THE BIOLOGICAL ART DRAWING HEURISTIC: VISUALIZING COMPLEX BIOLOGICAL SYSTEMS IN BIOLOGY EDUCATION & RESEARCH

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by

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ABSTRACT

STEM is a well-known acronym describing the intersections of science, technology, engineering, and math. Emerging from this paradigm is a relatively new interdisciplinary model entitled STEAM. STEAM endeavors to intersperse "the arts" into the sciences with the expectation of increasing student engagement and skills within the sciences. STEAM asserts that the arts will increase student interest in science and increase creativity and innovative skill sets. STEAM today is broad and, in some ways, nebulous about methods, teacher education, and outcomes. Interestingly, the integration of the arts with the sciences has always existed. Biology is considered the most visual of the sciences. Historically it has relied on the skill set of observation, experimentation, and (less-acknowledged) drawing. Many scientists, who have contributed to the foundations of biology and medicine, were also artists. The drawing methods employed by these pioneers of biology have been overlooked in history and rarely considered a methodology for research or educational practices related to complex biological topics such as evolution. Could the historical interdisciplinary skill set of scientist-artists of the past suggest a way forward to develop methods to add "the arts" into STEM in a teachable and transformative way?

In this thesis, I present a historical framework, with five case studies of artist-biologists and their experimentally informed, factually established methods of the artist-biologist synthesis. I outline the discoveries and the art processes in these five case studies as part of a comprehensive and flexible, domain-specific, and skill-based STEAM variation known as *BioSTEAM*. I have extracted and modified the historical methods and adapted them for delivering the arts with biological knowledge to the modern biology classroom in an active, teacher-directed synthesis. The BioSTEAM framework is presented through its primary skill-set of what I call the "drawing heuristic." I developed the drawing heuristic from classical drawing techniques as they specifically apply to biological systems. These drawing-teaching techniques were developed to be quantifiable and teachable. The BioSTEAM framework is compared and examined against other similar STEAM efforts. In this literature analysis, the novel approaches of BioSTEAM can be revealed. Attention to biology-specific skill sets and teacher-directed performance, products, and processes are explained.

To reveal the drawing discovery process's potential, the development of the drawing heuristic and BioSTEAM framework resulted in four BioSTEAM drawing-heuristic lesson plans published in four articles in the journal *American Biology Teacher*. In these articles, the importance of the historical bio-art synthesis and the biology-based drawing skills are emphasized through the topic of evolution. The evolution-based narrative and the arts focus in these articles demonstrate the flexibility and necessity of both the drawing heuristic and the need for domain-specific content. Each article serves as an integrated synthesis of art and biology that is teacher-generated and encompasses the multi-faceted skill-based nature of my novel hypothesis for STEAM.

The BioSTEAM framework and the drawing heuristic developed and proposed in this work were tested in an organismic biology lab where students are encouraged to do drawings under the microscope. In this experiment, which spans a full semester, the performance of a control group (little or no live drawing elucidations conducted) was compared against an experimental group in which the teacher demonstrates the drawing heuristic in biology in a live demonstration-lecture and in a narrative or storytelling way. Students' performance improved consistently, such that average scores from quizzes, mid-terms, and finals in "the arts" group were always higher, but they were only statistically significant sometimes. Interestingly, the variation of scores across studies in the arts group was always lower and statistically significant. Therefore, this quantitative research study illustrates the effects and benefits of historically developed biological synthesis-based drawing techniques and narrative delivery and their relationship to student performance. Implications of these findings and the limitations of in situ classroom experiments are discussed.

In summary, I have constructed a drawing heuristic for BioSTEAM through a deconstructive analysis of the practices of five artist-scientists which defines STEAM processes in a biological domain-specific way. This formed the basis of four BioSTEAM educational articles and an experimental study, which illuminated a historically inspired introduction of the arts into STEM.

DEDICATION

For Apollo, Ani, and all my feline and animal friends & family and
to Nature who has been my best teacher.

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I also want to thank Dr. Kumar for his hours and days of tedious proofreading, editing, attention, and discussion of this work and his patience and guidance on the direction and formulation of this work's framework and broader potential. I would further like to offer my appreciation to Dr. Kumar for exposing me to another arena of biology and including a novice in on discussions of molecular evolutionary medicine, enabling me to see patterns and processes that dovetailed with the scientific-artistic brilliance of the past, bringing that historic interdisciplinary thinking and skill into the present and this work. Finally, I would like to acknowledge his lenience in the lab, allowing me to draw all over the boards on the 6th floor and explore my creativity related to evolutionary thinking-encouraging it further.

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The winding road of this thesis has been long. It goes back many years to professors I had in Temple's biology department, many of whom supported my arts-based biology paradigm even though I was not in their program initially. Even those years ago, some of the professors encouraged me to apply the art to the biological. So, I would like to thank Dr. Joel Sheffield for allowing me to try this with apoptosis and microscopy, and Dr. Shohreh Amini for always encouraging me and suggesting that I apply to the biology program and for her great virology lectures, and Dr. Karen Palter, for her scientific- artistic point of view, and Dr. Ed Gruberg. I would also like to thank Dr. Mark Feitelson for his valuable insight into the artist-scientific domain and Dr. Mathew Helmus and Dr. David Liberles. I want to thank Dr. Richard Waring for guidance in the program and pleasant conversation.

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It is through the Temple’s Biology department that the innovation happened. This was quite amazing to me as I had observed institutions like Harvard, Princeton, MIT, and the Max Plank Institute venturing into the arts' territory and thought about my own native Philadelphia to initiate my journey. I never considered myself an “academic,” as I learned by example and doing. However, the Biology department offered me an opportunity to expand this cross-pollination of art and biology into academia. Temple has the opportunity to resurrect an extinct but reemerging branch of the biology domain, that is, the historic, artistic approach to living systems, and offer this to the students of the future. There is an essential and underlying principle to this bio-STEAM concept or the romantic biology of the past, one that sparks genuine innovation but places the love of Nature and its beauty at the center of that enterprise.

Future biology students at Temple may find prospect and optimism in a discipline that encourages their relationship with this planet and the life on it while fostering their artistic skills, keeping them deeply connected to the biodiversity, the evolutionary processes, and the life they are part of. Temple can be recognized for this pioneering vision

because of the biology department and build a biology domain that shapes the future towards the positive. This work is just a platform to present such a possibility for the future.

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CHAPTER 1: INTRODUCTION

The domain of accurate drawing is the basis of all visual arts (1). It is the necessary antecedent of visual literacy and visual-spatial skill sets as they are incomplete without descriptive drawing experiences with Nature and biological phenomena (2). Drawing and the use of artisanal methods for biology, as it was done in the past, is far more sophisticated than current STEAM practices suggest, as it relates to living systems that are themselves too complex a domain for educational, social, or psychological theory. As a result of these minimally relevant theoretical constructs, I will only occasionally elude or draw upon them, and in constrained ways, as current practices cannot sufficiently analyze the complex variables of drawing biological phenomena. Through this analysis, an understanding and a practical, truly interdisciplinary STEAM model may develop.

Drawing itself is a biological phenomenon, as it is a mix of evolutionary adaptations, neurocognitive activity, sensory perception, aesthetic practice, and cultural influence. It becomes activated through passion, vision, skilled craftsmanship, and focus. Focus gives rise to a shift in perspective towards the subject, sustained interest, and subsequent discovery process (3). In this way, biological drawing is a *heuristic,* an investigational practice and process. It becomes a complex, conceptual internalization of the outside world and an individualized discovery method applied to Nature and living systems through exploration and/or experimentation. This occurs particularly when knowledge is conceived in a narrative; that is, the subject is couched within the larger framework of evolution and ecology. This intricate merger has helped define life science's history, as drawing has always been an outward tool for inner cognitive verification and scientific conceptualizations. Drawing should, therefore, underpin authentic STEAM practice.

In this dissertation, I have explored the complex processes, skills, and products of five scientists who relied on drawing and art techniques to illuminate important biological concepts. From their works, I have extracted and modified the merged artistic and scientific skills of those scientists into a new synthesis of drawing discovery for biology education and research. I present those five historical scientific figures as a major part of this work to reveal processes, themes, and patterns in all five cases throughout subdisciplines of biology and through time. I have also tested the drawing techniques myself and, to the best of my ability, have applied them in the experimental conditions of this work to test my hypothesis. These five historical cases set the groundwork for a deeper understanding of how and why artistic practice and process benefit biological education and research and why we need to revisit the skills and environments of the past that produced such fundamental biological knowledge.

1.1 Literature

Although rarely used today, the drawing/observational process provides incubation of the complexities being observed, often clarifying or reframing the observable and the non-observable into a visualized estimation (1). Part of the STEAM initiative includes educational articles on drawing and thinking (4), drawing as a construction strategy for learning from text (5), drawing for understanding scientific diagrams (6), visual-spatial thinking in thinking about science (7), images as reasoning tools (Samuel 2013), drawing as a generative activity from the text (8), and creating mental models and 3-D visualization (9). The literature also includes drawing for science education (10) and how art and art practice alter brain function and increase memory (11). Drawing has also been utilized as a research technique in documenting new species (12) and creating visual explanations, improving learning outcomes (13). Also applicable is art as a component of enriched environments that can motivate science education (14). The use and benefits of a chalkboard drawing in science (15) have also been documented, as is the concept of expert demonstration in the classroom (16). The visual advantage of realistic drawing (17) and the drawing-to-learn framework for biology by Quillin and Thomas (18) have been the most recent contributions to this field.

Many other research articles on visualization, drawing, and thinking about drawing fall into one of the above categories. Taken collectively, current research, regardless of its scholarly contribution, does not explore the processes of the scientific artist of the past and their evolved synthesis model, which was cultivated in a different environment from the one that exists today. The environment and conditions the artist-scientist of the past experienced shaped and fostered a natural synthesis between nature and discovery processes (19). The current interdisciplinary frameworks and models posited in these works typically neglect the environment and the instructor's role in displaying and conveying the processes along with the content, as they pertain to the biological sciences where the instructor's background is essential. This "modeling" of drawing and exposure to nature in varied ways underpins the synthesis of the past. The lack of modeling skills also points to a general lack of teacher training in basic visualization skills and drawing for science educators. This, along with greater content knowledge, would develop conjointly to produce a synthesis for the teacher to model in the classroom and add to the teacher's competency when assessing or developing STEAM-based activities.

The literature has not provided a definitive practice regarding how the teacher will acquire these skills and what those skills might be. My work proposes that the teacher should display expert knowledge of the subject and the drawing activity, which is unique to teaching about living systems. Current studies rely on case studies or classroom studies of artists delivering art lessons or on students "discovering" art synthesis and mastering something that cannot possibly be understood by them or assessed accurately by the researcher or the instructor without actual experiences with those skills. Current STEAM studies have also isolated the drawing activity from narrative, lecture, and discovery in Nature, which all complement each other. The components of a model that integrates visual arts, in particular, should have the potential to foster genuine investigative and empirical methods for art and biology. A comprehensive model should have examples and processes clearly demonstrated and in the context of the narrative of the complex biological phenomena presented.

In some ways, the current models and research offer a tiny glimpse into drawing's benefit for learning through the arts for biology. However, a wider lens that explores the historical methods is more likely to reveal the true processes of more accurate drawing for biology educators and students through the development of skills, stimulating aesthetic environments, and techniques. My goal was to create a specific drawing heuristic for biology based on the development of a skill, a focus, and a passion early in student biology experiences, followed by less and less input from the instructor. It also requires that the instructor, as in the past, be able to demonstrate these skills and techniques and that students have exposure to Nature and aesthetic environments.

