

Draw Your Physics Homework?

Art as a Path to Understanding and Assessment in Undergraduate Science Education

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Abstract:

This chapter draws upon results of an ongoing study of using drawing for understanding in an undergraduate course, Symmetry and Aesthetics in Contemporary Physics. Results of eight years of teaching this course to students from a variety of majors at the University of California, Santa Barbara, suggest that drawing and other artistic representations offer powerful means for students to get in touch with their own visualization and thinking styles, as well as alternative assessment strategies for instructors.

1. Introduction: Arts-based teaching- A path toward increasing diversity in physics?

In spite of government initiatives to attract a more diverse population of learners into science and technology, results of a number of studies in the United States (Hazari, et al., 2010; Blickenstaff, 2005, e.g.) and Europe (Sjøberg & Schreiner, 2007, e.g.) suggest that the standard introductory physics curriculum – the gateway course for all science and technology majors - may be a deterrent for many students, particularly females. Thus, my initial motivation for incorporating arts-based teaching strategies in an introductory physics course was an attempt to redress the persistent gender bias in physics by attracting a broader population of learners *in general*, which would naturally include females. After eight years of teaching this course, I can report that, although it remains a small-sized elective, 41% of the students who have completed my course are female - slightly more than double the most recent count of the percentage of women earning bachelors degrees in physics (<http://www.aps.org/programs/education/statistics/womenstem.cfm>, 2015). The evaluations remain consistently high, with many students reporting in their anonymous exit comments that they would not have taken physics in college if not for this class, and several physics majors reporting that this course renewed their interest in pursuing a physics degree.

The separation of arts and sciences has been ingrained in Western society at least since the 17th century, and has been embedded in American education since the 19th century (Eisner, 2002). Eisner attributes the cultural dominance of science over the arts to the Enlightenment 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).

In spite of this separation in education, *people* are not so compartmentalized in their ways of thinking, and many scientists pursue serious recreational or semi-professional endeavors in the arts. Historically, there is a likely correlation between explorations in music and discoveries in physics (Pesic, 2014). In my own life in physics and dance, I have noticed a great many people, both men and women, whom I meet at serious amateur recreational dance events (folk dance, contra dance, and ballroom competitions) have jobs in science or technology, and I know a surprising number of other semi-professional dancers (like myself) who have Ph.D.'s in science, engineering, or medicine. An email survey I sent to three international recreational dance mailing lists revealed that no less than 60% of respondents who dance

have jobs in physics, engineering, or computer science (van der Veen, 2006). According to the U.S. Census for the year 2000, only 27% of middle-income urban populations held jobs in STEM fields, including architecture. The recent movement towards “turning STEM to STEAM” in K-12 and colleges in many states is evidence that educators, artists, and scientists are beginning to reach across the divide.

My research on arts-based teaching strategies in introductory physics is intertwined with my work on restructuring the introductory physics curriculum. In my undergraduate seminar, *Symmetry and Aesthetics in Contemporary Physics*, we explore Symmetry as the mathematical foundation of physics as well as the conceptual link between physics and the arts. We trace the development of symmetry and group theory from their origins in pure mathematics to their various manifestations in the phenomenological universe, and investigate how contemporary ideas of spacetime evolved from the discovery of broken symmetries in the late nineteenth and early twentieth centuries in classical mechanics, electromagnetic theory, and the discovery of the speed of light. Throughout the course we use drawing and other artistic representations to explore, explain, and comment upon mathematics and contemporary physics.

Symmetry in physics refers to the concept of ‘sameness within change,’ and is the basis of all the laws of physics. Symmetry is the set of rules that allow us to define the invariance of a system under rotations, reflections, and translations. Historically, when physicists have confronted an apparent paradox, it has been resolved by finding the symmetry that explains away the paradox by a change of coordinates (perspective). Thus, the search for deeper symmetries in Nature propels advancements in contemporary physics. Symmetry is also an important concept in human perception, biology, evolution, neuroscience, and chemistry. Symmetry and asymmetry are central to our aesthetic experiences in the arts, and thus provide a natural foundation for an interdisciplinary physics course that incorporates arts-based teaching strategies.

I start with contemporary physics as being more interesting and relevant to the lives of 21st century youth than classical Newtonian mechanics (Levrini, 1999), and treat math and the arts as complimentary semiotic systems for interrogating the physical universe (van der Veen, 2007, 2012, 2013). Teaching beginning students about Relativity and curved spacetime brings them face to face with some of the ontological questions that motivate contemporary physics at the largest scales. Moreover, teaching about Relativity in its historic context provides the iconic example of how symmetry has come to play a fundamental role in the development of contemporary physics. It also brings to the fore Professor Emmy Noether, whose theorems on the relationship between continuous symmetries in nature and conservation laws in physics have played a seminal, yet little known, role in the development of new physical theories, and thus foregrounds the discrimination that women in physics have faced historically, and continue to face.

The seminal question motivating my research is: Can we use the arts to bring more people into a healthy dialog with physics, thus potentially increasing the diversity of learners who choose to study physics, whether to become scientists, engineers, teachers, or as part of a contemporary education? From this starting point, several results have emerged which have implications for physics education as well as education in general, regarding drawing and other arts-based approaches in curriculum design and assessment, including:

- Having students draw their understanding of an article, concept, or equation allows students to get in touch with their own visualization and thinking styles, and provides instructors insight into the kinds of thinkers their students are, so as to design curricula appropriately;
- Having students design their own artistic representations of science concepts at the undergraduate level allows them a form of expression through which to develop their own voices in math and physics, and thus deepen their personal connection with these often impersonal subjects;

- Having students design their own representations of math and physics concepts provides instructors with an alternate, in many ways deeper and more comprehensive, assessment of their understanding;
- Incorporating arts-based teaching strategies at the undergraduate level, especially in intimidating subjects such as physics, has the potential to increase interest in the subject for students who may otherwise have avoided physics.

2. Drawing as a means for students to get in touch with their own visualization and thinking styles

In my work with college students, I have found that drawing is a means by which a learner (artist) can get in touch with and express her or his own inner language and visualization style, and understand how he or she goes about the internal process of making sense of externally received information. Swiss educator Johann Heinrich Pestalozzi (1746–1827) was the first to propose the idea of the *Anschauung*: mental imagery developed by abstraction from phenomena that have been directly experienced (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* at the Kantonsschule at Arrau (Miller, 1989).

Mathematician Jacques Hadamard studied thinking processes among mathematicians and scientists in the first half of the 20th century, and found a widespread reliance on visual thinking. In a frequently-quoted letter to Hadamard as part of this study, 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.... this combinatory play seems to be the essential feature in productive thought before there is any connection with logical construction in words or other kinds of signs which can be communicated to others. (Hadamard, 1945/1954, p. 142).

In training students to think like scientists, the use of drawing and other arts-based representations, both student generated original representations and the study of professional artists' representations of physics concepts, should be an integral part of our science and math curriculum. The importance of visualization in scientific thought and discovery cannot be overstated, yet most early physics training at the undergraduate level relies exclusively on problem solving and the interpretation of graphs.

Some students visualize mathematical relationships quite easily, as reported by this first-year male physics student in 2007:

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.

For others, visualizing and translating their mental images into a physical representation is more difficult, as reported by a female political science major in 2011:

It is definitely very difficult to translate my mental image from my mind through a pen and onto paper. Although they are formed by me in my head, I almost can't grasp exactly how it appears to me.

Never the less, by the end of my course all the students are able to create a representation of a concept which inspired them, through the artistic medium of their choice – drawing, painting, sculpture, computer graphics, literature, poetry, dance, music, or a combination of media. They are able to communicate their ideas through their physics works of art to each other as well as to a general public audience in a gallery showing of their final physics works of art. They leave with a sense of pride, accomplishment, and community.

To set the tone of the course, I begin by interrogating the process of physics and the role of mathematics as a language of nature. For the first art assignment I ask students to draw their visualizations of Einstein's description of the nature of physics in his article *Physics and Reality*. Although Einstein wrote this essay in 1936, it is still relevant today.

2.1 First Drawing Assignment: Representing an Article by Einstein on the Nature of Science

Einstein's highly visual thinking style is evident in his 1936 essay, *Physics and Reality*. I assign this article as the first reading assignment in my course, *Symmetry and Aesthetics in Contemporary Physics*, which I teach every year in the College of Creative Studies at the University of California, Santa Barbara. The foundational assumptions of western science as articulated by Einstein in this piece make it an excellent starting point for discussions on the Nature of Science, summarized in the following quotes:

1. *"The whole of science is nothing more than a refinement of everyday thinking" (p.23);*
2. *"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" (p. 23-24);*
3. *"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" (p. 24).*

In Einstein's 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 successively higher layers 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 (p. 25).

The first art project I assign each year is for students to draw their understanding of this essay by Einstein. His visual writing style, coupled with my opinion that to understand the nature of science one must read the opinions of those who create and define the field, make this article an ideal starting point for introducing drawing as a means of understanding and sense-making in physics, especially in a course that seeks to create an oppositional identity to mainstream introductory physics.

2.1.1. Classifying Visualization Styles through Students' Drawings

Over the eight years I have taught this course I have observed that students' drawings fall into certain rather clear categories, suggesting that visualization style is a characteristic that reveals the way in which an individual makes internal sense out of the external world – a *language of the mind* (John-Steiner, 1997).

Previous studies have looked at the binary classification of visual and verbal learners, while others have further classified visual learners either spatially-oriented or object-oriented. According to Kozhevnikov, Kosslyn, and Shepphard (2005), object-oriented visualizers process images holistically, as a unit, while spatially-oriented visualizers process images analytically, part by part. Results of their study suggest that

scientists and engineers tend to be spatially-oriented visualizers who have an easier time recalling processes, while artists tend to be object-oriented visualizers who have an easier time recalling static images as a whole. Other studies have claimed that males tend to be spatial visualizers while females tend to be object-oriented visualizers. The results of Kozhevnikov, et al. (2005) suggest that there is no clear correlation between biological gender and either spatial visualization strategy or ability to solve abstract mathematical problems. A number of studies suggest that males tend to perform better than females on a variety of spatial orientation and mental rotation tasks (Collins & Kimura, 1997; Geary & Soto, 2001, e.g.). Hegarty and Kozhevnikov (1999) found that visual-spatial representations used by elementary school children while solving mathematical problems can be reliably classified as primarily schematic, associated with understanding spatial relationships from multiple perspectives, or primarily pictorial and object oriented. Moreover, they found that the use of primarily schematic spatial representations was positively correlated with success in mathematical problem solving, while the use of primarily pictorial representations was negatively correlated with success in math but positively correlated with success in art (p. 51). On the other hand, studies of visual imagery by Campos, Gomez-Juncal, and Perez-Fabello (2007) suggest that it is experience, rather than gender, which dictates a student's competence at generating mental images, and that the ability to produce vivid mental images is a learned skill that can be enhanced through instruction and practice.

