority culture students in schools (van der Veen, 2007), suggesting that interdisciplinary strategies have the potential to provide the kind of hybrid space described by Hazari et al. in which arts-based students can begin to appreciate math and physics and see these subjects as meaningful in their own lives. As one student wrote in an exit card comment,

> 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. (February 9, 2007, reported in van der Veen, 2007).

The separation of arts and sciences has been ingrained in Western society at least since the 17th century and embedded in American education since the 19th century (Eisner, 2002). The separation in education between arts and sciences also seems to follow boundaries of gender and race, in that White males continue to dominate in science and technology fields in spite of government initiatives to attract women and minorities into physics and engineering, and women and minority students gravitate toward the more "emotional," nonscientific fields (Brown et al., 2010). In a study of implicit attitudes of college students at Yale University, Nosek, Banaji, and Greenwald (2002) found that math and science are still identified with being male and arts with being female. Thus, it is logical to ask whether integration of arts and sciences in education may also improve gender and racial integration in physics and engineering or, at least, reduce fear of physics and math and thus improve science literacy in general.

Like all communities, physics must have a way of managing the identities of insiders and outsiders and of reproducing itself (Traweek, 1988). Sheila Tobias (1990) and anthropologist Sharon Traweek (1988), who study the physics community from the outside, have explained how, from an anthropologist's point of view, physics education may be serving to reproduce the physics community in the image of its elders—namely, White males. Thus, there may be little hope of diversifying the physics and engineering communities unless we change the way we reproduce our members through education. The very real cultural differences between physics students and art students that emerged in this course may offer a fresh approach to understanding how to develop a more diverse community through interdisciplinary and multimodal teaching strategies. The very positive reactions of the arts-based students to learning about physics with physics majors suggest that interdisciplinary, arts-based teaching strategies had a positive effect on their sense of agency relative to physics.

> 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. (Female art major, 2007, from a post-course interview)

> I felt really comfortable and really SAFE to ask questions, and they [the physics majors] 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 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. (Female art major, 2007, from a post-course interview)

The male physics majors also appreciated the opportunity to think about physics in a new way, as well as the opportunity to interact with the art students.

> What I especially liked about [the course] 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. . . . Being able t' think about those sorts of things is not something I would get out of a typical physics class. So that was really good. (Male physics major, 2007, from a post-course interview)

> 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. (Male physics major, 2007, from a post-course interview)

With the current focus on attracting more females into physics and engineering, we may be overlooking those males who have difficulty with physics. The results of my initial study (van der Veen, 2007) suggest that this often-neglected group of male students also benefits from an interdisciplinary approach.

> It [the course] 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. (Male book arts major, post-course interview, 2007)

To test whether this approach will have the desired effect of increasing access to physics and diversity in the physics community, I suggest that it should be tested with a larger population in more diverse settings. The power of the method lies not in replicating it exactly, but in taking the topics and arts-based learning strategies and tailoring the readings and assignments to the appropriate target audience, utilizing examples from the art and music of the local culture to illustrate principles of symmetry, space and time, and Relativity.

Finally, Aesthetic Education has at its core the intent to develop empathy, an element that is missing in most traditional physics education, which, I suggest, may be at the root of the complaint by students that was penned by physicist Victor Weisskopf in 1976.

Note

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References

Aikenhead, G. (2002). Whose scientific knowledge? The colonizer and the colonized. In W-M. Roth & J. Désautels (Eds.), *Science education as/for sociopolitical action* (pp. 151–166). New York, NY: Peter Lang.