1.2 Hypothesis

My hypothesis explored the development of a model created from the complex process of drawing as a naturalist and a biologist for discovery. In historical literature, this process is described as the "aesthetic dimension" of scientific inquiry (20). In my work, I briefly explore scientists' histories in specific biological disciplines and examine the scientist's interdisciplinary methods, including narrative, metaphor, and classical art skills. I also model and demonstrate the practices that are part of the traditional biological drawing. I also considered the various art forms, such as descriptive drawing, wax models, lithography, and mandalas, as a synthesis and communication practice for the complexities of biology and developed prototype models for classroom use. As a result, I will call this process, which incorporates many facets of the aesthetic dimension, "*the biological-art drawing heuristic.*" I developed this heuristic from the historical case studies and classroom practice, providing the pattern for learning biology and doing biological research, particularly for those students, educators, and researchers attracted to the visual domain of biology. This heuristic employs classical drawing skills and can employ other art forms, considers the cultural environment/classroom where this practice unfolds, and establishes a framework for art in biology. It also considers that the art must contain complex biological content and observations, skilled realistic drawing, and the use of metaphor and narrative.

1.3 Rationale

Drawing and learning about living systems goes much deeper than enhancing memory, replicating an image, reading a graph, or improving test scores, all of which are what most educational and STEAM-related practices administer and measure (20) educational theories regarding visual-spatial domains and visual literacy rarely distinguish how different and unique thinking about biological systems actually is compared to thinking about "other" objects. Art and educational psychology research and research studies for educational purposes lump living things in with inanimate objects, not systems, or living, evolving transformations, applying the same ideas, formulas, and principles to all phenomena. Herein lies a major discrepancy in their application to this study. Nature's properties, energies, forms, movements, and interactions are ephemeral, auto- poetic, vastly interconnected, transformational, animated, regulated, conservative, subatomic, microscopic, macroscopic, synthesizing, and complementary. The qualities of living systems function this way at varying levels and to varying degrees, continually self-regulating, adapting, evolving, and producing novelty. Studying these qualities with drawing is very different from drawing a simple shape or understanding simple objects' rotation. Yet, for the human mind, the underlying simple forms are necessary to initiate the process but ultimately do not reflect the complex qualities aforementioned (20).

In this work, I have attempted to explore the drawing domain historically and present it as a form of evidence from several representative individuals and their biological disciplines. I have endeavored in this work to present the existence of the Biological-Drawing-Heuristic in the following domains: cytology, anatomy, embryology, evolution, ecology, neuroscience, genetics, and molecular biology through historical examples. Along with this historical evidence, I have also attempted to develop a teaching strategy that embodies the qualities and skillsets of the historical biologist-artists and apply these to a modern biology classroom experience. My goal was to recreate all of the significant collective strategies of the past, modify them slightly and apply them to a current biology curriculum or course. This included a variety of artistic interpretations of evolution, ecology, networks, and organisms that students would receive narrated lectures on. It was also to include nature walks and focused, discovery-based drawing practice for biological form and function modeled by the instructor. Due to the constraints and limitations, my focus was narrowed to only the drawing component, which I assert requires those other elements to be fully achieved as a genuine bio-art drawing heuristic. I will address the ideal format at the end of this paper in more detail. I developed a framework of teaching and exploratory drawing or heuristic-based practice on the content of the courses that were available for me to study within a shorter and more limited time frame than required. To re-summarize my work goals: I endeavor to establish a necessary criterion for visual literacy in biology and life sciences and a more precise and plausible model for a genuine STEAM curriculum that contains major biological domains teachable and underlies a deeper understanding of biological phenomena. I will present the master artist-biologists, their work, and their art and science methods in this work. I will present their core competencies and the model framework I have developed from them. I will call this discovery method through the artistic process a "drawing heuristic." I will also present my attempt to apply this model in a standard organismic biology lab and an evolutionary medicine course. I will present my methods and analysis of the results of these two experiences.

Following a discussion on this topic, I will offer an idealized curriculum that I would have presented and its design, rationale, and future implementation. Although numerous scientists were also artists, I have decided to explore only five and establish their insightful, unified drawing and biological research methods. From this historical analysis and investigation, I have created a beginner's methodology that embodies the core competencies that directed the historical processes of art/biology mergers in scientists that laid the groundwork for modern biology. Their successful and prodigious works, in their respective fields, have important applications and relevance in today's biological science education and research. It is from their methods of drawing, observing, and experimentation that suggests that drawing and biological knowledge, functioning together, create a coherent representation of the natural world that invigorates the sense of wonder, fosters the aesthetic dimension, and results in an appreciation of the natural world and its processes, ultimately leading to authentic visual literacy/STEAM in biology and to meaning scientific pursuits.

1.4 What is STEAM?

To explore the complex domain of biological-art-based mergers, I had to place them in their contemporary context, which is known as "STEAM." The concept of STEAM was important to this work because STEAM implies that art is a critical part of interdisciplinary science (21). *"For the past decade, the maker movement—an interest in working with one's hands in interdisciplinary environments that incorporate various tools and technologies—has been on the rise. In recent years, educators, administrators, parents, and policymakers have expressed a heightened interest in maker-centered learning* (22)." The STEAM movement is very broad and grew, not out of its apparent historical roots, but from the belief that STEM programs with help from the arts would improve student comprehension and interest in science. *"STEAM is a relatively new framework of educating across the disciplines. It has been evolving to support a new educational theory. STEAM is based on STEM education, which grew out of the vast need to have more students achieve success in understanding the systems and connections"* (21). The idea is to offer students alternative ways of thinking about science and math using craft and art so they can adapt to a rapidly changing world.

"*The goal of STEAM is also to be strongly benchmarked, measurable, and easily reinforcing. Exploring the Exemplary STEAM Education in the U.S. as a Practical Educational Framework of standards in unique and engaging ways"* (23). These goals are of interest to this work. However, the larger goals of innovative thinking in biology and eco-evolutionary awareness in the Anthropocene are critically important to this work as they will apply to the future of overall planetary health. However, they may or may not be a vision of STEAM. The accomplishment of "engaging" and "hands-on" requires thorough and precise skill sets to measure, which means that drawing must be descriptive and skilled in its application to discovery. This seems counterintuitive to the creative, innovative, and variable ways the arts would allow students to express themselves and learn science, as many STEAM articles have proposed. Art, creativity, and drawing are often grouped without acknowledging that they are sometimes related but are not always mutually exclusive.

For the biological sciences, STEAM stresses visual literacy and visual-spatial skills (24). However, it does not present a model that builds the underlying skill set of classical, descriptive drawing *from Nature,* which was of interest to this work and underlies creative practices in science and art, particularly in the foundational biology and anatomy of the past. Visual artists have always drawn on Nature for inspiration, and biologists study Nature with a particular science framework. Therefore, Nature should be the underpinning of both disciplinary efforts. More recently, the number of collaborative efforts between artists and scientists has increased, and these collaborations are also termed STEAM (25). To exclude Nature from the focus of any STEAM practice would seem counterintuitive and nonsensical. The popularity of art and science merging in interesting ways often rely on collaborations across the two disciplines but is rarely considered entangled and unified with a specific foundational protocol. One objective of this work was to construct a model of art and biology based on past practices, one that is teachable, content-driven, and skill-based with the objectives of deepening and expanding understanding of complex biological phenomena through an introductory biological curriculum. This may technically be termed a STEAM enterprise, but it is more content and skill-driven than educational theory-driven, which I assert is fundamentally what is necessary to produce a purposeful model in biology education.

Other aspects of STEAM that were relevant to this work was the employment of fine art, which had a biological theme, and which I had produced before this work, which would have been exhibited so that students and faculty could experience synthesized fine art that was designed to assist in explaining many and varied types of biological systems and processes. This biological exhibition space would be available for lectures and aspiring artist-scientists, teachers, and the general public. The plan was to test this experience with the other important components of the bio-art drawing heuristic. The flow of knowledge would then move from research to education to the general public and exposes the multitude of ways art can function within the biological science paradigm. The process of applying artisanal skills throughout this conduit encourages the scientist, science educator, and science student to also adopt the processes and practices of contemplative biology, which requires deliberate and thoughtful creation of drawing artifacts and which is inherent in the slow examination of the subject required for descriptive drawing. To refine this biological art practice would enable it to be taught to educators, students, and researchers. In this precise manner, it may be better assessed and comprehended as a discovery and originality process.

1. 5 The drawing heuristic and the modern biology class

The merger of these two processes of knowing (biology content and drawing skills) was the fundamental objective of this work. Within that umbrella of exploration are manifold objectives on this topic, including analysis and deconstruction of numerous “masters” of life science and drawing. This exploration or deconstruction and reconstruction of the actual art of the past is necessary to make sense of the complex skill set of biology research and art. It is also necessary to develop a teachable skill set taught to teachers as part of their science education. In this way, the drawing heuristic does not create a separate discipline but is one with the biology content and presented as such. This is particularly important today in the high school and college biology curriculum, which has become increasingly divided into subjects with continually increasing amounts of data, visual images, and information, which place a higher demand on students' time and memory (26). Most students are highly motivated to increase their scores and GPA for medical school or graduate work. Classical scientific drawing and art processes have historically fostered both creativity, interest, and furthering knowledge over hundreds, if not thousands of years. However, most teachers have abandoned this artistic heuristic in the modern classroom and are not taught these skills in educational curriculums and by higher education (27). Consequently, both students and educators spend little or no time dedicated to the tradition of scientific illustration as a discovery process, which may or may not focus on content. For students to develop this competency, some teachers may, particularly in introductory biology courses, model this practice (27).

The drawing-discovery practice requires a degree of skill, which can be developed. Once established, it can be applied to almost every biological area of study. This primary skill can create a combination of conceptual understanding and experimental skills as well as an "a dimension" to the beauty and forms of the natural world. Taken together, this is the underlying foundation of visual literacy in biology and visual-spatial-temporal conceptualizations, the kind required for molecular pathways and evolutionary processes, to name two. I argue that by providing students and teachers with an opportunity to develop this skill, alternative biology classroom experiences will emerge, students will receive a more varied approach to the subject, and STEAM practices will have a model based on historically relevant practices. This varied approach makes available new and innovative thinkers in biology education and research, which the STEAM curriculum suggests (23).

Teaching descriptive, biological drawing and art with science are also crucial to developing creative and rational thinking, especially for observation and questioning skills, and to encourage a deeper interest in living systems and Nature (28). Some students are more apt to benefit from this experience than others and become attracted to biology because of the creative aspect. This would include students who are not mathematically inclined, are strong visual learners, have greater emotional intelligence, or have an attraction to Nature and the aesthetic dimension of this planet, thus expanding the diverse pool of students entering into the life sciences and a deeper commitment to planetary health and ecological conscious by (29).

Due to limitations in the way I could present the drawing discovery model, my general hypothesis would be, "Does the biological-art drawing heuristic produce higher test scores in bio 1111 lab students' final grades?" This was a testable hypothesis with just the administration of the drawing component of the drawing heuristic. However, it is limited but not as limited as what is normally presented in the literature. I would function as the teacher who learned the drawing heuristic and model the skill.

In the studies I conducted in Temple University's biological science 1111 labs, first- and second-year biology students received instruction and demonstration on the classical drawing heuristic specifically for biology, albeit in a very limited, reduced manner. Another critical component of drawing for discovery, particularly in the modern classroom, is the teacher-led drawing experience. Drawing and narrating biological lectures allowed students to learn the process of drawing by replicating the teacher's drawing method, which included a narrative draw and blackboard drawing sessions about the subjects (27). Drawing on the blackboard or chalkboard became a common practice of the 19th century. At this time, specialized books, manuals, and lesson plans were created specifically so that teachers could model drawing from their students. The study of Nature was viewed as a particularly important subject, and teachers were encouraged to take students on Nature walks, draw and discuss natural elements in the context of a Nature-based lesson plan (27). Drawing and lecturing to audiences on biology, anatomy, and evolution was also at its height in the 19th century and the practice of naturalists and scientists (27). Historically at two different levels (grade school, adults, scientists), drawing on the chalkboard and delivering a lecture was common practice.