When I began analyzing my students' drawings, I was curious to see whether the drawing styles of physics majors, biology majors, arts majors, and humanities majors would have any distinguishing recognizable characteristics, and whether the drawing styles of biological males and females would be different. I find that elements of spatial, temporal, and part-by-part visualizations, as well as holistic, at-a-glance types of drawings described in previous studies do not follow boundaries of gender or major in college. Rather, I observe six general categories of visualization styles, which emerged after four years of collecting students' drawings of their interpretation of the Einstein article. In the spirit of Grounded Theory, in which theory emerges from data, I developed a means of coding students' drawings based on general characteristics I found in their representations from year to year:

1. the type of symbols used: abstract or pictorial;
2. the type of representation: direct mapping of concept in the article to symbol in the picture or representation of the article as a whole 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 (van der Veen, 2012).

Based on these characteristics, I named six categories of visualization style: *abstract-representational*, *direct-symbolic*, *metaphoric/analogical*, *allegorical-creative*, *flow chart*, and *hybrid* (van der Veen, 2012). After eight years, these categories remain. Moreover, certain themes within the general visualization styles have begun to repeat themselves.

Direct-symbolic drawings utilize recognizable objects or symbols to represent concepts in the article in a literal, one-to-one mapping of symbol to concept, sometimes with arrows drawn to indicate correspondences, or with labels placed directly on the drawing. Some drawings depict the hierarchy of concepts with a pyramid, while others use examples of what students consider to be a hierarchical ordering of concepts (microscopes to telescopes, e.g.), but all are more-or-less literal interpretations of the article (Figures 1- 4).

Abstract-representational drawings are also literal interpretations of the article, but use abstract symbols with a one-to-one correspondence between the symbol in the drawing and the concept in the article instead of recognizable objects. No labels are included directly on the drawing, but the direct, one-

to-one correspondence between symbol in the drawing and concept in the article is described by the student in the written or verbal description of his/her drawing (Figures 7 and 8).

Metaphoric/analogical drawings use a metaphor or analogy to represent the article as a whole with a single vision, almost a poetic painting that captures what the student artist senses as the gestalt of the article (Figures 9 – 11).

Allegorical-creative drawings represent the article as a whole with a pictorial story (allegory or ‘what if’ scenario) that seems to begin where the article leaves off (Figure 12).

Flow charts incorporate some element of temporal progression using arrows to indicate the sequential nature of science or the flow of concepts. The drawings I have classified as flow charts utilize a range of symbols connected by arrows to represent the flow of ideas in the article, from completely pictorial to completely verbal (Figure 13).

Hybrid drawings do not appear to fit squarely into a single category, but embody elements of two or more categories, such as direct-symbolic and allegorical (Figures 5a and 5b), direct-symbolic and metaphoric-analogical (Figure 6), and flow chart and metaphoric-analogical (Figure 14).

After four years of giving the same initial drawing assignment, I noticed these patterns and named them. I searched for a theoretical model through which to build a case for a relationship between students’ preferred visualization styles and their preferred learning styles, and found Felder and Silverman’s (1988) model of learning preferences of engineering students (Felder & Silverman, 1988; Felder, 1993). In their original model, Felder and Silverman describe five opposing traits which, in varying proportions, describe students’ learning preferences: sensory vs. intuitive, visual vs. verbal, inductive vs. deductive, active vs. reflective, and sequential vs. global. I looked for a correlation between the visualization styles I found in my students’ drawings and Felder and Silverman’s learning preferences model (van der Veen, 2012). However, after eight years of giving the same initial drawing assignment, I feel that it is more appropriate to interpret these visualization styles as “languages of the mind” (John-Steiner, 1997) rather than constrain them by any specific cognitive-behavioral descriptions, as students who draw the same type of visualization do not necessarily fit into similar learning patterns. Rather, students’ preferred visualization styles are a kind of window into their minds, providing insights into their backgrounds, the experiences they bring to the study of physics, their prejudices and personal philosophies, as well as how they process information. In a very real sense, students’ drawings in an undergraduate physics seminar reveal the literacy narratives they bring with them (Kendrick & McKay, 2010), and use to make sense out of their study of physics.

I use this first drawing assignment not only to set the tone of using drawing as a means of sense-making and communication in physics, but also to encourage students to find their individual ‘visualization voices,’ and understand their own internal ways of knowing and sense making. My students continue to develop their representational competence in three more arts-based assignments throughout the course, culminating in their final physics works of art. The final projects are displayed in one of the campus art galleries, with a public reception in which the students must explain the concept(s) they have chosen to represent to an audience of peers, faculty and staff, and members of the public (see, for example: <http://www.news.ucsb.edu/2015/015237/art-physics>).

Next I present examples of the six types of visualization categories that have emerged from the first art assignment, “Draw your understanding of Einstein’s article, *Physics and Reality*.”

2.1.2 Data: Drawings of Einstein’s 1936 Article, “Physics and Reality”

Direct Symbolic Representations

The unifying feature of direct-symbolic drawings is the one-to-one mapping of symbol in the drawing to concept in the article, often with labels written directly on the drawing. Some students choose to represent the *process* of doing science described by Einstein as a linear progression, while others choose to represent the *hierarchy of concepts*, but in either case there is no ambiguity as to the correspondence between symbols in the drawing statements in the article. Examples of of direct-symbolic drawings by a literature major, a political science major, an art major, and a religious studies major are shown in Figures 1, 2, 3, and 4, respectively. I have chosen these examples because they are all direct symbolic drawings, but also display a range of interpretations by students who have had limited or no prior exposure to physics.

Figure 1, drawn by a literature major, who stated that she would have been more comfortable doing a literary interpretation, such as a poem (which she did for her final project), than a drawing:

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.

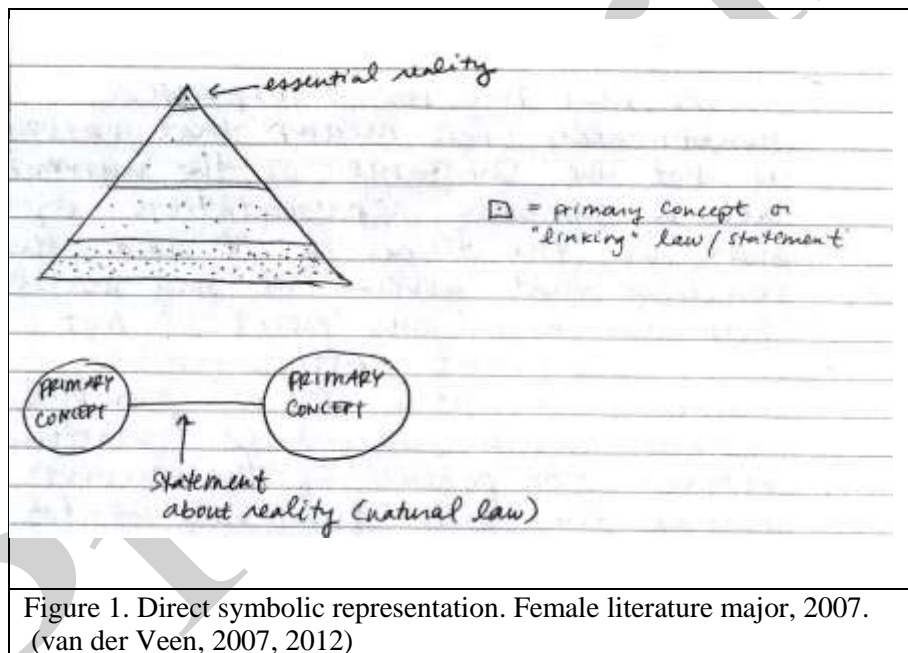


Figure 1. Direct symbolic representation. Female literature major, 2007.
(van der Veen, 2007, 2012)

Figure 2, drawn by a female political science major, depicts the process of doing science as linear, starting from external events which are taken in by the senses to form an internalized concept of reality, represented by an array of mathematical and musical symbols, depicted in no particular order.

The ability to construct a reality or external world comes from the associations we make between our sensory inputs and our concept of bodily objects. Our minds give significance to these concepts and the relations between different concepts allow us to connect sense expressions and create a "reality." This translates into comprehensibility which is the production of some sort of order among sense impressions.