American Institute of Physics Statistical Research Center. (n.d.-a). *Minority and ethnic profile of physics PhDs, classes of 2007 & 2008*. Retrieved from http://www.aip.org/statistics/trends/highlite/edphysgrad/table5a.htm

American Institute of Physics Statistical Research Center. (n.d.-b). *Percent of PhDs earned by women in selected fields, 1958–2006*. Retrieved from htttp://www.aip.org/statistics/trends/highlite/women05/figure7.htm

Angell, C., Guttersrud, O., Henriksen, E., & Isnes, A. (2004). Physics: Frightful, but fun: Pupils' and teachers' views of physics and physics teaching. doi:10.1002/sce.10141. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/sce.10141/abstract

Bazerman, C. (2000). *Shaping written knowledge: The genre and activity of the experimental article in science*. Retrieved from http://wac.colostate.edu/books/bazerman_shaping/

Blickenstaff, J. C. (2005). Women and science careers: Leaky pipeline or gender filter? *Gender and Education*, *17*(4), 369–386.

Bourdieu, P. (1977). The economics of linguistic exchanges, *Social Science Information*, *16*(6), 645–668.

Brekke, S. E. (1995). *Changes in the physics curriculum in American high schools from Revolutionary War to the present*. U.S. Educational Services document, ED 393 655.

Brown, B. A., Kloser, M., & Henderson, J. B. (2010, October). *Building bridges towards cognition: Cultural continuity and the language-identity dilemma*. Presented at the annual meeting of the American Educational Research Association, Denver, CO.

Brooks, M. (2009). Drawing, visualization and young children's exploration of "big ideas." *International Journal of Science Education*, *31*(3), 319–341.

Byers, N. (1998). E. Noether's discovery of the deep connection between symmetries and conservation laws. arXiv:physics/9807044 2(23), Sep 1998.

Campbell, P. (2004). Seeing and seeing: Visual perception in art and science. *Physics Education*, *39*(6), 473–479.

Chambers, D. W. (1983). Stereotypic images of the scientist: The draw-a-scientist test. *Science Education*, *67*(2), 255–265.

Corson, D. (2001). *Language, diversity, and education*. Newark, NJ: Erlbaum.

Crafton, L. K., Silvers, P., & Brennan, M. (2009). Creating a critical multiliteracies curriculum: repositioning art in the early childhood classroom. In M. J. Narey (Ed.), *Making meaning: Constructing multimodal perspectives of language, literacy, and learning through arts-based early childhood education* (pp. 31–52). New York, NY: Springer.

Duschl, R. A., Schweingruber, H. A., & Shouse, A. W. (2007). *Taking science to school: Learning and teaching science in Grades K-8. Report of the Committee on Science Learning, Kindergarten through Eighth Grade*. National Academies Press. Retrieved from http://www.nap.edu/catalog/11625.html, 10/17/2011

Edens, K. M., & Potter, E. (2003). Using descriptive drawings as a conceptual change strategy in elementary science. *School Science and Mathematics*, *103*(3), 135–144.

Einstein, A. (2003). Physics and reality. *Daedalus*, *132*(4), 22–25. (Original work published 1936)

Eisner, E. W. (2002). What can education learn from the arts about the practice of education? *Journal of Curriculum and Supervision*, *18*, 4–16.

Eschenberg, K. (2006). Scientist as artist: The role of imagination. *Physics Today*, *59*(7), 10.

Felder, R. (1993). Reaching the second tier: Learning and teaching styles in college science education. *Journal of College Science Teaching*, *23*(5), 286–290.

Felder, R. M., & Silverman, L. K. (1988). Learning and teaching styles in engineering education. *Engineering Education*, *78*(7), 674–681.

Getzels, J. W., & Jackson, P. W. (1962). *Creativity and intelligence: Explorations with gifted students*. London: Wiley & Sons.

Gosling, C. (2004). Challenges facing high school physics students: An annotated synopsis of peer-reviewed literature addressing curriculum relevance and gender. *Journal of Physics Teacher Education Online*, 2(2). Retrieved from http://physicsed.buffalostate.edu/pubs/PHY690/Gosling2004ClassEnv/Golsingp3-9jpteo 2(2)nov04.pdf

Greene, M. (2001). *Variations on a blue guitar. Lincoln Center Institute Lectures on Aesthetic Education*. New York, NY: Teachers College Press.