For this thesis, I have proposed and developed the engaging method of chalkboard or whiteboard drawing to include complex qualities of living systems such as motion, transformation, dimensionality, and narrative to enhance students' experience of drawing and being engaged with the content of biology. Drawing keeps students focused, develops skills, and allows for interconnected stories to emerge. These simultaneous elements are modified from the traditional 19th-century chalkboard drawing and a component of the bio-art drawing heuristic I have developed. This method also allows for immediate visualization of the process to occur, a real-time depiction of biological process, which the teacher can demonstrate in response to a question. The other learning advantage is that students can witness processes of biological topics drawn with intermediate steps, many of which are critical for a more complete visual view of the phenomena.

Individual Bio-art drawing discovery processes include a step-by-step assessment of the major elements of drawing practice for the biological process. This requires that students develop a plan and a skill for how they will approach observing, interpreting, and inferring from biological data, knowledge, artifacts, and daily observations of the natural world. This outlined practice's rubric and steps were created for the biological specimens and organisms of the Biology 1111 lab and called a “rubric of skills.” The specimens were primarily protozoa and invertebrate animals. These smaller specimens were easier to interact with and draw. The drawing heuristic rubrics and sample drawing methods reflect those specimens and can be found under figures and tables in section 3.7.

To present only the drawing heuristic model as a standalone process, I would attempt to do draw-along mini-lectures in the lab, and I would offer a workbook, which I created solely for the BIO 1111 biology lab. It would include many of the complex topics of drawing rotations, transparency, sectioning, and visualization skills, along with easy to follow along with drawings and some evolutionary phylogenetic concepts, mirroring the content of the entire course in a simplified schematic and cartoon style workbook that students could draw in, color in, and study from. It would only be offered to students in my experimental group. The control groups would receive the standard PowerPoint presentations and could not offer a grade for doing the workbook. Using observational and quantifying drawing techniques, coloring diagrams, rotation, transparency, and transverse sectioning, students would attempt to revisit the skill set of artist-scientists and rely on observational drawing skills to create a “visual vocabulary” of the courses’ content. This study examined, "Will a demonstrated drawing biology strategy with observations of standard biological subjects increase performance and overall grades?" and "Will metaphoric drawing activity provide a focus to Evolutionary Medicine students to increase their quiz scores?” The independent variable is the scientific drawing heuristic strategy developed for this study. There were two dependent variables: student test scores and student opinion/attitude regarding the art processes in learning and perspectives biology and evolution. I predicted students in bio 1111 would develop strong observational skills and use drawing and a tailor-made workbook, which was largely visual as a study aid, which would generate greater interest and increase test scores. I also predicted that metaphorical drawing would increase quiz scores in the Evolutionary Medicine course. The drawings students produced would be focused on morphological structure with implied functions. This study provides insight into the drawing heuristic underpinning the STEAM paradigm in college-level biology.

CHAPTER 2: FIVE CASE STUDIES AND SYNTHESIS

Artisanal knowledge is a form of bodily knowledge of making, synthesizing, experimenting, and exploring the physical. It is often portrayed as a "craft" and distinguished from theoretical knowledge (19). The artistic process, which a component of artisanal skill, also employs the physical but may use imagination and metaphor to conceptualize the nonphysical. The history of artisanal-based knowledge is a history of human evolution and culture. Humans can be described as "tool making," but also as "art making" (30). The history of Western and Eastern explorations into nature and life science can also be viewed as a history of artisanal knowledge as the artisanal body of knowledge brought the emergence of the experimentalist who regularly experienced natural phenomenon and could theorize about its properties and workings (19). Over time theory and practice, however, became separated. The individual experience with nature and the materials of nature gave rise to unique and novel creations through the process of making things. Even the method of producing an old painting's work can be considered a record of visual interpretation and visual activity. Modeling and imitating nature with wax and glass models became an artistic process of the scientific method (19).

The tangible and imperceptible aspects of nature were brought and scaled to the human mind and body's physical level and senses through the arts. From this, the theoretical and philosophical were hypothesized and experimented with (19). Naturalistic representations were models of the real thing, simplifying, exploring them, and experimenting them into existence through materials that could imitate nature's processes and porotype the qualities of nature. Creating art of many forms, especially visual art, is human behavior and is universal across cultures (30). Artisans historically knew how materials behaved by experimentation. They internalized the domain of their materials, which allowed them to "play" with those materials and engage with them creativity, discovering properties not normally observed (19). Without internalizing a domain, whether it is an instrument, part of the earth, paint, math, or any subject, the scientist or artist cannot play or innovate fully (31). We can see those who have successfully mastered domains creating and generating new ways of looking and thinking about phenomena. Leonardo DaVinci is perhaps, the most universal and best example of this. I refer to him often because his work is fully documented in notebooks. Through his illustrations and studies, he revealed the function and workings of the valves of the heart (32). He also experimented with materials for making models and revealing structures never observed before. Through painting, he studied the properties of light, the comparative anatomy of humans and animals, and the universal branching pattern in trees and lungs (33). Similarly, Ramon Santiago Cajal, upon exploration and dissection of retinal photoreceptors and working with his illustrations and staining techniques, could elucidate the retina's function. Darwin’s simple metaphorical illustration of the tree of life demonstrates his internalized domains of knowledge about evolution (34).

With scientists who were artists or scientists that worked very closely with artists, a crossover of disciplines emerged. The neurosurgeon Harvey Cushing, a remarkably skilled illustrator himself, worked alongside Max Brodel, the carbon dusting technique's creator, to reveal new methods for treating pituitary gland tumors (35). It was noted that Brodel did as much dissection as his partner Cushing and understood the anatomy at the level of a neurosurgeon (36). Similarly, the standard medical/anatomy text that all medical students use today was created by the artist/physician Frank Netter. No other body of work is as descriptive and practical as Netter’s creation (37). Even the popular author, Vladimir Nabokov, a professional lepidopterist, kept meticulous illustrations about his blue butterflies and used literary metaphors to understand their evolution. He also used his scientific knowledge in his fictional writings, often alluding to evolution and speciation in interesting and novel ways (38, 39).

To introduce my hypothesis and my arrival to it, I have chosen to explore the techniques and biological questions five biologists-artists employed to make groundbreaking discoveries. Their historical accounts and artifacts are critical for understanding how and why innovative life science emerged and the patterns, processes, and skills underpinning this work's synthesis. These individuals may also be referred to as scientists who employed artistic models for their research. Some of these historic individuals used traditional art in every facet of their scientific work (DaVinci), others used a variety of classical artisanal methods with experimental methods (Cajal, Haeckel, Boveri), and some used theoretical artistic principles and art process to argue experimental work (Pauling). Through analyzing these scientists, I hope to establish the principal and crucial aspects of the scientific-artistic discovery process based upon drawing.

2.1 Case Study I: Leonardo DaVinci (1452-1519)

Leonardo DaVinci's life and work are important to this thesis because of DaVinci's documentation of his thoughts, experiments, and conceptual framework on studying natural phenomena using art as a methodology. Leonardo DaVinci clearly stated in his notebooks that he intended to use drawing and painting as a method for scientific discovery to explore Nature (40). Many other artists/scientists do not directly state that their art was used as a scientific discovery method, but DaVinci was emphatic about his purposes (33). DaVinci's notebooks and art consistently state these purposes, his underlying impetus for studying Nature, and an organized framework for accomplishing this work. This is extremely relevant to this thesis, as the Bio-Art Drawing Heuristic proposed in this thesis is largely a modified version of Leonardo DaVinci's scientific-artistic treaties and other scientists presented in this paper.

DaVinci constantly perfected his realistic and aesthetic drawing and painting skills to improve his analysis and depiction of natural phenomena. If artists did not accurately depict anatomy, there would be no documentation or verification of structure and inference of function. DaVinci is also relevant in that his anatomical work, which follows the scientific treaties that he posited over 500 years ago, his accuracy in anatomical renderings have been documented by modern imaging technology to be precise, repeatedly demonstrating that the classical, skillful drawing method, observation, and emergence in Nature and passion for it, were the essential elements of investigations that contributed to his artistic methods of success with natural phenomena. His other work in the area of natural history, comparative anatomy, and physical sciences, as revealed in his notebooks, confirm that accurate, descriptive observations of Nature through drawing are essential tools of the scientific method and importance and should be of interest in applying drawing to biological education research.

Within drawing's process is an elegant knowledge-building framework for science education. Therefore, DaVinci's work has broad applications for science education and research as a model and framework. While much has been written on DaVinci, and his life, art, and science have inspired STEAM endeavors as well as revitalized interest in art and science, very little, if any, has been created from his work with the specific scientific illustration treaties as applied to teaching the biological sciences. Even though DaVinci's work demonstrates and provides evidence of success with these methods, neither STEM nor STEAM have developed a model system from his work or others like DaVinci and tested it in the classroom or lab. Part of this dissertation is to corroborate this method with a current application and establish the artistic heuristic as part of life science and biological drawing discovery method in teaching college-level biology and promote a renewed interest in his methods as a research paradigm in the life sciences.

Leonardo DaVinci's scientific drawing treaties offer a glimpse into the thought process and drawing process that underlie drawing discovery. Leonardo DaVinci is probably the best known, most heavily documented historical figure in the area of art and science (41). My dissertation and the artifacts I have created to use as my biological drawing heuristic was largely based on the practices of DaVinci. It might be suggested that antiquated, historical figures are of little value now that we have the knowledge and technology to illuminate what took DaVinci a lifetime to discover. However, let us also consider that each student and each researcher come into their field with their own way of looking at the world and their desire to discover. We must acknowledge that all knowledge is new knowledge.

One of DaVinci's most notable contributions to biology is his anatomical studies. DaVinci's anatomical drawings are a visible window into the evolution of the drawing heuristic and how it works. DaVinci's drawings were closely tied to his dissections and allowed him to invent new ways of representing the results of the anatomical investigation and inferring function (42). This discovery model of artist/experimentalist was best recorded in history by Leonardo DaVinci within volumes of record-keeping in drawing notebooks. Leonardo DaVinci outlines the procedures for his investigations using art and drawing and posits his treaties on scientific illustration as a scientific investigative practice into biological systems (43).

2.1.1 Rotation, transparency, and transverse section

There are three pivotal concepts in DaVinci's treaties of scientific illustration: rotation, transparency, and transverse Section (43). There are also characteristics of

DaVinci's life that underscore the importance of learning environments, student engagement, and observation that I attempted to recreate for this work and that clearly impacted DaVinci's use of the drawing skill in discovering nature. These characteristics were a passionate love of nature and animals, descriptive writing; skillful, aesthetic, art techniques and art for viewing and discussion; and the continued use of drawing and painting to experimentally uncover patterns in nature as well as speculate about function. Rotation, Transparency, Transverse section underlies the basics of visual-spatial skill and visual literacy in biology, particularly microscopic and gross anatomical structures, line, volume, form, movement, and perspective (43). In Figure 2**,** we can see how DaVinci applied his treaties of scientific illustration to approaching the skull and brain problem. For biology students studying cells, the anatomy of all types, molecules, developing the ability to draw rotations, use transparency for depth, and consider structure from transverse sections solidifies those concepts. While viewing these qualities, creating them suggests a firmer understanding. Throughout his study of the natural world, DaVinci employed this method in his paintings and scientific investigations (43).