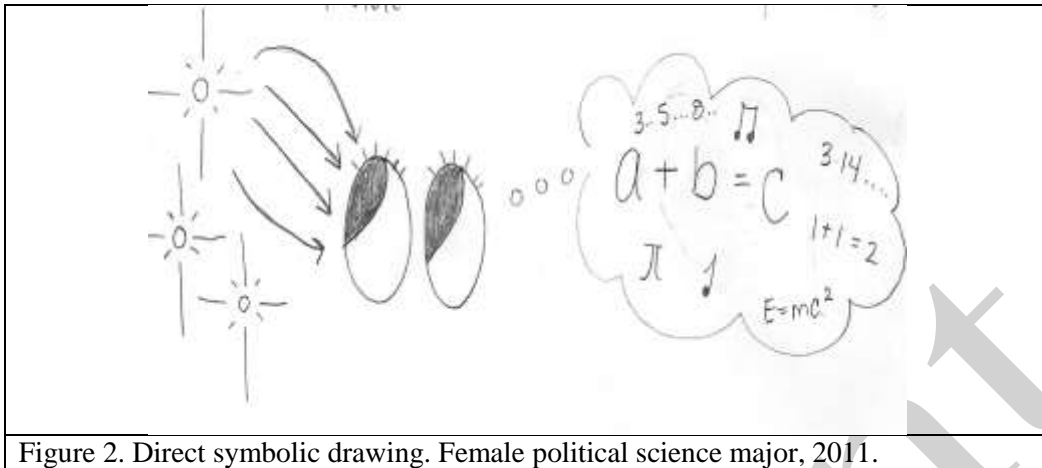
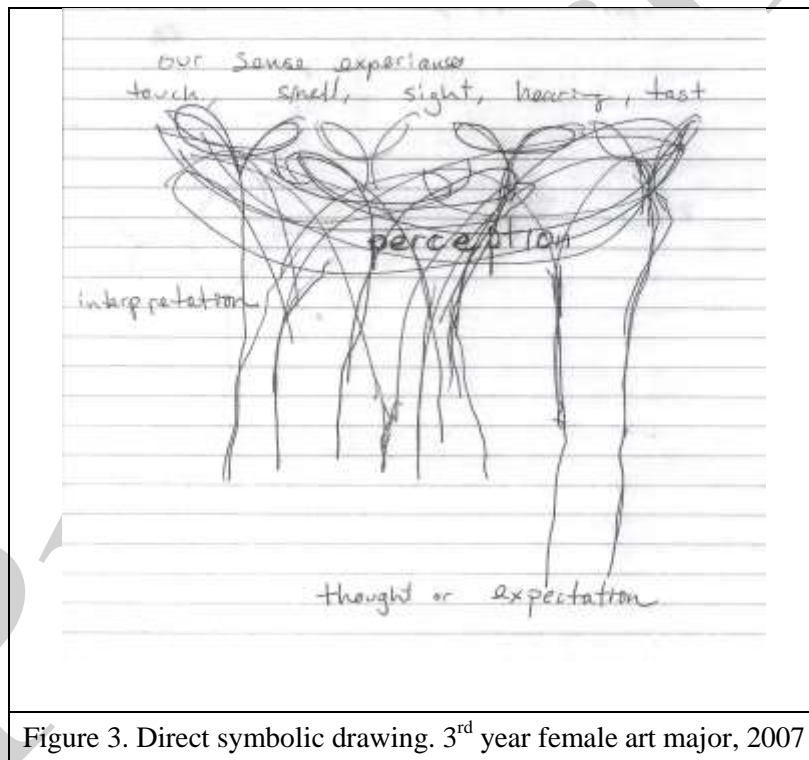


Figure 3 was drawn by a third year female art major. I classify it as direct symbolic because of her use of labels on the drawing.



In her brief description she referred only to statements made by Einstein in the first two pages of the article, before he

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

Her interpretation of Einstein's culmination of the layers of sensory input and theory leading to the "greatest conceivable unity" of concepts as merely "thought or expectation" could represent the fact that

she did not complete the reading assignment, but did not want to come to class empty-handed, or perhaps I should have recognized her drawing as a sign that she was going to need extra help. Throughout most of the course she expressed an intense mistrust of physics and physicists, including physicists' use of language and their emphasis on theory over sensory perception. Her frustration reached its peak expression in her literary argument with Nobel Laureate Richard Feynman's description of the surface of a cylinder as a flat space (Feynman, 1963):

"...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 because a cylinder is obviously curved to an outside perspective despite not having intrinsic curvature."

She continued and her verbal confrontations about this issue with me, with the physics majors in the class, and after class with a post-doctoral scholar with whom I shared an office at that time. By the end of the course, though, she reversed her opinion, and wrote in her final evaluation:

I found this course to be wonderfully exciting. The instructor and the students were wonderful and passionate, which made the class a pleasure. I had to overcome and grapple with a lot of struggles with math and understanding the language of science. I wish that this class would continue and I could continue to study the maths and science in such an integrated way.

Figure 4 was drawn by a third year male religious studies major. I classified his drawing as direct symbolic because he lists his legend in the upper left, and uses labels and arrows to indicate the correspondance of symbols in his drawing to his legend.

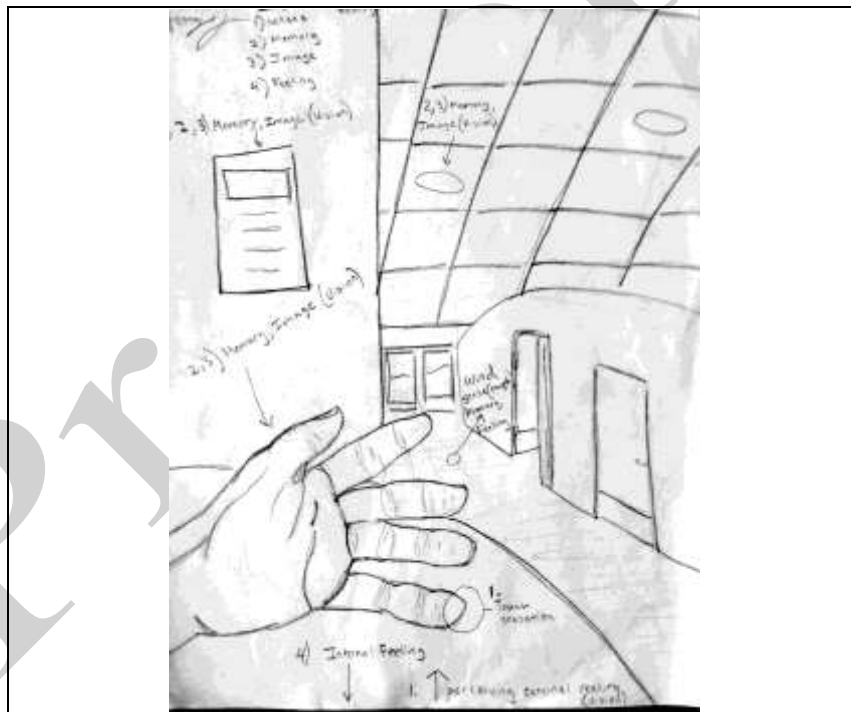


Figure 4. Direct symbolic. 3rd year male religious studies major, 2014.

Like the art major who drew Figure 3, his interpretation of the article also diverges from Einstein's intention. He starts with sensory input, but ends not with "logical unity" but with *feeling*. In his drawing, "Internal Feeling" is indicated with an arrow as being outside the perimeter of the drawing, off the page (bottom) or out the door. Kendrick and McKay (2002) suggest that children's drawings reveal a great

deal about the literacy narratives they bring with them to school. Referencing Vygotsky (1978), they suggest that drawings represent “a graphic speech that conceptualizes an internal representation of story” . Both Figures 3 and 4 suggest that the science-literacy narratives their creators brought to the course differ significantly from the majority opinion in the physics community. For his final project, the artist who drew Figure 4 chose to draw his interpretation of an article we read by theoretical physicist Andrei Linde about the “multiverse” – the possibility that ours is only one of an infinite number of universes – as a male being inflating a balloon. He wrote:

The idea behind the drawing is that someone is blowing up the balloon bringing up the question of a divine being behind all of the universes [sic] activity. [...] It seems that there is [sic] always new theories pertaining to the external world, and a lack of looking inwardly for explanations of physical reality.

Figures 5a, 5b, and 6, drawn by male physics majors in 2013, 2015, and 2014 respectively, are examples of what I consider hybrid drawings because they combine elements of direct symbolic mapping of the narrative of the article with allegorical and metaphoric elements.

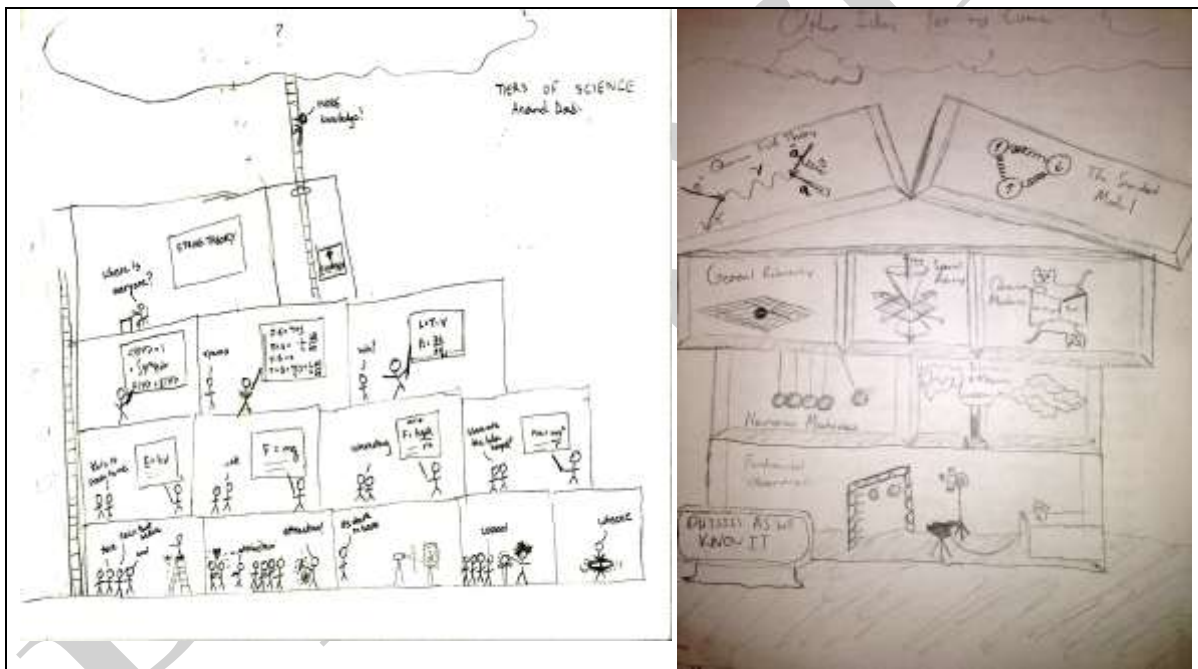


Figure 5. Hybrid: Direct symbolic/ allegorical. 5a (Left): Ananda Das, 3rd year physics major, 2013. 5b (Right): 1st year male physics major, 2015.

Figures 5a and 5b show the process of doing physics, starting from sensory observation on the first floor, moving up through increasingly abstract levels, and ending with the unknown - represented by clouds above. As cartoon-like interpretations of Einstein’s article, these drawings relate his levels of abstraction described to the artists’ personal experiences. The artist who drew Figure 5a explained:

This was my interpretation of Einstein’s article. The bottom floor represents the “sense impressions”, those basic observables that everyone sees and agrees with and as you go higher up, we see the scientists need to attain logical unity, creating more and more abstract formulas to

describe more and more general stuff. As you go higher in the building, less people can relate as we go farther from the “sense impressions”.

Figure 5b represents the first instance in 8 years that I have seen of the recurrence in a subsequent year, not just of a drawing type, but almost a repeat of the same drawing.