Gumperz, J. J. (1968). The speech community. In *International encyclopedia of the social sciences* (pp. 381–386). New York, NY: MacMillan.

Hadamard, J. (1945). An essay on the psychology of invention in the mathematical field. Princeton, NJ: Princeton University Press.

Hanrahan, M. (2002). Learning science: Revisiting humanist dimensions of intellectual engagement. The effect of learning environment factors on students' motivation and learning. *International Journal of Science Education*, *20*(6), 737–753.

Hazari, Z., Sonnert, G., Sadler, P. M., & Shanahan, M. C. (2010). Connecting high school physics experiences, outcome expectations, physics identity, and physics career choice: A gender study. *Journal of Research in Science Teaching*, *47*, 978–1003.

Hestenes, D. (1998). Who needs physics education research? *Am. Jour. Phys*. 66(6), 465-467.

Hickman, R., & Huckstep, P. (2003). Art and mathematics in education. *The Journal of Aesthetic Education*, *37*(1), 1–12.

Holton, G. (1996). On the art of scientific imagination. *Daedalus*, *125*, 183–208.

Holzer, M. F. (2005). *Teaching and learning at the Lincoln Center Institute*. Retrieved from www.lcinstitute.org.

Ivy, R., & Ray, K. N. (2005). *Women in physics and astronomy*. Retrieved from http://www.aip.org/statistics/trends/reports/women05.pdf.

Izmirli, O., & Baird, B. (2002). A model for integrating arts and technology in a liberal arts college. *Journal of Computing Sciences in Colleges*, *17*(6), 102–109.

John-Steiner, V. (1997). *Notebooks of the mind: Explorations of thinking* (Rev. ed.). New York, NY: Oxford University Press.

Katz, P., McGinnis, J. R., Hestness, E., Riedinger, K., Marbach-Ad, G., Dai, A., & Pease, R. (2011). Professional identity development of teacher candidates participating in an informal science education internship: A focus on drawings as evidence. *International Journal of Science Education*, *33*(9), 1169–1197.

Kendrick, M., & McKay, R. (2002). Uncovering literacy narratives through children's drawings. *Canadian Journal of Education*, *27*(1), 45–60.

Kessels, U., Rau, M., & Hannover, B. (2006). What goes well with physics? Measuring and altering the image of science. *British Journal of Educational Psychology*, *76*(4), 761–780.

Korey, J. (2000). *Dartmouth college mathematics across the curriculum evaluation summary: Mathematics and humanities courses*. Retrieved from http://www.math.dartmouth.edu/~matc/Evaluation/index.html

Krauss, L. M. (2007). *Fear of physics*. New York, NY: Basic Books. (Original work published 1993)

Latour, B. (2002). Lecture on Iconoclash Exhibition, ZKM, Karlsruhe, Germany, given at the Center for Contemporary Art, Kitakuyshu, Japan. Retrieved from http://www.cca-kitakyushu.org/english/voices/latour_voice.shtml

Lee, O. (2003). Equity for linguistically and culturally diverse students in science education: A research agenda. *Teachers College Record*, *105*(3), 465–489.

Lemke, J. (2000). Multimedia literacy demands of the scientific curriculum. *Linguistics and Education*, *10*(3), 247–271.

Levrini, O. (1999). *Teaching modern physics on the basis of a content knowledge reconstruction*. Retrieved from http://www.ipn.uni-kiel.de/projekte/esera/book/118-lev.pdf

Mazur, E. (1997). *Peer instruction. A user's manual*. Englewood Cliffs, NJ: Prentice Hall.

May, D. B., & Etkina, E. (2002). College physics students' epistemological self reflection and its relationship to conceptual learning. *American Journal of Physics*, *70*(12), 1249–1258.

Miller, A. I. (1989). Imagery and intuition in creative scientific thinking: Albert Einstein's invention of the Special Theory of Relativity. In D. Wallace & H. Gruber (Eds.), *Creative people at work* (pp. 171–185). New York, NY: Oxford University Press.