Today, in a general biology course, students will encounter cross-sectional microscopic images of cell types, whole organisms, and anatomical structures. They will be asked to identify organisms from multiple perspectives. In biological imaging, such as fluorescence microscopy, transmission electron microscopy, and advanced cellular imaging technologies, researchers will need to consider their observations in three and four dimensions (time) to interpret what they are viewing. DaVinci illustrated what would become the hallmark of the radiology image 500 years ago. His treaties are perhaps even more valuable today as students, researchers, and physicians must either visualize living forms in these positions or interpret them from increasing sources of outputs. In my drawing heuristic, I have made these three principles a foundational concept that is an essential part of the drawing process (44).

Leonardo DaVinci's drawing materials and style were consistent with the period in which he lived; however, it appears that DaVinci pioneered the concept of perspective (33). The innovation of viewing objects from points of perspective changed the way an artist would depict form. Perspective is as important to the way we think about anatomical organs related to how we think about cellular architecture and protein binding sites. The perspective offers us insight into the way forms interact with each other. DaVinci used perspective to think about the relationships of form, making perspective part of his scientific-artistic skill set. The process of observing, interest, compassion, and discovery of natural phenomena required visual analysis that would allow for precise replication and from a particular point of view (45).

Anatomy rendered for portraits did not necessarily have to be accurate in its underlying form. However, rendering for anatomy for the discovery of its processes and functions required extreme precision. DaVinci was fascinated by life processes. He developed a drawing style that complemented the precision, geometrical and visual-spatial drawings he made to analyze structures to understand them better. The technique of sfumato was used for landscapes and convey depth in images (44). DaVinci also created repeating contour lines around objects to imply motion or movement. He used lines repeatedly for motion as well (33). This is obvious in his depiction of water, in the movement of blood through the heart, and the movement of limbs of horses and birds in flight (40).

Transverse sections while rotated in anatomical structures created many new perspectives on anatomy. Many of DaVinci's anatomical renderings are multiple renderings of the same structures around an axis. His skull sections reveal the complexity of the nasal apparatus and sinuses (45) and the intricate anatomy within the skull. In a project that examined the precise nature of his discovery-based drawings, scientists overlapped DaVinci's anatomical drawings with actual MRIs, CT scans, anatomical models, and cadavers (46). DaVinci's drawings were identical to the most recent imaging technologies, shown in Figure 1.

This drawing heuristic, pioneered by DaVinci, is probably the most overlooked and the most significant protocol for understanding anatomical and biological structure. The simplicity of the process places the burden of skill on the scientist/artist and develops alongside the experimental nature of the work. In this way, we see how drawing with an investigation into form and function work together. My emphasis for students was to increase their ability to perform rotation, transparency, and transverse sections, thus providing them with tools for exploring anatomical forms from microscopic protozoa to larger anatomical structures and drawing on the board to illustrate the process of sectioning and rotating living forms.

2.1.2 Anatomical studies

DaVinci may have originated the concept of systems thinking regarding Nature. In his book on Leonardo DaVinci's science, author Fritjof Capra describes how DaVinci helped transition the Renaissance into a deeper analysis of form in nature: *"As a systematic empirical method for gaining knowledge about the natural world, did not exist. Knowledge about natural phenomena, some accurate and some inaccurate, had been handed down by Aristotle, and others…" "Leonardo DaVinci broke with this tradition. One hundred years before Galileo and Bacon, he single-handedly developed a new empirical approach to science, involving the systematic observation of nature, logical reasoning, and some mathematical formulations-the main characteristics of what is known today as the scientific method"* (33). DaVinci describes why visual analysis is important in his notebooks: *"The eye, which is said to be the window of the soul."* He wrote *"is the principal means whereby sensory awareness can most abundantly and magnificently contemplate the infinite works of Nature." "Leonardo DaVinci's approach to scientific knowledge was visual. It was the approach of a painter"* (33). Capra finalized his assessment of DaVinci with: *"Painting, he declared, embraces within itself all forms of Nature. Nature as a whole was alive in Leonardo DaVinci."*

According to Capra, he saw the patterns and processes in the microcosm as being similar to those in the macrocosm. DaVinci also used metaphor to describe his observations and speculated about planetary and human relationships: *"We may say that the Earth has a vital force of growth and that its flesh is the soil; its bones are the successive strata of the rocks which form the mountains; its cartilage is the porous rock, its blood the veins of the waters. The lake of blood that lies around the heart is the ocean. Its breathing is the increase and decrease of the blood in the pulses, just as the Earth it is the ebb and flow of the sea* (43)."

Leonardo formulated these ideas two centuries before the microscope. We can recognize DaVinci's concepts and thought processes in several scientists that followed him centuries later. Robert Hooke, as an example, using the microscope, applied many of the same concepts posited by DaVinci, only on a microscopic level (47). (Many repeated at least some of DaVinci's methods for studying Nature. Based on his understanding of geometry, shape, form, and movement in living systems, DaVinci, despite his lack of formal schooling, wanted to develop mathematical formulas that would model natural systems. This type of mathematics would be qualitative and would represent the qualitative qualities of Nature. At the time, there appeared to be no form of nonlinear math in the Western world. *"He experimented with rudimentary forms of topology in his studies and "continuous quantities" and "transmutations." Leonardo's principle, too, for the representation of analysis of Nature's forms was his extraordinary facility of drawing* (33)."

DaVinci posited many new ideas and revisited concepts in both painting, drawing, and scientific investigation. In his treaties on Painting, he emphatically posits that painting is the unifying perspective that integrates and connects all his fields of study (43). From his work, a coherent conceptual structure emerges, which can be used as a model today. He may have intended to publish his works but did not. Examining DaVinci's notebooks clearly illustrates the drawing and painting heuristic of exploration and his systematic observation science. *"Leonardo saw his discoveries in optics and the physiology of vision as the ground of his science of painting beginning with the science of perspective* (33)."

2.1.3 Davinci's concepts of movement and transmutation in living systems

"The science of living forms, for Leonardo, is a science of movement and transformation, whether he studies mountains, rivers, plants, or the human body. To understand the human form means to understand the body in motion (33)." His interest in dynamic systems in Nature and transformation is equally applied to his subjects and painting style. Observing the drawings and sketches for paintings, artists like Leonardo created motion with line and focus on movement in the sketch or initial drawing, ultimately settling for a particular perspective (40). Leonardo gained insight into these processes of dynamic systems and transformation through painting. *"From the early Madonna's, through the portraits, to St. John the Baptist, Leonardo caught the figure in motion. The*

immediate and exceptional impact of The Last Supper was largely because Leonardo replaced the traditional arrangement with a rhythmical composition that literally changed the idea of the subject (33)."

Unlike Descartes, Leonardo could see the difference between machines and living systems. He never thought of living things like machines, even though he was an innovative and highly skilled engineer (33). *"Leonardo did not pursue science and engineering to dominate Nature. As Francis Bacon would advocate and state a century later. He had a deep respect for life, special compassion for animals, especially cats, horses, and birds, as well as great awe of Nature's complexity* (33)." This aspect of DaVinci's personality is significant in designing a drawing discovery and teaching model. I intended to develop an emotionally-intelligence-based narrative of biology with illustrated lectures on various topics to encourage DaVinci's passionate and emotional intelligence towards living systems.

Throughout his notebooks, DaVinci weaves his emotional life and views in with his scientific and artistic visions. He scorns and admonishes anyone causing harm to animals, eschewing meat, vivisection, and advocating for other living beings. Leonardo can be thought of as the first Western ecological figure as he encouraged the practice of an ecological conscious in his writings and practiced it in his lifestyle (33). Today in the Anthropocene, with accelerated environmental destruction, the rapid loss of species and biodiversity, students and society need a science that honors and respects life's unity (48).

DaVinci's inherent ecological perspective is also a part of the drawing heuristic and requires that students of science spend time in Nature. DaVinci spent most of his time outdoors, and this 15th-century agricultural small town is where he acquired his love of Nature and animals (33). In capturing movement and emotion in living systems, DaVinci often jumped from topic to topic but carried the themes of motion and movement into the topics that sparked his interest at the time. DaVinci spent his later years studying and drawing the mechanisms of reproduction, noting that emotional aspects of the parent are passed down to the fetus; *"desires, fears, and suffering are common to this creature as to all the another animate parts of the body, so that something desired by the mother will be imprinted on the members of the child within her when she experiences the desire, and the* *sudden terror and eluded to the idea imprinting, epigenetically, emotional experiences in conception* (33)."

2.1.4 Neuroscientific discoveries

As a result of Leonardo's concepts on perspective and treaties of scientific illustration, DaVinci was able to apply his compositional art techniques to anatomical illustration. These concepts were of particular importance when exploring the eye, the brain, the skull, and the nervous system (49). DaVinci wrote: *"…my works are the issue of pure and simple experience."* The dissections of Galen dominated the medical arts from the 2nd to the 16th century. Perhaps due to his exclusion from the university, DaVinci was determined to demonstrate that art and experience with Nature would better inform than book knowledge (49). DaVinci often started by exploring anatomy for his paintings and then began deeper investigations out of curiosity into the functioning and origins of these living systems. The eye and the way the eye processes light was of particular interest, which would make sense for the painter. A beautifully sectioned sepia skull drawing allowed DaVinci to consider the position of neuroanatomical structures from positions within the skull. This drawing was the first accurate interpretation and portrayal of the anterior and middle meningeal arteries and the anterior, middle, and posterior cranial fossae (42). The drawing also includes cranial nerves, revealing the optic and auditory nerves.

Leonardo's many brain and eye illustrations focus on varying positional changes in the viewers' perspective. In another drawing, he depicts the brain's ventricles and verifies this anatomical feature by utilizing his sculpting skills. The handmade 3-D model helps him to devise a way to study the brain of an ox he obtained from a butcher (42). *"Leonardo performed a brilliant, original experiment to define the shape of the cerebral ventricles* (49)." DaVinci writes: *"Make two vent-holes in the horns of the greater ventricles, and insert melted wax with a syringe, making a hole in the ventricle of memory and through such a hole, fill the ventricles of the brain* (43)." Once the wax had hardened, DaVinci would illustrate, accurately with a skull, their actual shape and deduce their function. The image of the formed ventricles was then illustrated based on the model and in accordance with DaVinci's aesthetic interest, as shown in Figure 3, which are drawn with the entire brain and cranial nerves (Figure 2). He did similar experiments with the heart, the function of the valves, the chorde tendinea, and the ventricles, similarly deducing their function and building glass models of the heart (Richter 1970). *"Leonardo's contributions to neuroscience also show what could be known five centuries ago, and how research problems could be approached* (49)."

DaVinci's lack of formal schooling may have contributed to his curiosity and closeness with the natural world and his insight into it. It has been revealed that formal education inhibits creativity in children (33). DaVinci learned to build models, read, write, and do math by studying the subjects independently and sometime after the age of 40 (40). This means that his largely academic knowledge base happened after he had perfected many artisanal skills. His earlier successes were not the result of formal schooling but of art techniques and personal investigations. It has also been recorded that he had received most of his education through oral storytelling, something he later dabbled in, writing his own fictional encounters and parables, which can be read in his notebooks (43).

When DaVinci was old enough (18), he became an apprentice in a Bottega (artisanal studio). These workshops were where artists developed techniques and worked with materials such as understanding and experimenting with distillation, pigments, dyes, mordents, and metallurgy (19). They also learned nature study, anatomy, goldsmithing, sculpting, and painting (50). Knowledge was intimately gained by experience and experimentation (19). Members of the Bottega regularly exchanged ideas. Young apprentices followed strict methods but experimented on their own (51). The "study program" of these workshops was highly investigational and allowed the apprentice to perfect both art and science skills without formally studying the theories behind the science. Principles of art used today, such as perspective, were discovered in this period. *"Artist -artisans who had everything to discover and who in less than a century indeed discovered everything by themselves (the principles of perspective, the science of anatomy, the laws of light)* (19)."