Hybrid: Figure 6, a water color painted by first year physics major Eric Martinez, is a picture at a glance of the process of physics, with a beach scene as a metaphor for the development of theories from direct observations, but also has elements of a direct symbolic drawing because of his one-to-one mapping of concept in the article to symbol in the drawing.

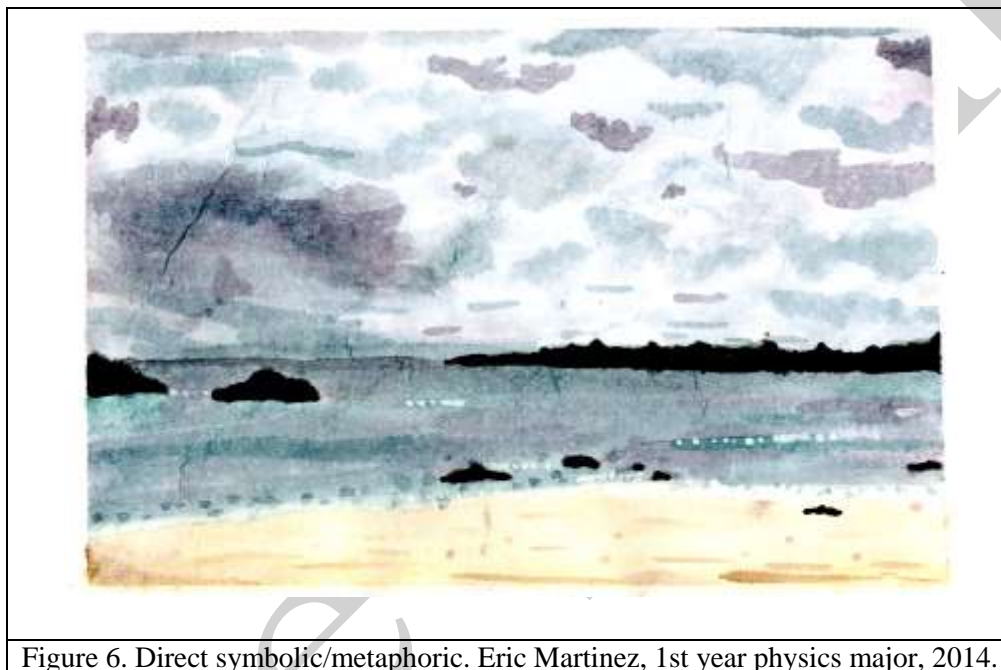


Figure 6. Direct symbolic/metaphoric. Eric Martinez, 1st year physics major, 2014.

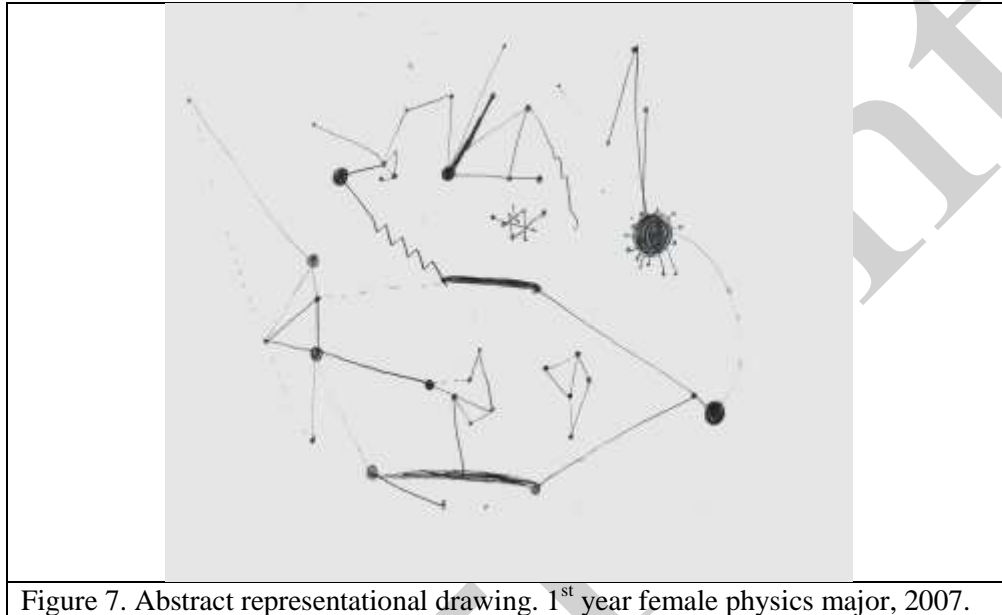
The artist described his work thus:

I took the process of “doing physics” not to mean how an individual does physics, but rather how we as a people do physics. Furthermore, I see physics as the restless science, it never ceases to look for answers. Where biology and chemistry stop, physics continues. It seeks to understand the true nature of everything. Here I have a watercolor landscape of a beach. It is a metaphor for our understanding of everything. You may notice the island out in the distance and the small rocks embedded in the surf. I used the rocks and the island to symbolize distinct points of knowledge waiting to be discovered out in the universe. We start from one, perhaps the smallest might be our realization of kinematics; it is closest to us relative to our sensory experiences. We can all observe a falling object, an object in motion. From here we may build upon our observation and form layers as Einstein described it. The next rock perhaps the discovery of the unity of Electricity and Magnetism, and the large rocks to the left a truer glimpse of reality as we know it. They might represent Relativity, Quantum Mechanics. The island is a great distance away, but one might say reachable. As you can see the colors are typically muted. I used an assortment of grays to give the impression of a fog, in order to symbolize the obscurity in the universe and the

abstraction that comes with the accumulation of layers, in this case symbolized by the distance from our rather modest start, the humble pebbles in the surf.

Abstract Representational Drawings

Abstract-representational drawings are one-to-one mappings between concept in the article and symbolic representation on the paper using abstract symbols, rather than recognizable objects. Figure 7, drawn by a first year female physics major in 2007, is my iconic example of an abstract representation of the article.



She wrote:

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. [...] 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."

Figure 8 was drawn by a fourth year male physics major. He explained that the five corners with different types of abstract designs represent the five senses, each sense giving a different perception of external input.

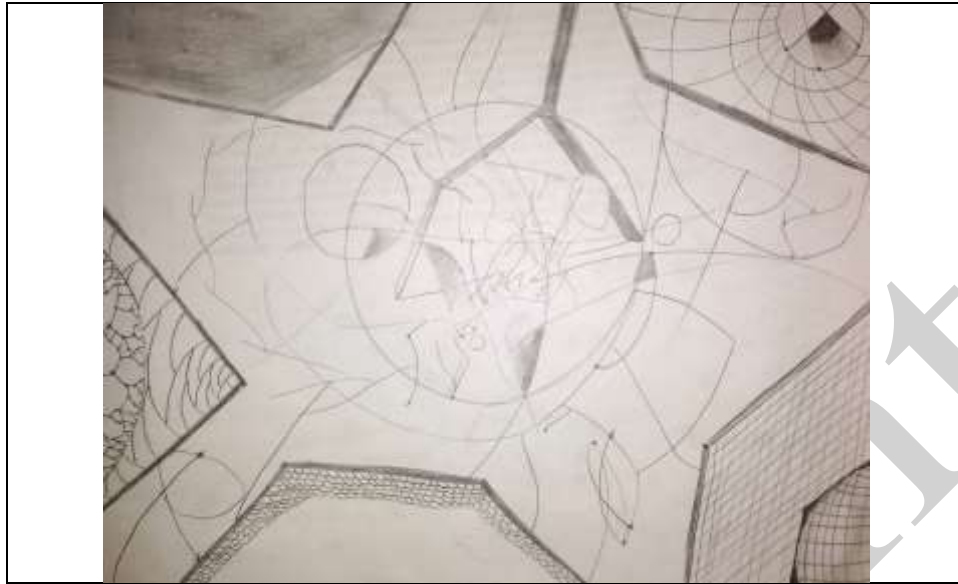


Figure 8. Abstract representational drawing. 4th year male physics major, 2015.

Metaphoric / Analogical Representations

Figures 9 through 11 are examples where the student represented Einstein's description of the process of doing physics with a single pictorial metaphor. Whereas the direct symbolic and abstract representational drawings are more or less pictorial mappings of the *processes* described by Einstein, these metaphoric drawings are a snapshot of the *gestalt* of the article *as a whole*, as experienced by these artists.

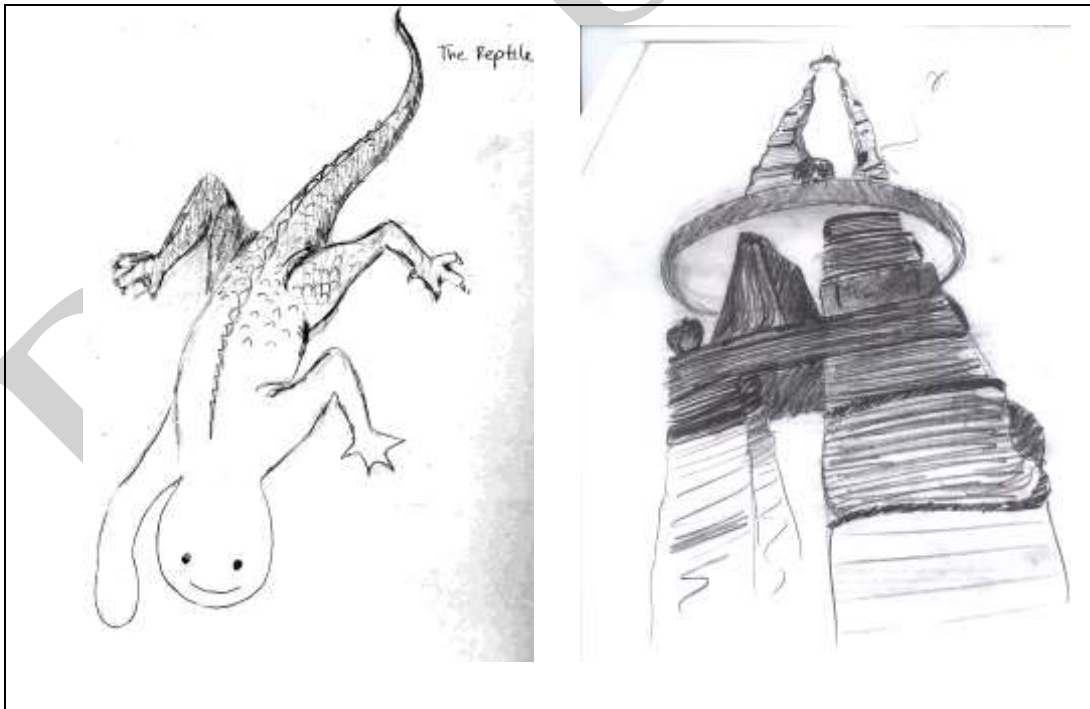


Figure 9. Metaphoric-analogic drawings. Left (9a): The Reptile of Science, second year male math major, 2008. Right (9b): (no title), first year male physics and math major, 2007.