Nosek, B. A., Banaji, M., & Greenwald, A. G. (2002). Math = male, me = female, therefore math $\neq$ me. *Journal of Personality and Social Psychology*, *83*(1), 44–59. doi:10.1037/0022-3514.83.1.44

Osborne, J. (1990). Sacred cows in physics—Towards a redefinition of physics education. *Physics Education*, *25*, 189–195.

Pestalozzi, J. (1894). *How Gertrude teaches her children an attempt to help mothers to teach their children and an account of the method* (L. Holland and F. Turner, trans.). London; Syracuse: Swann Sonnenschein. (Original work published 1805).

Peterson, R. W. (2005). Crossing bridges that connect the arts, cognitive evelopment, and the brain. *Journal for Learning through the Arts, 1*(1). Retrieved from http://escholarship.org/uc/item/8jm7t2x8

Phelan, P. K, Davidson, A. L., & Yu, H. C. (1993). Students' multiple worlds: Navigating the boundaries of family, peer, and school cultures. In P. K. Phelan & A. L. Davidson (Eds.), *Renegotiating cultural diversity in American schools* (pp. 52–88). New York, NY: Teachers College Press.

Redish, E. F., Saul, J. M., & Steinberg, R. N. (1998). Student expectations in introductory physics. *American Journal of Physics*, (66)3, 212–224.

Rinne, L., Gregory, E., Yarmolinskaya, J., & Hardiman, M. (2011). Why arts integration improves long-term retention of content. *Mind, Brain, and Education*, *5*(2), 89–96. doi:10.1111/j.1751-228X.2011.01114.x

Root-Berenstein, R. S. (1985). Visual thinking: The art of imagining reality. *Transactions of the American Philosophical Society*, *75*(6), 50–67.

Schreiner, C., & Sjøberg, S. (2005). *Science education and young people's identity construction: Two mutually incompatible projects?* Retrieved from http://www.roseproject.no/network/countries/norway/eng/nor-schreiner-values2006.pdf

She, H-C. (1995). Elementary and middle school students' image of science and scientists related to current science textbooks in Taiwan. *Journal of Science Education and Technology*, *4*(4), 283–294.

Sjøberg, S., & Schreiner, C. (2007). Science education and youth's identity construction—Two incompatible projects? In D. Corrigan, J. Dillon, & R. Gunstone (Eds.), *The re-emergence of values in the science curriculum*. Rotterdam: Sense Publishers.

Sjøberg, S., & Schreiner, C. (2010). *The ROSE project: An overview and key findings*. Retrieved from http://roseproject.no/network/countries/norway/eng/nor-Sjoberg-Schreiner-overview-2010.pdf

Stuver, A. (2001). *Analysis of the undergraduate curriculum department of physics* (Unpublished master's thesis). Pennsylvania State University, University Park.

Sweller, J. (1999). *Instructional design*. Camberwell, Victoria, Australia: Australian Council for Educational Research Ltd.

Tobias, S. (1990). *They're not dumb, they're different: Stalking the second tier*. Tucson, AZ: Research Corporation.

Tobias, S. (2006). Letter to the editor. *Physics Today*, *59*(7), 10.

Traweek, S. (1988). *Beamtimes and lifetimes. The world of high energy physicists*. Cambridge, MA: Harvard University Press.

van der Veen, J.(2007). *Symmetry and aesthetics in introductory physics: An experiment in interdisciplinary physics and fine arts education* (Unpublished doctoral dissertation). University of California, Santa Barbara.

Weinberg, S. (1992). *Dreams of a final theory*. New York, NY: Pantheon Books.

Weisskopf, V. (1976). Is physics human? *Physics Education*, *11*(2), 75–79.

Zee, A. (2007) *Fearful symmetry*. Princeton, NJ: Princeton University Press. (Original work published 1999)

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