DaVinci later repeated what he learned by observing and working alongside other skilled professionals. He then modeled those skills for his students. *"The painter must strive to the universal, capable of representing the countless forms contained in the world…and hold them in your mind* (40)." DaVinci was continually perfecting his skills and endeavored to move from liner representations to those with volume. To understand the art of another, one typically copies that art. I redrew DaVinci's brain image and then deconstructed it to understand better the way he was thinking. A rough sketch of this can be seen in Figure 4**.** DaVinci was also interested in how light reflects, refracts, and passes through the eye to the brain, but despite his rigorous stubbornness, much of his time was devoted to the amusement (52). DaVinci did not separate or write about his anatomical discoveries without adding humorous commentary. In exploring human reproduction, he noted, "*The productive parts were only for the absurd multiplication of human beings and for "various diseases.* (43)." Humor and criticism are intermingled constantly, along with analogies throughout his scientific and artistic notebooks.

Leonardo DaVinci embraced a wide variety of scientific disciplines simply to cover his cost of living. His interest in machines involved reducing most machines into one system, a focused goal (33). He also attempted to apply a similar vocabulary for biological concepts such as embryology, botany, reproductive biology, entomology, geography, and engineering.

Patterns in Nature were of particular interest to DaVinci, and trees, rivers, and veins are often considered together. In DaVinci's famous drawing of the branching of trees, he depicts the pattern that is frequently observed in Nature and human anatomy of branching systems and bifurcations (53). His notebooks contain mixtures of personal views and scientific investigations with stories and images. The informality and personalization of his notebooks reveal a personal process rather than a standardized curriculum. This is an important element for considering the structure in art-based science programs. My goal was also to achieve a degree of originality in the drawing discovery process based on DaVinci's notebook style. Another important component of drawing discovery is emotion and feeling. DaVinci, despite his rigor for experimentation, felt that all human scientific endeavors proceeded from emotion. *"All our knowledge proceeds from what we feel* (Richter 1970)." He also presents a reductionist method in describing the analysis of things for study, *"If you wish to gain knowledge from the forms of things, begin with the detail and only move from one detail to another when you fixed the first firmly in your memory and become well acquainted with it* (43)." Adding that "*human memory could not contain all the forms and phenomena of Nature."*

DaVinci's notebooks provide a wealth of knowledge and skill sets that can be modeled for today's biology curriculum or course. They create a standard that has been verified through centuries. For this thesis, my focus is on the drawing. Many artists, who laid the foundation of fine art, recognized that drawing served many purposes and was the foundation along with the geometry of understanding form, shape, and morphology. *"The artist had to perceive (or conceive) form but also to preserve, analyze, and transmit it: there was no better method than drawing* (33)." Observing and drawing became the same processes for DaVinci and were integral in his scientific investigations. Having studied the arm and hand mechanics, DaVinci combined this knowledge with his study of the eye, light, and the brain to recognize an evolved system. He noted that they became coordinated through determined training (40)." In this way, Leonardo DaVinci trained himself to become the best, most precise instrument for recording, analyzing, and creating from the natural world. *"There have been virtually no better technical drawings until the coming of computer-assisted draftsmanship* (33)."

DaVinci, in his art, was also preoccupied with the dynamic nature of the living world. He continually studied motion, motion in birds, and motion of limbs, the motion of water, clouds, and rocks. *"Motion is the principle of all life* (43)." DaVinci uses the word "universal" for his many interests. This was translated into recognizing the interconnectedness of living systems from different facets of Nature (33). *"The patterns interconnecting the basic structures and processes of living systems* (43)." This aspect of DaVinci's work points to how are processes foster interconnected thinking about interdependent and connected systems on the planet. One aspect that is of particular importance to the overlap of science and art with Nature is an understanding of continual intellectual processes, which was apparent in many other polymaths who made apparent leaps in their investigations.

"DaVinci noted that pure intellectualism was of little value without manual operations such as drawing, painting, building, and experimentation (33)." DaVinci was intent on making the painting and drawing part of academic tradition. He repeatedly demonstrated that love of Nature, manual skills, observation, and experimentation were critical to a synthesis. DaVinci did not separate the design process from the process of material production (33)." Capra further adds: *"Leonardo's anatomical drawings were so*

radical in their conception that they remained unrivaled until the end of the 18th century. Leonardo introduced numerous innovations; drawing structures from several perspectives; drawing in cross sections and "exploded" views; showing the removal of muscles in successive layers to expose the depths of the of an organ or anatomical feature. None of his predecessors or contemporaries came close to his anatomical detail and accuracy (33)." DaVinci referred to his anatomical drawings as experimental demonstrations, similar to a mathematical proof, DaVinci they revealed "truths" about the relationship of organic forms and therefore each drawing could be interpreted as a visual equation or proof (33)."

DaVinci has used various drawing techniques, experimenting with red chalk, charcoal, and oil to mimic the variation in form and motion for dynamic systems and movement. These contouring lines give the feel of and visualize patterns of movement, such as in the heart and with water. He also created variations of the form to reveal its other "possibilities." This contrasts sharply with the computer graphic-generated illustrations of today where even molecular (which one would assume fundamentally functions through Brownian motion) structures and pathways are presented as static, non-vibrating, smooth, and solid. DaVinci's contour method made the viewer think about the dynamics of this form, which he was obviously thinking about as well when he draws it, and that could invariably alter how you interpret or communicate this system (33). DaVinci also used many experimental preparatory drawings to work out the problem he was studying. Here is another area of drawing that a modern model would employ. One drawing is not sufficient to understand a form, and multiple attempts should be made to capture form and variability.

These kinds of drawings are still used today by computer graphics programming artists who must draw and estimate the mechanism of interest. Examples of this are addressed in another section of this thesis. Many qualities benefit scientific thought and can be attributed to DaVinci's drawing style, allowing for different forms of conceptualizations. Leonardo DaVinci, later on in his life, became focused on mathematics and models. He was particularly interested in geometry and topology. His interest in geometry was its ability to deal with continuous variables (54). These he would apply to living systems and forms. Continuous quantities would be a good fit for dynamic systems, which contain basic geometry and as their underlying unit. They would help to explain the two problems DaVinci wanted to verify in life forms, and they were movement and transformation. Both of these qualities have vexed the life sciences since their inception. The originality of DaVinci's use of geometry is apparent in his notebooks, where he discusses the geometry of continuous transformations and rectilinear and curvilinear shapes.

Towards the end of his life, DaVinci wrote about the conservation of volume and its authority over transformations of natural forms, giving life the quality of plasticity and the ability to change shape (55). DaVinci frequently wrote about these topics as they applied to the living form but used a dodecahedron to demonstrate the transformation in four steps (33)." Mapping curved space and curved surfaces was not simply a scientific pursuit but a valuable technique in painting and drawing living things. In his early studies on topology, he noted the invariant nature of stretched, bent, or transformed geometry or topographical transformations (56). He found all this necessary when studying Nature as he believed Nature was not expressed or its forms made clear through quantity and numerical relationships but through geometrical relationships and changing of shapes according to rigorous laws (33)." The line is also a fundamental element of drawing, and DaVinci often analogized using a single line to represent the duration of time. This is not an uncommon thought, as he wrote, *"The line is similar to a length of time, and as the points are the beginning and end of the line, so the instants are the endpoints of any given extension of time* (1)." The line is of particular importance in phylogenies today as branch length (line length) represents the duration of geological time and the points or nodes bifurcation events and speciation, as well as the flow of nutrients in plants and many other branching and bifurcating events in the natural world (57).

DaVinci, through overlapping practices, made overlapping discoveries. While demonstrating his understanding of linear perspective in his art, he explored the anatomical relationships through the same venue of the geometry of perspective. A sectioned skull revealing the delicate internal structures through innovative sectioning was simultaneously created, while DaVinci was focused on the eye and how light enters it and how vision works to receive and create these visual perspectives (33).

To merge art and science effortlessly, DaVinci used the same haptic tool; drawing. *"DaVinci's scientific method was based not only on the careful and systemic observation but also induced a detailed and comprehensive analysis of the process of observation itself. His approach being predominantly visual and through the drawing discovery process* (33)." In the exploration of Leonardo DaVinci, several potential key protocols emerge that are testable in the biology classroom and provide insight into the benefits of developing a biological-art drawing heuristic model. Those protocols revolve around DaVinci's treaties on scientific illustration (rotation, transparency, and transverse section) applied to all studies of biological form and function They also include the naturalist experience which exposes the student to real sensory experiences with the living world and are consistent with astute observations of natural processes through drawing notebooks and fine art. These experiences also reflect the 19th century romantic view of biology, which utilize fine art to envision evolution, ecology, cytology, and other disciplines of biology. These combined efforts encourage biological scientific inquiry, ecological conscious and inspire a sense of wonder about nature (48).

2.2 Case Study II: Theodore Boveri 1862-1915)

Theodore Boveri is important because of his complex use of visual imagery and drawing as a discovery process in genetics, cancer biology, and cytology. Boveri was a zoologist in Victorian Germany who developed visionary concepts about genetics, chromosomal abnormities, chromosome function, and cancer biology. He coined the terms "centrosome" and "centromere," two areas of his research (58). He is primarily recognized and remembered for identifying chromosomes as the primary site of genetic factors or genes (58). He also approached the development of the sea urchin egg with the fundamental question: Is the developing embryo's character determined by nuclear chromosomal factors or cytoplasmic factors (59)?At the time, several people were developing diagrams for cell division and chromosomes and reconsidering Mendelian genetics. This renewed interest in Mendel dovetailed with Boveri's research and with evolutionary theory. Over one hundred years have passed since Boveri's drawings and observations depicted fertilization events and early embryonic development, and his ideas regarding tumorigenesis were put forth.

He was also the first to observe chromosome diminution in the process of early cleavage divisions in the parasitic nematode *Parascaris equorum* (58).

Today Boveri's work is being rediscovered and reconsidered by molecular biologists (60). Boveri and his wife, Marcella, who collaborated on many research projects, experimentally manipulated chromosomes and cytoplasm while recording the research through elegant and descriptive drawings, proposing hypotheses on heredity, the behavior of chromosomes, and cancer. Boveri spent much of his life studying botany and music. While focusing on zoology and mathematics, he became a highly skilled artist and illustrated throughout his most productive years of research (61).

While learning sophisticated staining techniques in cytology, he developed his observationally-based, descriptive drawing skills further and his lithography technique based on classical drawing techniques of the 19th century. He tailored these skills to zoological research and document and reasoned out his experiments (60). Initially, Boveri was interested in becoming a painter but was discouraged by his father and instead pursued his second interest; zoology and nature study. He spent much of his life traveling to Italy to collect sea urchins and Ascaris, admiring the landscapes and considering them as part of his observations. Most of his work and illustration were done with the gametes of invertebrate organisms and their embryonic states, of which a diagram of (Figure 6). Boveri's combined techniques of lithography, drawing, and cytology brought new light to Mendelian laws. "*The rediscovery of the Mendelian laws in 1900 is usually seen as the important starting point for the discipline of genetics* (58)."

The 19th century also brought new experimental methods to manipulate chromosomes and conceptualize hereditary factors, later named genes. Boveri and his wife were responsible for resurrecting Mendel's laws and verifying their significance, including the law of segregation (61). Boveri made notable contributions to cell polarity, cell differentiation, centrosomes, chromosome behavior, recombination, and segregation. His meticulous drawings played a pivotal role in his discoveries and documenting biological processes (60). Boveri's formative contribution regarding chromosomes could explain Mendel's laws, as it was the chromosomes themselves that carried the genetic information. While other scientists may have uncovered transmission of genetic factors independently, Boveri coupled this discovery with another important observation and model; the origin of malignant tumors, for which he posited a genetic basis of malignancy (62).