Figure 9a was drawn by a second year male math major. He explained his drawing:

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 stickfigure-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.

The artist who drew Figure 9b was a first year male double-major in physics and math. Rather than give his reader (in this case, the instructor) a blow-by-blow description of his drawing, he lets the symbolism speak for itself:

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

Figure 10 was drawn by Lodovico Griccioli, a first year male physics major. He likened the process of doing physics to peeling back the layers of an onion:

The way I picture the creative process of scientific discovery, especially in theoretical physics, it's quite overwhelming. The amount of theories and equations before one can find the truth, are endless and even then we can only be so sure. This contrast of beauty and struggle reminded me of an onion; on the outside it's wrapped in crunchy, dirty brown paper but as the first layer is removed it's quite shiny and pretty and as each layer is torn off the next is smoother and whiter, quite like how science is less messy and more elegant and symmetrical at each major breakthrough. But in the process of peeling back the platinum layers of the onion there's a pungent smell and tears begin to flow this reminded me of the feeling of awe when learning about Einstein's theory relativity for the first time, how it seems wildly incompatible with the reality we experience but at a closer look it is absolutely correct. At the center of the onion I drew an eye at the point where the onion stops being layers, when there is normally just a small white bulb, to represent the final truth, as if to be looking into the eye of god at the end of the journey.



Figure 10. Metaphoric/analogical drawing, Lodovico Griccioli, 1st year male physics major, 2015.

Hybrid: Figure 11, drawn by Nikola Kapamadzin, second year male math major, I have classified as hybrid, as I feel it combines elements of a metaphoric/analogical representation of the article as a whole with an allegorical/creative story in which the artist interprets Einstein's intentions with a scenario that goes beyond the article. He writes:

My picture is of a man meditating inside of a particle accelerator. However the darkened, meditating man is only a symbol for Einstein's "sense experience." [...] This person represents the essence of the creativity and intuition of whoever made what's being studied possible. [...] The man in the middle of the accelerator is referring to this intelligent being of collective thought that has been produced alongside the information that was received by the researchers, the people that made the hardware possible, and the theorists. This seems to encourage the collaboration of mankind toward science as well as advocate intuition in physics and science. When gathering information from this particle accelerator you not only see the information you're after, but you also see the stream of intelligent thought that went into this creation in knowledge. I think in his article Einstein wants to portray the importance of intuition and creativity in the scientific method for discovery.



Figure 11. Metaphoric/analogical drawing, Nikola Kapamadzin, 2nd year male math major, 2015.

Allegorical Representations

Allegorical representations take off from the article with a pictorial allegory or a 'what if?' scenario. These drawings often have a whimsical flavor reminiscent of the drawings of highly creative adolescents described in the famous study by Getzels and Jackson (1962), in which they contrasted high-I.Q. and highly creative adolescents in a Midwest suburban high school. When asked to produce drawings, the students identified as high-I.Q. depicted literal representations of the drawing prompts, whereas those identified as highly creative drew whimsical, less rule-bound interpretations (Getzels & Jackson, 1962). Figure 12 is my iconic example of a 'what if?' scenario, drawn by a second year female political science major. In her drawing she explores the possibility of a different reality that would be developed by beings which the sense of sight is missing. She wrote on her drawing, "This is a lighted version of a world with

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

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 [sic] 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 paper: “6th sense: heat sensory? Privacy is not a term. Beauty changes.”

Other examples of allegorical drawings that my students have depicted include the familiar story of Plato’s Cave (see van der Veen, 2012, p. 388) and the story of the blind scientists who try to define an elephant by each investigating a small portion of the animal.

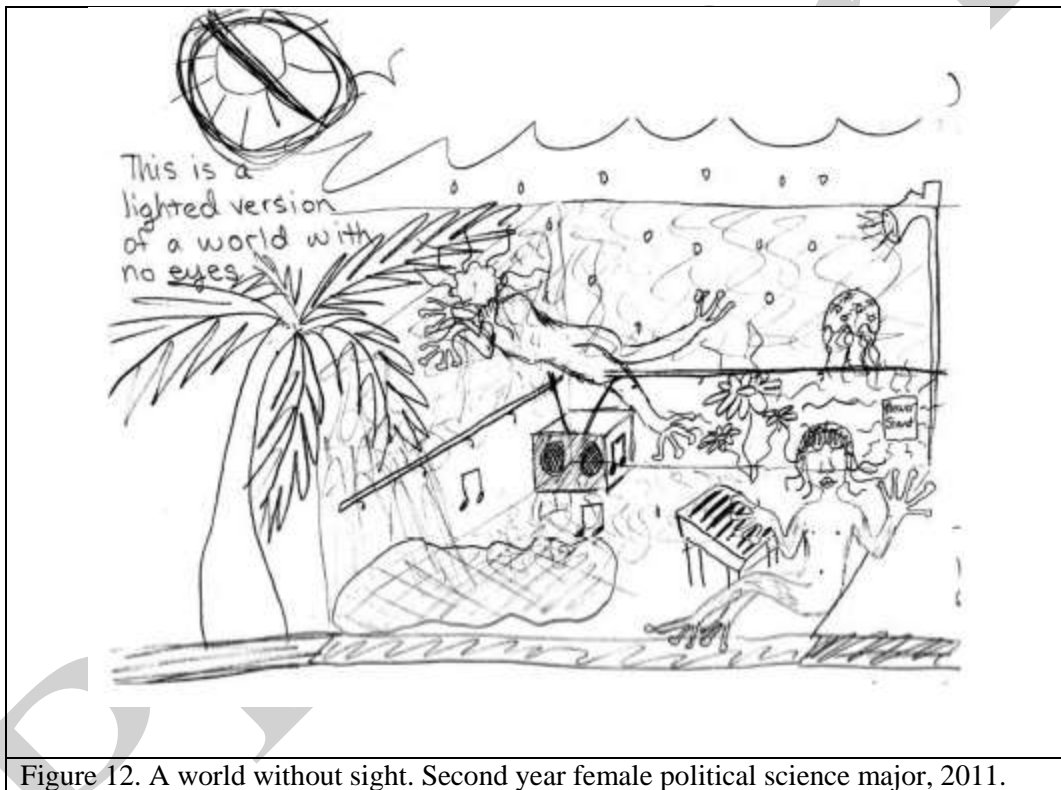


Figure 12. A world without sight. Second year female political science major, 2011.

Discussion: The use of drawing for understanding has the potential to reveal highly creative students, who would probably go unrecognized in a conventional introductory physics class. Anthropologist Sheila Tobias refers to the search for talent that is “differently packaged from the norm” (Tobias, 2006) as *stalking the second tier* (Tobias, 1990). In her study of highly motivated, “A” students from non-science majors, some of whom had positive experiences with physics in high school but all of whom avoided physics in college, Tobias found that the impersonal culture of the introductory physics classroom and the lack-of-narrative, no-room-for-questions pedagogical style were some of the main reasons why a large portion of talented students avoid physics in college. From my students’ weekly and end-of-term evaluations (which are supposed to be anonymous, but some students choose to sign them), it is evident

that the approach taken in this course has the potential to redress some of the culture of physics issues which serve as barriers to many talented, non-traditional students:

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 (female political science major, 201).

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 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, 2007).

Thank you so much for teaching this class. I don't think I've ever been quite so stimulated by a class here as much as your class has done for me. I thought the material was awesome and the readings were great, although difficult at times. Thank you for opening up my mind more! (female biopsychology major, 2010).

Flow Charts

I define flow charts as visual representations that indicate progressive relationships between concepts, often depicted with arrows or connecting lines. Though other drawing styles may contain elements of temporal progression, in flow chart drawings the mapping of the flow of ideas is the dominant characteristic. Figure 13 was drawn by a fourth-year male physics major in 2007. 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.

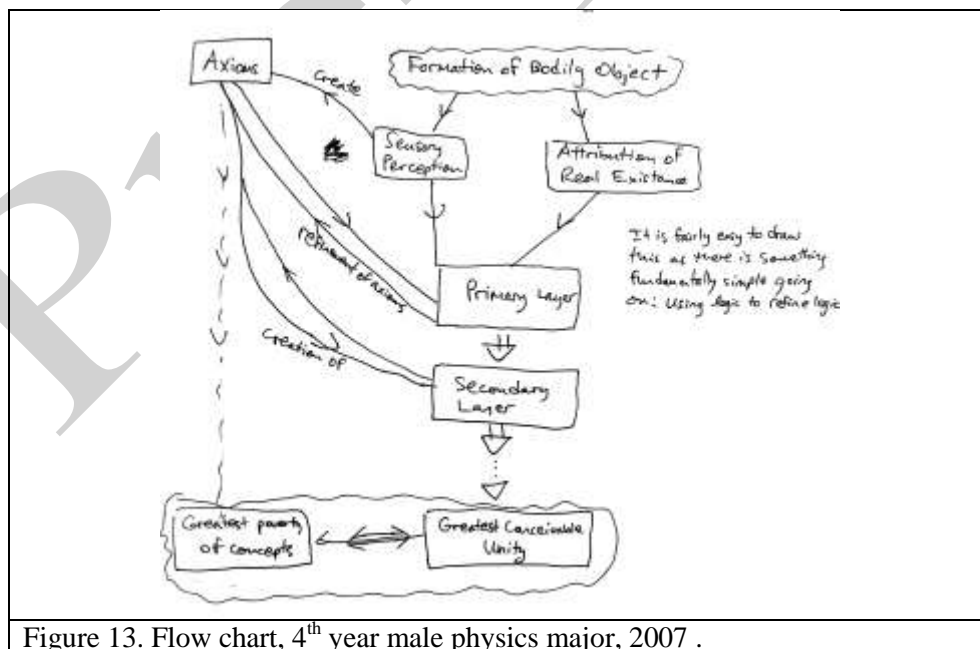
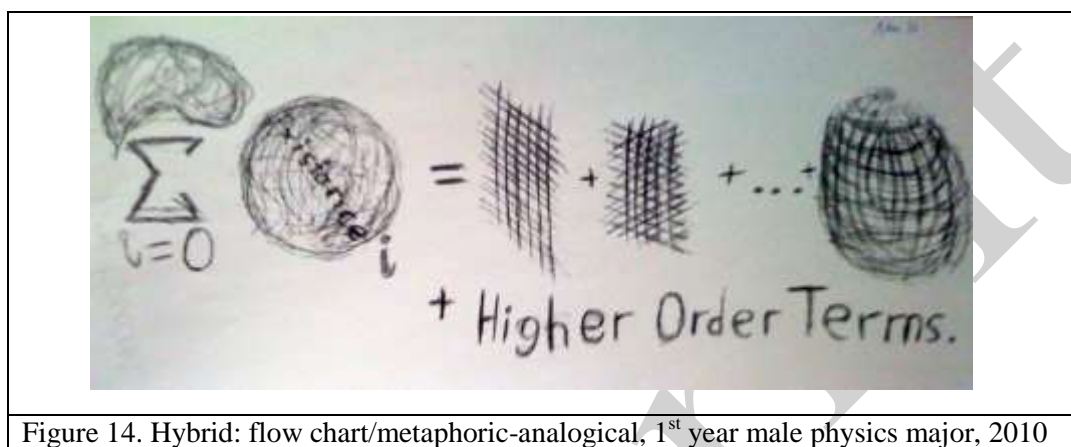


Figure 13. Flow chart, 4th year male physics major, 2007 .

Figure 14 is a hybrid between a metaphoric/analogical representation of the article-at-a-glance and a flow chart, in the sense that it depicts a temporal progression of the development of ideas as an equation, going from left to right across the page, but uses the metaphor of a pictorial representation of an equation to represent the hierarchy of the layers of understanding. The artist explained his drawing, “The sum, from $i = 0$ to infinity 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.



Over eight years of teaching this course and giving this assignment, with an average of ten to twelve students in each class, only five students have drawn what I call flow charts, and only one student drew a flow chart without any accompanying pictures (Figure 13). (He also used the same drawing style in a later assignment (van der Veen, 2007, Fig. 6.13, p. 265).) I cannot say whether visualizing in temporal progression is an uncommon thinking style, or whether a course called Symmetry and Aesthetics in Contemporary Physics, which advertises a physics work of art as the final project simply does not attract these kind of thinkers.

Discussion: Assigning a visual representation of Einstein’s essay as the first drawing and reading assignment of the course sets the direction in terms of both content and expectations. His article describes physics as the search for deeper and more unifying theories; this sets the trajectory for the course, in which we take the point of view that symmetry provides the framework for that search. Having students draw their interpretation of his article sets the expectation of developing one’s internal visualization style for the purpose of understanding and communication of ideas and opinions; and critiquing this article by one of the most idolized icons of the physics community encourages and endorses students’ forming and sharing their own opinions about the practice of physics. For most students, this assignment represents their first experience with being asked to draw their understanding of a text, and being asked to give their opinion about physics. This first drawing assignment is also an opportunity for the instructor to get an idea of his or her students’ visualization styles. While students’ comfort levels and competence at designing representations of physics concepts is expected to improve over the duration of the course, their visualization *styles* do not change. Thus by getting an idea of how each student processes information, the instructor can use this knowledge to assess students’ understanding of concepts through their visual representations throughout the course. In the next section I present examples of students’ representations of concepts in theoretical physics, comparing correct representations with representations that illustrate where students are having difficulty.

2.2 Undergraduates' artistic representations of concepts in Special and General Relativity

Having students design their own artistic representations of science concepts at the undergraduate level allows them a form of expression so as to develop their own voices in math and science, and provides an alternate, in many ways deeper and more comprehensive, assessment of their understanding. Having students design their own representations of concepts in physics also encourages the development of *meta-representational competence* (diSessa, 2004, p. 293-294) which includes having students invent or design new representations for concepts in science, explain and critique representations, and understand how representations function in conveying ideas (ibid.). In conventional physics classes, students are taught to interpret and reproduce standard representations (graphs, force diagrams, e.g.), but by inventing their own representations, they are actually participating in the work of scientists, who continually seek ways to artistically represent new ideas and discoveries to the public and to each other. In this section I present examples that illustrate when students' clear understanding is apparent from their artistic representations of concepts, as well as examples of how to use students' representations to understand where they need help as well as what they do know. In addition, I have included some of the same artists whose visualization styles were represented in the previous section, to highlight the consistency of students' visualization styles.

2.2.1. Students Representations of Concepts in Special Relativity

For the final physics work of art students select a topic from the course that most interested them, or one which generated questions they wish to explore beyond the scope of the course. Figures 14 and 15 show two different representations of the concept of the light cone. Figure 14a, a wire sculpture representing the intersecting light cones of two observers in relative motion at a constant velocity, was done by third-year physics major Ananda Das (see also Figure 5a). In a post-course interview the artist explained his motivation to create this physics work of art:

My motivation behind creating this piece was that Special Relativity confuses everyone, even the physics majors, and I definitely needed to see it three or four times before I really grasped it. And so I wanted to come up with a way to easily demonstrate weird three dimensional, four dimensional concepts that they talk about. And in particular, a certain paradox that I've found interesting, and easy to illustrate as well.

Figure 14b, a computer-generated work of art, produced by second-year computer science major Tai Rodrigue. In his written explanation the artist describes the concept and his fascination with the ideas of Special Relativity, approaching a kind of awe or reverence, and he uses his work to inspire others. He writes,

For my final project I decided to present the Einstein-Minkowski spacetime, characteristically represented by a light cone which was first conceived by Hermann Minkowski. The double cone is centered at every event in spacetime, with the upper (future) cone representing the future of a light-flash emitted at that event, and the lower (past) cone representing all the direction from which the light-flash could have come from [sic]. The slope of the cone is dependent on the speed of light. <...> For me, the light cone is a symbol that represents not only how modern physics has changed our perception of space and time, but also causality, existence and the physical limitations of what is possible for us to detect and know.

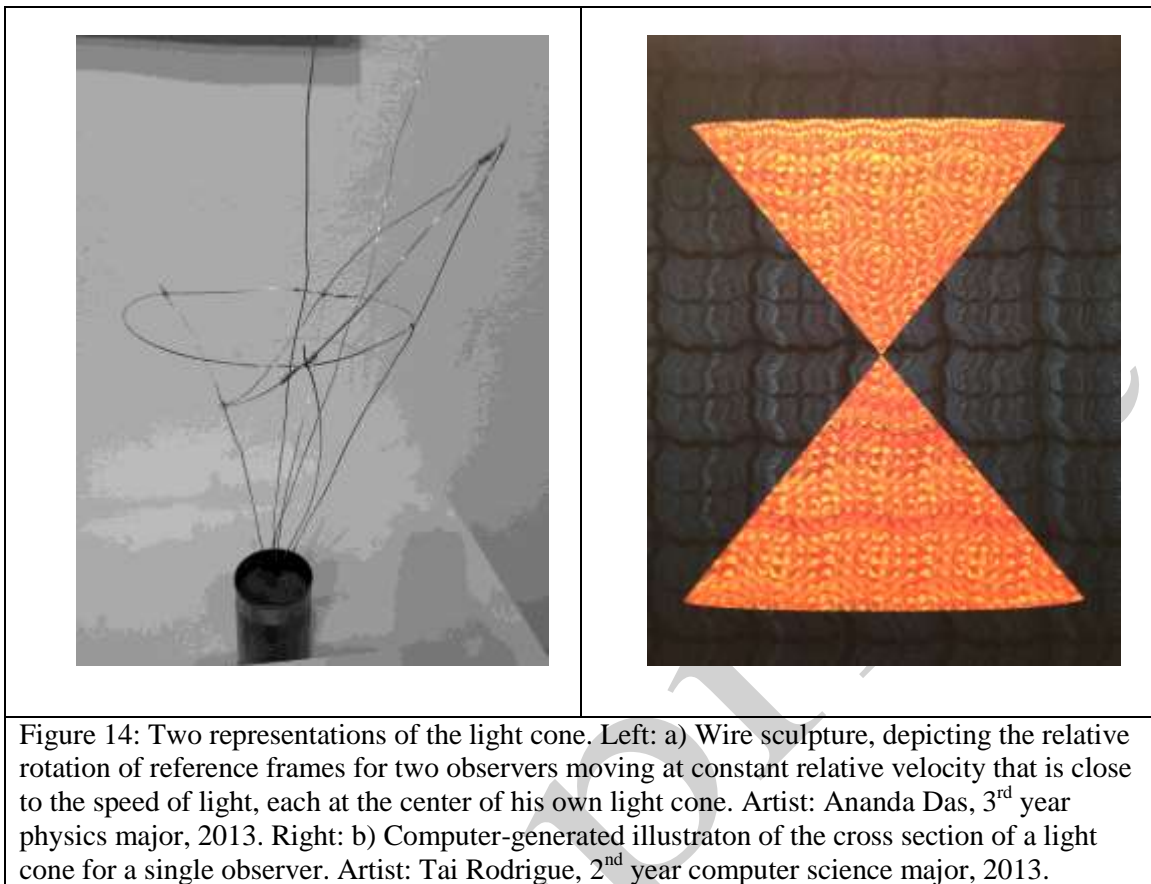


Figure 15 shows part of the illustrated explanation of the wire sculpture shown in Figure 14a. The artist writes,

If a person in the dark emits a flash of light, he perceives himself to be at the center of an expanding sphere of light, but another person running away from the first will also perceive himself to be at the center of an expanding sphere of light. How can this be? The explanation is that motion can rotate your perception of space and time.

He wrote a multi-page illustrated explanation, which he designed in the traditional physics way of posing a question, confronting an apparent paradox, and then removing the apparent contradiction with a change of reference frame in which the paradox vanishes. His visualization and representational style is consistent, from his first assignment (Fig. 5a) to the final project, as is his incorporation of humor.

The top row of the cartoon depicts a single person, who is apparently in the dark (“It’s dark. I’m scared.”) and who turns on a light (“what does this button do?”). From that ‘event’ in spacetime (i.e., turning on the light) we then see a cross section of the expanding light cone. In the bottom row we see a second observer appear, whose motivation to run in a different direction is the fact that he stole the first person’s wallet (“Hey, he stole my wallet!”).