From 1887 to 1909, Boveri formulated at least twenty known hypotheses (58). Boveri's use of sketching, drawing, and observation helped formulate mathematical models and theoretical constructs about clonal tumor formation. Even though he had not studied tumors experimentally, he compared abnormal embryos with normal embryos, focusing on abnormal development explanations. His observations about aneuploidy, genome instability, and their relationship with tumors and cancer were recorded in notebooks and later published "*Concerning the origin of malignant tumors* (63)." The question one might pose is how did Boveri's observations, drawings, and analogies produce various hypotheses at the turn of the 19th century using only a microscope that is still relevant today? The intersection of Boveri's varied skills and interests, like other polymaths of this thesis, had several consistent variables throughout their lives that may shed light on that question, making the historical and artistic skill perspective critical to developing authentic bio-STEAM practices. These works also seek to explore the intersection of observations made, phenomena observed, and the transformation of observation and phenomena into a visual hypothesis. Boveri provides this example for the specific domain of microscopy and cytology and its expansion to other fields, such as cancer biology.

The model of biological-art-based drawing with just a microscope has meaningful application to the standard biology curriculum and offers insight into a potential authentic skill-based STEAM experience with microscopic observations that can encourage the development of conceptual and insightful drawing. Boveri's life examples reveal some of the necessary and complex interactions of highly focused content-based drawing as part of the experimental process.

2.2.1 Boveri's visual-spatial chromosomal territories

Today chromosome territories are components of a major feature of the spatial domain of overall chromosome architecture, an often-little appreciated complex micro-habitat of the genome and rarely, if ever, discussed with units of on cell production in biology class. Could the standard drawings of whitefish blastula or onion root tip enhance student understanding of cell reproduction if they followed Boveri's classical drawing and chromosome territory metaphor? Boveri's studies of chromosomes' uniqueness and organization are applicable today regarding the different epigenomes and their functional implications, particularly in chromatin organization and nuclear architecture (64) Even today, the functional significance of chromatin diminution remains an enigma (65). For most students examining the interphase stage of cell mitosis, chromatin and the nucleus appear as a mass of disorganized spaghetti, with little consideration for nuclear infrastructure. However, the nucleus is a highly organized organelle with chromosomes occupying distinct locations and compartments or "territories" of immense complexity. The concept of chromosomal territories was appended from 1950 to 1980, but it has started to receive new interest in its possible role in epigenetic gene regulations (66).

Historically the first chromosome theory of heredity coincided with Darwin's theory of natural selection (67). Many scientists were studying cell division and chromosomes, including Flemming, who coined the terms "chromatin" and "mitosis," illustrating his observations of nuclear division and mitosis (66). In 1880, August Weismann proposed the first chromosome theory of heredity, working with sea urchin and Ascaris fertilization (Cremer 2006). Many different types of drawings and diagrams were being developed to communicate observations from experiments. Those visual ideas were spawning new theoretical concepts and evolving illustrations and visual representations of both cytology and evolutionary thinking. This included schematics of the process of meiosis, mitosis, and development (66).

Darwinian ideas were now influencing how cytologists thought about the cell, and views of representations such as tree diagrams were used to depict the genealogy of early development (68). Theodor Boveri built on the hypothesis of a constant number and continuity of chromosomes throughout interphase, but Boveri had also linked chromosome individuality and chromosome territories to heredity (66). Through illustration and continual trips to Mediterranean ecologies, Boveri collected specimens and in lab experiments followed individual chromosomes during mitosis, noting that they maintained strikingly similar conformations and "mutual" positioning (66). Boveri used the term "chromosome territory" to illustrate that chromosomes were being transformed at a nuclear site. The space they occupied was a chromatin network, an interchromatin-like web, an active and inactive nuclear-cellular matrix. Boveri described these events as chromosomes building their own reticulum's and essentially, as he stated 'its own territory," creating a niche of unique genomic functionality, a specific architecture within the nucleus. He documented this with illustrations. He proposed that since the chromosome actively created its own genomic/chromatin network or web, it should reappear at prophase in the same space of the nucleus (66). He set out to test this hypothesis with his illustrations and observations by fixing two and four celled embryos (66). He observed and illustrated protrusions in his experimental cells that served as landmarks where the chromosome territory was likely to have existed and made a point to accentuate these protrusions in the illustration. Boveri had two postulates, one, the constancy of chromosome territory neighborhoods, and two, the changes of chromosome neighborhoods in prometaphase due to chromosomes' movement (66).

Boveri's contemporaries argued that chromosomes disintegrate and then aggregate or reemerge and were somewhat lifeless structures. However, Boveri had an important metaphor for chromosomes that may have influenced his drawings and perspectives. Besides territories and neighborhoods, he viewed chromosomes as *individuals* and called them individuals in his writings, somewhat akin to primitive organisms (69). This may have helped Boveri imagine their behavior and existence as a temporal-spatial living system within the nucleus of a cell, a much more independent and animated system. With his collaborator Walter Sutton, and Gregor Mendel's theory of heredity, Boveri asserted that each chromosome is an individual that carries a unique combination of genes and that mitosis is an evolved mechanism, which safeguards that both daughter cells, which receive the same number and a combination of Mendel's hereditary factors (69).

"*With only meager facilities that he had at the time – a light microscope, basic stains and painstaking hand-drawn diagrams – he was able to make fundamental predictions on the mechanics of fertilization and the role of the paternal centrosome during the development of the round worm and the sea urchin…* (70)." Boveri made classical illustrations first of his observations and then reduced the artwork down to a simpler version where he examined the quantitative behavior recorded in the illustration more closely.

"Boveri's original work on the 'centrosome theory of fertilization' formulated the hypotheses and predicted that the centrosome was the active center of cell division and that spermatozoa and egg were complementary structures. He presented his predictions in the following way: (I) The centrosome is a cyclical structure – a permanent reproducing organ of the cell. (ii) Centrosomes are part of a central apparatus or 'microcentrum' in cells. (iii) They are 'dynamic centers' of cells and the true division organs of the cell. (iv) Centrioles (one or two) are contained within centrosomes (70)."

Boveri's drawings mirror his exact hypothesis for the centrosome and visually define his underlying observational, aesthetic perspective (Figure 6). Ascaris sperm are similar to human sperm in that they both contain two centrioles. however, some significant differences are that one centriole is responsible for organizing the distal centriole. The other centriole is transmitted to the embryo of Ascaris, but similar processes occur that are clearly defined and illustrated. Like DaVinci, the remarkable accuracy and beauty of Boveri's drawings are authenticated by digital images (70), revealing the structural similarities. There are also many unresolved questions about the function of the centrosome and centrioles that Boveri may have alluded to, such as the role of the centrioles and chromatin in inheritance and that the centrosome/centriole as the activation center of initiating the dynamic processes of the zygote, which he did state (60). The drawing and redrawing of this process may have encouraged Boveri to speculate further on the process of development and evolution simultaneously. Boveri also showed that the centrosomal cycle is synchronized with a normal cell cycle or that it is closely tied to cleavage or mitosis (71). This line of thought on mitosis also led Boveri in the direction of abnormal cell cycles and the astute observation of unstable cellular entities. Is there a connection between his observational drawings and his hypothesis of tumorigenesis? Boveri's rule of centrosome inheritance (paternal) also allowed Boveri to predict the inactivation of the maternal centrosome during oogenesis (69). Could Boveri's work shed light on epigenetic or transgenerational inheritance as well? Do complex aesthetic drawings incubate scientific ideas? Some transcription factors and other proteins involved in patterns of gene expression circulate from the nuclear chromatin to the centrosome in cycling cells, and it was possible that Boveri made this connection through drawing.

The orchestration of events in the development of Ascaris captured and enhanced through the drawing heuristic reveals a highly harmonized networked narrative of genomic assessment by the cell and an astute cohesion of Boveri's knowledge. To revisit and explore Boveri’s ideas today, a variety of visualizing technologies are used, but in authentic STEAM collaboratives, similar drawings and observations would accompany a researcher’s work and inspire a parallel mindset such as Boveri’s. In other words, the researcher would be drawing, making sketches, and revising visual hypotheses alongside the research, which they would be fluent in. One might call this a ‘tight feedback loop’ or a rapid feedback loop, only possible through the continual use of drawing and familiarity with the organism's key characteristics and its natural history. Boveri followed what he called the “natural experiment,” where the organism's integrative complexity dictated the experiment. The living system dynamics could be best followed by observations and evolving the drawing and then projecting those rapidly changing findings onto more complex levels of integration and variations of visual output and according to their natural behavior. *“Organisms are not functionally divisible into the established fields of specialization with which most biologists identify. The organism is a real unit, one’s specialty is an artifact of convenience* (72).” In the narrowed artificial boundaries of biology disciplines, many key characteristics of a system are ignored in favor of fitting the system to the question or the method. Boveri, like other polymaths, crossed those boundaries through the artistic method and maintained a focus on a larger system, perhaps, enabling the consideration of the staggering complexity of the entire system and thus allowing the system’s unique qualities to emerge through the art, then posing the question. Today, experimental evidence of stained cells and autoradiographic images can reveal territories and visualize chromosome territories through artistic methods and inculcate processes.

In contrast, computer-generated visualizations bypass it, often only focusing on elements of interest without consideration of the biological wholeness. In Boveri’s time, researchers were limited to direct observation, illustration, imagination, and metaphor, and this suggests a powerful tool for science education training. Boveri’s seminal contribution regarding chromosomes could explain Mendel’s laws, including Mendelian ratios that were testable (73). This may have occurred through his other method of reducing the artwork into a schematic. From Boveri's life, we may learn about a "whole person," not just their main contributions, offering us insight into key practices for biological knowledge.

Through detailed observation and drawing of Ascaris and sea urchin fertilization, Boveri, like Haeckel and Pasture, utilized and developed multiple artistic skills and worked with several media types. One was descriptive, observational drawing, which is fundamentally drawing realistically what one observes. The other was a development of expertise with the challenging art technique of lithography. Lithography is both a drawing and printing technique and requires knowledge of inks and chemistry. Thirdly, from realistic drawings and renderings, diagrammatic model drawings, which simplified the visual hypotheses for communication purposes, were created. The artwork created by Theodore Boveri was a mix of these techniques and methods. Combined, they helped precisely record his experiments while offering perspectives about the actual mechanisms, particularly those concerned with spindle formation, centrosomes, and fertilization (60). While not a focus of this thesis, the complexity of drawing methods, techniques, and media influences the thought process. Some media, skill levels, and techniques alter the perception of the observed. The favoring of lithography and drawing was a preferred method of 19th-century artists.

It was Boveri's transition from observations of multipolar mitosis in sea urchins to a chromosome theory of heredity and the theory of cancer as a disease of the chromosomes that makes his work so remarkably unique and broad, revealing art's application to a variety of biological conceptualizations. However, most of Boveri's work remained confined to two organisms, the sea urchin species from the Mediterranean, the echinoids, and the parasitic round worm *Ascaris meglocephala univalves* and *bivalves* (71). Boveri extracted and mined a tremendous amount of knowledge from these two animals' cells, suggesting that his art was distilling and unifying his knowledge concurrently with his research processes. The round worm had the advantage of having one and two pairs of chromosomes, clearly visible during cell division. Sea urchin eggs had the advantage of being transparent and were available in large numbers. In this way, experiments observing egg and sperm behavior in natural and artificial conditions afforded the experimenter many opportunities to repeat an experiment and, with it, the necessary drawings, which could be altered continually.