I would also include my write-up as part of the art project, because I enjoyed doing it, and I definitely think that humor and simplicity are very important in communicating a deep concept, because I definitely found a lot of people just switch their brains off when someone talks about their physics to them. And it’s important to kind of trick them into learning something new.

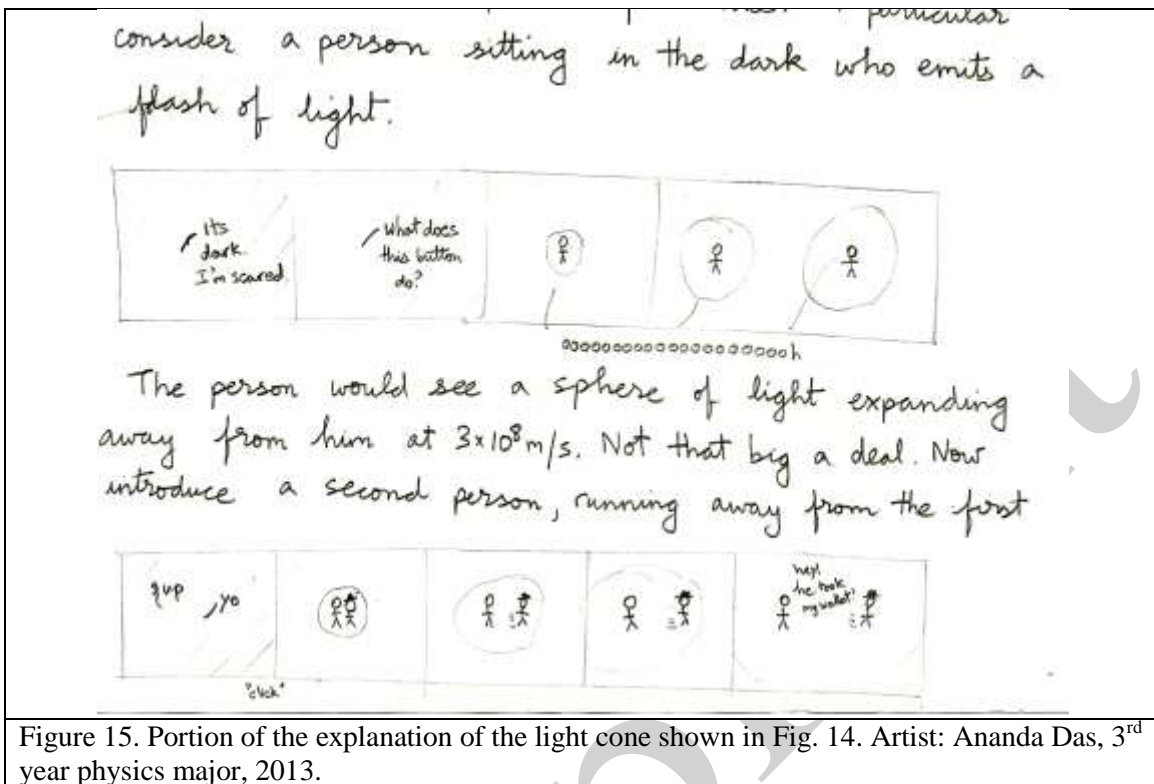


Figure 15. Portion of the explanation of the light cone shown in Fig. 14. Artist: Ananda Das, 3rd year physics major, 2013.

Figures 16a and 16b contrast two students: the first, a physics major, who has a solid command of the topic of length contraction and time dilation for two observers in relative motion at constant velocity close to the speed of light; and the second, a non-physics major who is struggling with the concepts, has understood some of them, but has missed some of the key elements. Both were drawn in response to reading a short section about the Lorentz Transformation from Einstein's short book entitled *Relativity – The Special and the General Theory – A Clear Explanation that Anyone Can Understand*, which he intended for a general audience. Prior to assigning this reading, students had a lecture-presentation on the historic development of Special Relativity. The class was then given the reading by Einstein for homework, with the assignment to draw the way they visualized what he was describing through his equations and discussion. The goal of this assignment was to see whether, after having had some practice with visualizations of Einstein's writing and some of the math of symmetry, students could read a new text and apply their visualization strategies to a new concept.

Figure 16a (drawn by a fourth year physics major) is an allegorical representation illustrating the apparent paradox of two reference frames – the frame of the snake and that of the platform - in relative motion at speeds close to the speed of light ("c"). The caption says:

Snake moving at .99c: In its reference frame, the cutters appear to be closer together, and will easily cut the snake in 3. But, in the cutters' reference frame, the snake seems shorter, short enough not to be cut. Which happens?

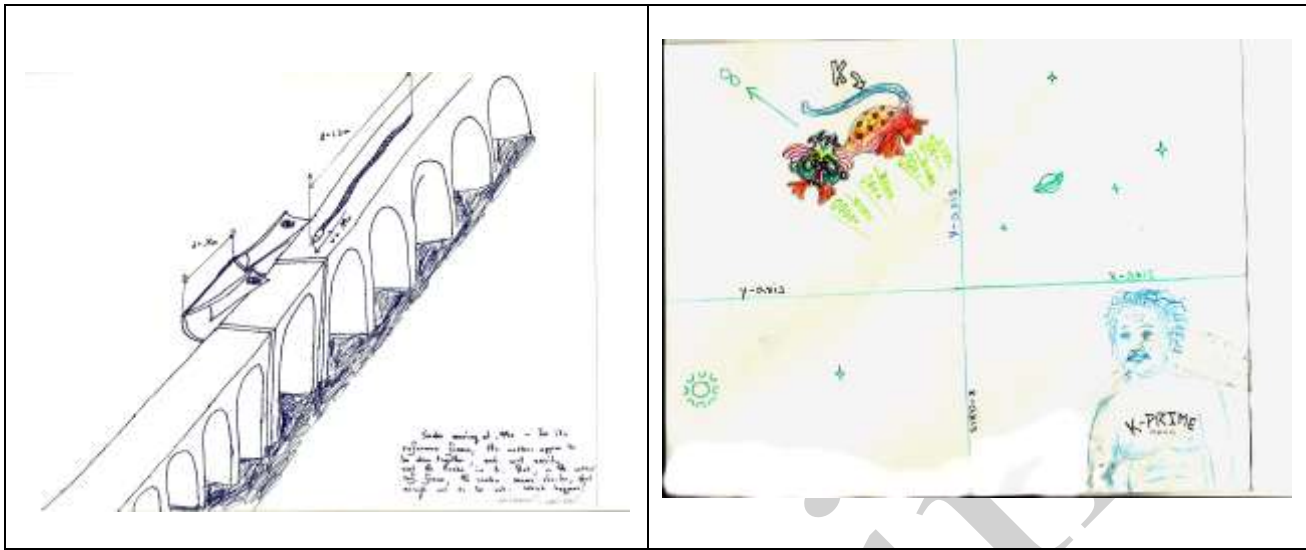


Figure 16. Representations of the apparent paradox of relative motion of two observers at a constant velocity, when their relative speed is close to the speed of light. 16a, Left: Will the snake get cut? 4th year male physics major, 2011. 16b, Right: Observers in two reference frames, K and K'. Second year female political science major, 2011.

His drawing of the snake was also in part a criticism of my choice of the reading assignment, which he felt fell short because it lacked an explanation of the consequence relative motion, namely the lack of simultaneity of events. In his reading reflection on the text, he writes:

[Einstein] doesn't explain the consequences of the Lorentz transformation very much: time dilation and length contraction. There are real-world consequences that elevate this beyond a purely mathematical exercise – I would like to see a discussion of them, and in particular their consequences for near-c travel. Also, I would like to see a discussion of how all this destroys the notion of simultaneity, which leads me into my Einstein drawing.

The destruction of the notion of simultaneity inherent in his drawing is that if the front and back blades descend simultaneously from the viewpoint of an observer on the cutters (at rest with respect to the platform, represented by the eyes drawn on the cutters), from the viewpoint of the snake the front blade will descend before the back blade does. (I leave the gruesome consequences to the imagination of the reader.) This drawing depicts a story, a what-if scenario, so that I would categorize his visualization style as allegorical/creative.

Figure 16b was drawn by the same student who drew the World without Sight (Fig. 12). In her description of her drawing she wrote:

Disclaimer: I had a lot of trouble understanding any of this, but this is what I do understand. K is a reference frame...for example if I was on a train and I threw a ball, to me the ball goes up and down, but from the earth perspective the ball moves horizontally. Einstein looked at a light pulse in both reference frames <...>. X is the distance traveled, c is the speed of light and t is the time. The assumption, that if you look at ct light in one reference frame, time and distance change. The only thing that stays the same is c...I think that's the idea.

Note that even though she struggled with the concepts in this assignment, her characteristic allegorical/creative visualization style still comes through in her drawings of the two observers in relative motion (Einstein and a dragon).

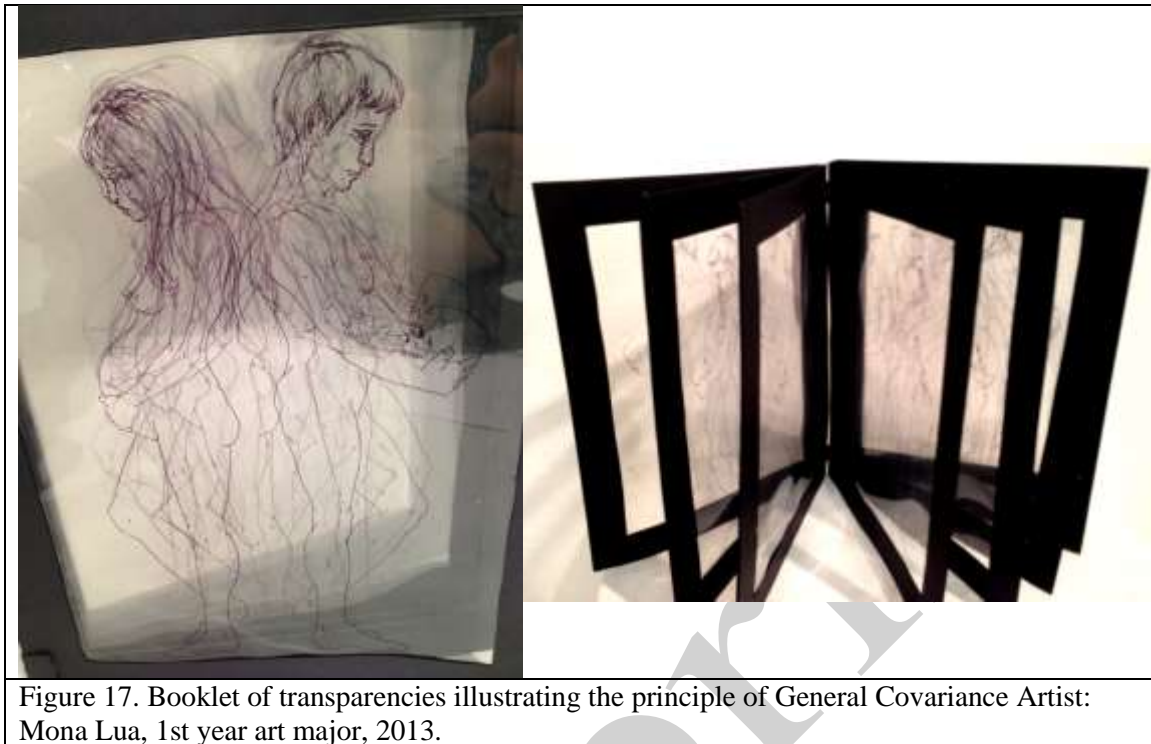
I chose the examples in Figures 16a and 16b to contrast the representation drawn by a student who clearly understands the material with that of a less experienced student. To be able to assess students' comprehension through their drawings requires that an instructor be completely familiar with the concepts, so as to be able to differentiate the nuances of understanding demonstrated by students' representations. Any physics instructor can recognize the problem correctly posed by the drawing of the snake, and assess that this student understands the material. The drawing is sparse and to the point, including only relevant details (the eyes on the cutters represent the observer on the platform). The drawing of Einstein and the dragon contains many irrelevant and unconventional details, but on closer inspection it is clear that this student does understand some of the important points that are brought out by the Lorentz Transformation: namely, that the speed of light is constant for all observers, and that relative motion at high speeds rotates the reference frames of two observers.

2.2.2. Students Representations of Concepts in General Relativity

Professor Andrea DiSessa (U.C. Berkeley) coined the term *conceptual homomorphism* to indicate a description that is less detailed than the full (mathematical) description of a concept, but preserves the relevant structural relationships (2013, pers. comm.). The piece shown in Figure 17 is an example of a conceptual homomorphism, a representation of the concept of General Covariance, the dynamical symmetry of General Relativity which describes the deformation of 4-dimensional spacetime due the presence of mass-energy. Created by Mona Lua, first-year art major, it is a booklet of transparencies which represent 2-dimensional slices through 4-dimensional spacetime demonstrating distortion of an image in regions of spacetime that are distorted by the presence of mass (gravity). The drawings are accomplished by understanding the rule that maps one image into the next through consecutive slices of distorted spacetime. In her description she wrote:

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

This physics work of art is an excellent artistic rendition of the conceptual meaning behind Einstein's field equations of General Relativity, which are the set of rules that tell you how spacetime is curved in a particular region due to the particular local configuration of mass and energy contained within that volume of spacetime. Mona's nine grids, layered on top of one another, are the set of rules that tell her how to distort the image of the man and woman drawn on the top transparency. She has represented curved geometry as we experience it, by representing slices through it (think of a contour map). Quoting Professor Andrea diSessa, "[A] 'curved' shape is actually (typically) a slice of space that is up/down symmetric, and which would look like a 'flat plane' from the side, e.g., the plane of an orbit" (diSessa, 2013, pers. comm.).



Compare the correct conceptual homomorphism shown in Figure 17 with the representation shown in Figure 18, in which the artist, a third-year art major (Fig. 3) attempted to represent the way mass curves spacetime with her hanging installation of dried beans deforming knitted squares which are suspended from all four corners by string. This representation is really an *embedding diagram* – a two-dimensional analog of four-dimensional spacetime curvature – and, although it is commonly used in text books, it is actually not a correct conceptual homomorphism of true spacetime curvature.



As with Figures 16a and 16b, Figures 17 and 18 contrast a student who demonstrates a more complete understanding of a concept with one who has a partial or incomplete understanding. The drawings of Figure 16 were in-progress assignments during the course, while those of Figures 17 and 18 were final projects. Through the students' drawings, a discerning instructor can see which students understand the concepts fully, and where some students need help with incomplete understanding. The artist who drew Figure 16b understands that a Lorentz boost rotates spacetime axes, but because of her lack of familiarity with physics, needs help seeing that such a rotation goes through "complex" space, so that rotated axes appear flattened from our perspective (as in the light cones of Figure 14a). The artist who created the installation shown in Figure 18 understands that mass deforms spacetime, but needs help to visualize this as taking place in three dimensions (for example, with the analogy of the gravitational field of the Earth, where the notions of "up" and "down" vary from the northern to southern hemispheres).

3. Discussion

I started teaching *Symmetry & Aesthetics in Contemporary Physics* as an experiment to develop an alternative to the standard introductory physics curriculum which was designed to make physics more appealing and accessible to a broad spectrum of learners, including students who might be curious about physics but avoid the traditional large introductory classes. Over the eight years I have taught the class, I have continued to refine the curriculum and improve my own understanding of how to use what I have called *arts-based teaching strategies* to help students visualize abstract concepts, as well as use students' creative representations to assess their understanding of the concepts. The progression of assignments through the course is designed to have students first understand their personal visualization styles, and then to use their visualization strategies to develop effective ways of communicating their understanding of concepts to others.

Other studies have emphasized the importance of having students develop their own visualizations and creative representations of concepts as an important strand of science education. The term *meta-representational competence* (MRC) coined by Professor of Physics and Education Andrea diSessa (2004) is described as "the ability to choose the optimal external representation for a task, use novel external representations productively, and invent new representations as necessary" (Heggarty, 2011, p. 1240). DiSessa (2004) suggests that "learning may implicate developing one's own personally effective representations for dealing with a conceptual domain" (p. 299), while Heggarty recommends that "more attention should be paid to teaching people to use, design, and critique external spatial representations, in addition to training their internal visualization abilities" (p. 1241). Psycholinguistics professor Vera John-Steiner defines thinking as "to hold an idea long enough to unlock and shape its power in the varied contexts of shared human knowledge" (John-Steiner, 1997, p. 9).

Overall, students' reactions to the curriculum and methodology have been quite positive in all years, as indicated by their final evaluations. In 2007, I administered the Maryland Physics Expectation Survey (MPEX) (Redish, Saul, & Steinberg, 1998). The students in my class demonstrated significant gains in attitudes toward physics as compared with students in the original survey of 1500 undergraduates, whose attitudes towards physics declined after a one-year introductory course (van der Veen, 2007). I have not administered the MPEX again; rather, students' weekly exit cards and end-of-course evaluations indicate their positive reactions, and the course scores well above the standard undergraduate physics courses in the end-of-quarter numeric evaluations. Since we started displaying the final physics works of art in the college's art gallery and holding a public reception, the course has been attracting additional attention, so that this year I had students who enrolled in the class because they have seen the gallery show and wanted the opportunity to participate. At the time of this writing, in response to an article written about the recent

gallery show (March, 2015), my students have been invited to exhibit their work in a prominent place in the university library for three months.

4. Conclusion: The Importance of drawing and other artistic representations in science education

Incorporating arts-based teaching strategies at the undergraduate level, especially in intimidating subjects such as physics and math, can increase interest in the subject for majors and non-majors alike. Thus by providing alternate mental pathways to access these subjects we may actually be able to increase diversity in physics, math, and engineering by allowing students the opportunity to express their own voice and creating hybrid spaces within classrooms (Hazari et al., 2010, p. 19). Having students get in touch with their inner visualization strategies and creatively use them to communicate their ideas and opinions should be an important part of science education, both for science majors and non-science majors. Students' comments support this recommendation:

This course has been my favorite course that I have taken thus far at UCSB. I am so glad I got the opportunity to interact with you and my fellow classmates and to engage in discussions that dig deeper than most classes. Every project was challenging but left me more interested in the material (Anonymous final evaluation, 2014).

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

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 (Anonymous final evaluation, 2011).

It is really refreshing to see an unconventional approach to physics and view the world around us from both points of view. My mind was opened up to so much this quarter. <...> These ideas really apply to art but nowhere does art teach it or explore the questions that one might have. I was really glad to make my final project, it helped me develop my view of the interconnectedness of things (female art major, 2011).

I'm really glad that I got to take this class & that classes like this exist. I feel like I learned a lot & that I will retain it because I enjoyed learning it, and I think it is useful & really interesting information. It was awesome to learn about something so unlike what I normally study, and from so many different perspectives (anonymous student, 2012).

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).

I think - I was - I was very, kind of disillusioned from my other physics classes, and I'm glad I had this class t' take, and remind me that physics is cool, and that there's lots of - there's broad concepts out there that we should get excited about. To me, if you add physics and creativity to it, that's the part of physics that I love ... instead of the... Oh, I can solve an integral which is really hard. 'Yay!' - 'h-h'. Yeah. As a physics major in my senior year, I've felt that our curriculum,

pre-print of chapter for Invited book chapter, *in The Use of Drawings in Science Education*, Phyllis Katz, Ed. Sense Publishers. *in press*, 2015

though very demanding and informative, lacks the history of how the laws came to be, as well as the thought process that was taken to get to that point. Your class seems to be one that will fill those holes, and I am truly excited to learn more about it (anonymous exit card comment, 2013).

In conclusion, I suggest that:

- Having students design their own representations of abstract concepts in physics, and explain their representations to non-experts, helps them develop meta-representational competence;
- Teaching physics in an interdisciplinary setting in which high importance is placed on students designing their own representations improves self-confidence regarding the study of physics for arts and humanities students who might otherwise avoid a traditional introductory physics course;
- Students' drawings, along with students' written and verbal explanations, can serve as an alternative form of assessment to traditional tests and problem sets, that give deeper insight into students' understanding of concepts as well as the way students process information;
- Students' drawings, along with students' written explanations provide valuable feedback to the instructor as to the effectiveness of his/her instruction, which the instructor can use in refining the course and assignments;
- The use of arts-based teaching strategies and open-ended assignments that encourage students' creativity has the potential to increase access to physics, and thus attract a broader population of learners to study physics.

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websites: web.physics.ucsb.edu/~jatila and planck.caltech.edu/epo/epo-team.html

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