It is important to note that Boveri, like most other scientist-artists in this work, worked from start to finish on scientific investigations (74). The drawing's remodeling was not left to another researcher or an artist with the repeated experiment but persisted as one person's internal speculation. Boveri visited the aquatic ecologies where he collected specimens, made drawings and notes of the environment, including landscape watercolor paintings as Haeckel and DaVinci did, and conducted the preparations and the research. Concomitantly the researcher was also engaged in readings on a wide variety of subjects in the arts and sciences, attended exhibitions, and infused new illustration styles and scientific visual models into their work, perfecting their illustration process along the way, in other words, the science was in the context Nature and of the artistic. In this way, the scientist- artist was fully immersed in the biology and the art of their interest. While Boveri had a great disdain for writing, he emerged as a proficient and articulate scientific writer, noting that since he despised writing, he would treat it as if he were making a work of art (58).

In the 19^{th} century, the relationship between cytoplasm, the nucleus, and heredity was not yet established, and observations of variation in nuclei size, as well as changes in nuclei function, were of interest to cytologists. Until Boveri's discovery, following interphase, most cytologists imagined that chromosomes disintegrated and not organized, self-regulating figures (75). Little was known about polar bodies, centrosomes, and centromeres. Polar bodies, whose function is not clearly understood to this day, serve different functions in different organisms, were one of Boveri's deep interests. Ascaris fertilization allowed cytologists to observe centromeres and spindle apparatus during cycle cycles. The duplication of the chromosomes and the findings produced by Bovari's drawings are still recognized as being of value today, especially in cancer biology.

2.2.3 The genetic basis of a tumor, a by-product of discovery drawing?

Boveri's tumorigenesis concept of inflammation and instability remained relatively obscure until recently. After a century of increased pollution, toxins, radiation exposures, and mechanical irritations, inflammation became a salient feature of the disease process and cancer (69). Chronic inflammation, which may lead to cancerous cell lines, was deduced by Boveri from his embryological discoveries (69). Boveri was able to take his artistic renderings of normal mitosis, refine and reduce them into schematics, and compare and contrast cell lines within the diagram and with abnormal mitosis. Boveri noted an inhibitory mechanism in the cell cycle from his work on abnormal mitosis, which he proposed resided in the chromosomes, assuming the chromosome housed the hereditary material. He observed variation in sex cells vs. somatic cells and remarked on the differences, "*These different potencies are also observed in the development of the whole dispermic egg. Such fertilized eggs show an almost unlimited variability from complete normality to abnormalities of the highest degree* (69)."

The diagram in Figure 7 was generated from a whole organism/ecosystem perspective to the cell line of an embryo (Figure 5 and 6) and then into a schematic, followed by a reduced cellular line or tree (see Figure 7). It was this visual recording process that may have contributed to his appreciation that chromosomes "communicated" with each other and that it was the normal communication (genes on chromosomes) that resulted in normal cells rather than abnormal ones, and therefore, as Boveri put it "*individual chromosomes must possess different qualities* (58)." This discovery process from start to finish was accomplished through conceptual drawings and ideas Boveri obtained from diagrams made by other scientists that were available at the time. Herein lies another aspect of the drawing heuristic; the need to create beautiful art that embodies the significant features of the research and then continually comparing drawings and observations, transferring those salient features of observations to refine a schematic. Like a visual equation, the process itself reveals key processes of the phenomena. Exposure to other visual ideas may have informed the synthesis of new concepts and furthered Boveri's art and research expansion.

Logically, Boveri noted that tumors occurred in highly proliferative tissues more frequently and that "additional stimuli" promoted tumor growth more easily in those tissues (69). He also noted that numerous causes and a variety of factors contributed to tumor formation and metastasis. This was based on speculation on the function of chromatin and morphologically fragile, unhealthy appearing chromosomes (76). He mentioned that this was a resultant effect that was observable as a disturbance and disruption of chromatin. The *Echinus* embryo Boveri induced multipolar mitosis and recorded the abnormal growths, describing malformed cells' clustering into what he would call tumors. He did not necessarily see this as a disease. However, just the cell taking a 'wrong direction'(69)." He also labeled these disturbances "irreparable defects." He suggested that if normal or inhibiting chromosomes were removed, metastasizing tumors would result (60).

Boveri also stated that "*every tumor arises from a single cell,"* or tumor stem cell, which results in local disrupted metabolic activity in the local environment, which is also disrupted. The stem cell linage concept by Weisman and-Haeckel may have sparked this conceptualization (77). In the 19th century, a mingling of contemporary ideas about the nucleus, heredity, cancer, and evolution created new philosophies about living systems, and impressions of the cell itself were changing as arguments for and against Lamarckism and Darwinism persisted. Again, we must ask what combination of factors led down this road of discovery? How might Boveri apply his art to the questions of chromatin remodeling, genome reorganization, and evolution today? With his expertise in nematodes, mitosis, and drawing, he might shed light on the evolution of chromatin loss and why it existed in his favorite organism, and why such germline genes would be eliminated. Boveri had already proposed that germ-line limited DNA had important functions for germ-line differentiation (78).

The immersion in both science and art regularly may be considered an impetus behind the insights as they are neither forced nor fragmented and divided. This aspect of an authentic STEAM-collaborative and methodology cannot be neglected. Consideration of how time is used and the flow of it play a key role in discovery. It is not common knowledge to non-artists that many sketches and drawings are made, along with frequent visits to galleries and exhibitions to explore other artists' techniques up close. Often, unrelated subjects and side "hobbies" indirectly influence research, providing metaphors and new domains of insight. It may also take years before a single style or idea emerges, one that best fits the area of nature being studied, which may happen by chance alone. This is common among all the case studies in this thesis and not necessarily visible, as many of those drawings are discarded, and it is not easy to imagine the circumstances presented to these scientists of the past. It is known that Boveri reworked and copied directly from diagrams leading to his uncovering the nuclear architecture (79). Boveri used drawings to elaborate and build on ideas that he believed were valid and recognized as valuable to his work. The descriptive also played a critical role as words formulated images for artists like Boveri. Like Virchow, the term *chromosomal* or *nuclear architecture* may not have been original but is often attributed to Boveri, who advanced the idea. Virchow used the term *omnis cellular*, which Francois Raspail coined and described as *"every cell is derived from a preexisting cell* (80)." This idea and stem cell diagrams may have had a tremendous influence on Boveri's clonal tumor theory, from which he builds his own stem trees (81).

In his discussion on the chromosomal mitosis and segregation in Ascaris, sea urchin, insects, and vertebrates, Boveri notes that size and other differences exist. However, chromosomal abnormalities are different from the variations he has meticulously recorded in words and drawings. *"We may therefore regard it as probable that individual chromosomes have different properties in vertebrates too, and it is this assumption that forms the basis of the tumor hypothesis I have put forward. A malignant tumor cell is – and here again I take up the ideas of Hansemann – a cell with a specific abnormal chromosome constitution* (82)." Von Hansemann recorded that there was a tight association between abnormal numbers of chromosomes (aneuploidy) and malignant tissues. However, he did not imply or resolve that one would be the cause of the other as Boveri did (83). However, Von Hansemann, a lesser-known pathologist of Boveri's time, coined the term *anaplasia* and defined it as "*a process that carried the cell in an entirely new direction*." He also stated that each tumor and its progression would be different and would have an altered fate. Even in the same tumor, different cells would have different abnormal paths- *"The anaplastic cell is one in which, through some unknown agency, a progressive disorganization of the mitotic process occurs* (82)." Perhaps another lesson from Boveri is that merely using images, diagrams, and formulas do not translate into an understanding of biology. Understanding them from a scientific artist's perspective, not just an artist's perspective, raises new questions. Through the combined drawing/observation/discovery, an understanding of the integrated transformations in biology emerges.

2.2.4 Stem cell and cancer cell diagrams

Boveri's hypothesis for tumors was partially the result of studying other's diagrams and writings, which admits he has done in the case of cancer (81). For Boveri, a master of visual biological literacy, working backward from a diagram to the original idea would be a highly effective way of deliberating on the hypothesis. When a visual novice views a diagram, this process may be less likely to occur, as it is through the creation of images that an understanding of them emerges. It is the real experience that provides greater insight. So Boveri may have used that knowledge to rework concepts and drawings into various hypotheses and diagrams of issues and questions regarding cytology and neoplasia. This points to how an artistic perspective and skill set in biological research can reframe a question and serve as an investigative tool into previously existing ideas, transforming them into new hypotheses. Did Boveri's remodeling and merging of the stem cell tree offer insight into his cancer hypothesis? It would seem that this is a likely possibility since he never worked with cancer directly. It also reveals how being truly visually literate in a subject requires artistic skill and content knowledge.

Chromosome missegregation leading to aneuploidy was identified as a recurrent defect in many types of cancer cells. It was a discovery of the late 1800s, and Boveri was current on these discoveries through reading and discussion with other scientists (Weaver 2011). In his observations of chromosomes, without studying actual tumors, and rarely seeing cancerous cells, Boveri formulated several hypotheses about the metastasis of aberrant cell lines based on the sea urchin and Ascaris development. His "Tumor Anlage," has also been consistent with the modern concept of cell adhesion and metastasis (84). He also posited that inflammation precipitated the original clone or rouge cell that ultimately gave rise to cancer cells' clonal evolution (84).

Like others of that period, Boveri was exposed to Darwinian diagrams, trees, and natural selection. The stem cell diagram produced by Weissman and Haeckel looks much like Boveri's "tree." As one explores the history, it becomes apparent that what Boveri visually created and constructed himself was influenced by circulating diagrams from other labs and scientists (85) At this time, there was a competitive but freely mixing, highly cultural environment of scientific discourse. Of his twenty recorded hypotheses, Boveri used the analogy of parasites such as Ascaris in promoting tumorigenesis through the inflammatory response, which was intimate with in more ways than one. This observation was made of tetraploid genomes and correlated with his concept of genetic instability, inflammation, and tumor clones (84).

The visual communication and drawing discovery process demonstrate how another artist-scientist, like Haeckel, could develop a visual schema fully integrated with his research and expert knowledge and produce a visual hypothesis or even a metaphorical term that would seep into the minds of other scientists such as Boveri with profound and lasting influence on their experimental work. This is another level of scientific communication- between very like-minded and similar skilled individuals. In his hypothesis regarding different cell types and cancer, Boveri notes that *"Tumors derived from the same organ can consist of different cells, which could be explained in different clones with different chromosomal abnormalities* (84)." He also notes that *"There may be hereditary transmission only in the sense that a certain disposition is transmitted."* This alluded to the concept of recessive alleles and noted that "inbreeding" would increase the risk of transmission of disease (84)" In some of his writings regarding chromosomal instability, he speculates about those instabilities leading to additional genetic changes in the tumor (84). There appears to be further speculation on genetic instability in his writings regarding chromosomes and cancer as his drawings and observations of unstable chromosomes suggested an unstable genome (58). While Boveri knew nothing of defective DNA repair mechanisms or mutation, he was observant of chromosomal integrity and its relationship to healthy cells and tissues through a coherent method of art/science.

2.3 Case study III: Earnest Haeckel (1834-1919)

Earnest Haeckel is rarely mentioned in biological science courses and comes in second and sometimes not at all in evolutionary discussions. Interestingly, Haeckel may have set the tone for the future of modern biology. He contributed valuable perspectives to evolution and biology through diagrams, prolific amounts of scientific fine art, terminology, and an exhaustive study of living form recorded in beautiful lithographs (86). It is not just evolutionary trees that Haeckel illustrated but also terms such as "phylogeny," "ecology," the concept of "evo-devo," as well the recognition of a cellular diagram for the conceptualization of the stem cell (87). As a highly skilled fine artist, scientist, and physician, Haeckel clearly understood the power of diagrams, illustrations, and terminology to promote scientific ideas. Aside from the phylogenetic tree concept (which was first published officially by Haeckel), Haeckel's interest in describing biological processes such as phylogeny and working on hierarchical systems may have prompted his use of the word stem cell *Stammzelle*, representing what he was observing and positing a progenitor cell or a beginning, first event all- important ancestral form (74). From this term, multiple modern conceptual frameworks came into being.

Like DaVinci, Haeckel was concerned with aesthetics, geometry, morphology, and the dynamics that shape life. He applied a typological way of looking at living systems. From his studies of radiolarians, he described countless new species. From his morphological perspective and his *General Morphologie*, Haeckel made an astounding revelation about evolution, concluding that all life started from bacteria. He understood (88). Haeckel was not interested in paleontological studies, even though form and reconstruction illuminated organisms' natural history. Instead, he agreed with Darwin's theory and chose to demonstrate his results with comparative morphologies (88). Identifying common characteristics or forms as distinct characters in a constant metamorphosis was a series of evolving complexities of nature, and that was viewed through the lens of ontogeny.

Haeckel described nature as "*creating the forms it needed* (88)." Haeckel focused on form and meticulously illustrated from hundreds of specimens. One focus was the natural selection of sponge spicules. Haeckel used the morphology and diversity of spicules and natural selection to consider what he called biocrystals (89). "*He (Haeckel) simply saw in the form and arrangement of the spicules something which "best fitted," for its purpose, that is to say for the support and strengthening of the porous walls of the sponge, and clear evidence of utility through the process of natural selection* (89)." The study of evolution through drawing forms was not just a study of matter but more a view of matter as a repository for energy transformations or processes, *"Matter as such produces nothing, changes nothing, does nothing: and however convenient it may afterwards be to abbreviate our nomenclature and our descriptions, we must carefully realize in the outset that the* *spermatozoa, the nucleus, the chromosomes, or the germ plasm can never act as matter alone, but only as seats of energy and as centers of force* (89)." For the scientist-artist discoveries, drawing was an attempt to capture or see into form and extract the elusive transformative, dynamic processes. Haeckel made his artistic skill set coherent with theory (89).

From Haeckel's phylogenetic standpoint, the blueprint of life was extending and morphing and crystalizing into a necessary form in a moment of geological time. The biogenic law became Haeckel's drawing heuristic of evolving form. *"The individual will repeat its evolution in nature, thus fixing its evolutionary program* (88)." This view of repeating patterns connects with Haeckel's application of the artistic view of expressing the most essential morphological characters in his drawings to see relationships between species. Like Cajal and Boveri, Haeckel would draw out and formulate through an aesthetic dimension, the right points of view and what he perceived as the best points of view, of the most significant morphological characters and features of what he was studying (88). Haeckel was also studying forms as changes in time and as relationships in time, which were constrained by human perception's limitations. Haeckel also noted that all life must have evolved from a very simple form and saw the laws of development of form and evolution of the form as similar processes (90). Drawing protocol, which involves drawing from simple forms to a more coalescing complex image, only reinforced Haeckel's artistic perspective. Basic geometry, planes, sections, and rotations are a foundation from many perspectives (1).

The embryo drawings Haeckel created a century ago of vertebrates in the early stages of development have been frequently criticized. However, based on a modern-day understanding of gene expression, there appears to be a greater similarity to Haeckel's early evo-devo concept or the individual's development and evolution of a phenotype than he was given credit for. The ontogeny recapitulating phylogeny point of view that he championed may have arisen through a deeper understanding of form and from the artistic perspective he practiced. Did Haeckel's drawings of vertebrate embryos capture the idea of a shared evolutionary history before conserved genes were realized? Was it art that perpetuated the underlying patterning that he observed? "*Haeckel was more correct than the data of his day allowed* (91)."

"Commonalty in early embryos is more apparent from molecules than morphology (91)." Whether or not Haeckel intuitively understood this through his drawings is unknown as molecular data was nonexistent, but from morphology, he extracted an evolutionary-developmental connection. *"Anterior-posterior patterning by a complex of homeodomain-containing transcription factors is a prominent example of conserved molecular events*(91)." The similarities in development to an astute artist/scientist, including patterning of posterior/anterior, would be observable in the process of drawing itself and would become salient features of those drawings, which may have been intended as representatives of the artistic concept. While Haeckel's ideas, through drawing, were hypothetical, they linked embryology to heredity and evolutionary history. This process/progression of form- thinking is also apparent in the stem cell schematic diagram.

2.3.1 Stem cell drawing and phylogenetic tree drawing

In collaboration and observation of another diagram and drawing, the concept of an undifferentiated cell line began to emerge. August Weismann developed a stem cell diagram and collaborated with Haeckel to posit the stem cell expansion into variations of the original totipotent cell. *"Even today, the understanding of stem cells, especially in popular perception, is to a large extent a Haeckelian- Weismannian one*(74)." Cytogenetic trees inspired future generations of researchers and students to imagine the progenitor or first cell (ancestral cell) bifurcating into clones, which specialize and become more restricted in time or lose their totipotency and/or become unique entities with variations of function as they are depicted in immune cell cytogenetic tree lines (74). This 19^{th}-century vision of cell proliferation also carries over to the conceptualization of cancer cell lines, with cancer cells typically remaining as unspecialized, nonfunctional clones and illustrated in cell line developmental tree.

Somatic cells are viewed as having inherent, preprogrammed genetic instructions, which dictate their future. This is why cancer, when viewed from genetic aspects, follows a similar diagrammatic expansion and spread into tissues but without a normal cell cycle or cellular function (81). Today a variety of experimental evidence and conceptualizations can influence current views. Epigenetics and micro-RNA transcriptional and posttranscriptional control factors and other unknown transcriptional control factors no longer offer a straight-line vision from early ancestral cell to defined cell. We see “pathways,” networks, and network variations because of the historical significance of the stem cell diagram. It provides a framework for a cell’s potential or its possibilities, whether it be embryological or evolutionary. Boveri, Weismann, and Haeckel were largely responsible for this view through their visual conceptualizations. *“Boveri explicitly took Haeckel's definition of a stem cell as the fertilized egg one step further: Boveri proposed that cells along the germline lineage between the fertilized egg and committed germ cells be called stem cells* (81).” However wavering and undetermined the path is from embryonic stem cell to specialized cell is, the diagram remains pivotal and a point of theoretical and experimental departure for scientific investigation. *“Stem cells began with a word, not a discovery* (81).” This is important because scientific investigations followed an imaginative concept through a philosophical term reflecting on the natural world. Our perceptions of all things “tree-like” were spawned from one word and one image type.

Aside from Haeckel’s refined, skillful, and aesthetic abilities as an artist, Haeckel was prolific with his metaphors in biology (92). Haeckel’s art, like most descriptive artists, attempting to replicate what is observed, envisioned geometry and form in motion before making detailed sketches. Haeckel was able to combine both descriptive drawing techniques with exquisite precision. At the same time, he was envisioning, speculating, and imagining non-visible possible functions and processes in biology. Spending significant time in nature propelled this line of thinking and doing. To accomplish this, Haeckel, like DaVinci, had created a nexus of cognition that was both biological and skillfully artistic and functioned as a collaborative within the individual. This was a major component of the naturalist’s approach or “romantic biologist” (93). He also had to know his art processes well and become an expert in lithography and watercolor media. Only then could he manipulate these processes to illuminate his vision of biological function. The properties of each of these disciplines mingled and overlapped, informed each other, with each one enhancing the other.

Artists who draw classically or descriptively must think about the simplest forms before they elaborate on details. This geometrical framework establishes the realistic and the fantasized realistic view. For artists who do not study biology, biological functions are not typically part of the work they produce were as artists/scientists think about biological functions as they produce the work. As a naturalist, biologist, and physician, Haeckel was aware of the art forms he was making, imitating, or modeling nature. His artwork was itself a recapitulation of that simplest shape to more complex forms, continual experimentation and practice that would embody the content, natural history, morphology, including Darwinian views of the time (94). The word for stem, *Stammzelle,* reflected ideas of origins, descendants, and generations as Haeckel often spoke of "stem trees," and "stem forms" (74). Haeckel's ideas were also based on Kant and the concept of organic forms transitioning (86). The cell theory was an established part of his medical curriculum, and eggs were now recognized as cellular and the beginning of a new complex life form (Richards 2008). Haeckel's evolutionary thinking, in which he supported Darwin's theory of evolution, was also reflective of cellular life, both single-celled and multicellular. *"For Haeckel, during ontogeny every organism recapitulated its phylogenetic states, and therefore the ontogenetic stem cell- the fertilized egg cell- was the corresponding entity of the phylogenetic stem cell or the unicellular organism* (86)." Drawing embryos and cells in a traditional, geometrical way would only reinforce this idea as the artist moves from a simpler, spherical form to more complex.

An artist without an experimental, biological background would not typically seek any further investigation or evaluate evolution or development theories but would simply be interested in the form itself. Since Haeckel was studying form as a biologist and an artist, the progression of form and its underlying purpose was of extreme importance and reflective of processes of life modeling through drawing practice. This was a continual convergence of diverse but related experiences in his life. Haeckel states: "*The form of every single crystal, like the form of every single organism, is the result of the interactions of two opposing forces the inner formative tendency, which is determined by the chemical constitution of the matter itself, and the external formative tendency, which is dependent upon the influence of surrounding matter. Both these constructive forces interact similarly also in directly inherent in the substance of the body* (Haeckel 1876 I, p. 37, 1868 pp. 277278, his emphases) (74)."

While Haeckel was supporting Darwin's theory of natural selection, he was also teaching his students that the nucleus contained hereditary material, combining this idea with discoveries such as the first *homo erectus,* fossil, which he brought back from the West Indies. Haeckel made informed drawings concerning fossil evidence and direct observation and discoveries around his central concept of the biogenic law (86). Ontogeny recapitulating phylogeny would be highly scrutinized and criticized in decades following its inception. However, the law's formulation was based on his observations and illustrations of living forms he encountered and their underlying geometric similarities. Haeckel carried sketch books and canvases to paint wherever he ventured, depicting landscapes, environments, organisms, and ideas about what he observed (86). Haeckel was also entertaining a wide range of biological concepts and was not a specialized academician. Haeckel's artistic depictions of radiolarians, which he studied rigorously, provided a "standard" representation of a given species. Much of Haeckel's art, which itself is technically very difficult to do and is itself a lost skill in modern times, has been discredited as non-Darwinian and lacking variation, but it rendered in a particular style, hence the similarities between images, and was the *average* depiction that was of interest to Haeckel as he states below the advantages of drawing and painting over the photograph:

"I have been convinced that colored images (even of a mediocre production) are much more valuable for a vivid intuitive awareness of nature than a photograph or the simple black and white illustration. Indeed, a crude color sketch has a deeper and more stimulating effect on the best black and white illustration of photographic representation. This distinction lies not only in the effect of color itself- since different individuals are sensitive in different measures- but also because the painter, as thoughtful artist, reproduces in his subjective image the conceptually articulated character of the landscape and emphasizes its essential features. The objective image of the photograph, by contrast, reproduces equally all parts of the view, the interesting and the mundane, the essential and the inessential. This the colored photograph, if it should be brought to perfection, will indeed never be able to replace the individually conceived and deeply felt image of the painter (Haeckel, Wanderbilder, pg. 5 of unnumbered pages.) (86)." Style or *stylized* art has a consistent line, tone, and value, which a non-artist may not appreciate.

2.3.2 Drawing as a biological-conceptual framework

Earnest Haeckel's life work is another example of a pivotal period when drawing. Art skills were so amalgamated with a scientific method and an exposure to nature that produced exceptional results. Haeckel's art was on the scale of skill, exceptional, and today would be considered too time-consuming to practice. However, in that practice, mastery, and dedication lie in moments of discovery. It is also apparent from the drawings and writings that he sometimes used his art for "advertising" Darwin's theory of natural selection, which is now called "science communication." Many people objected to Haeckel's art, condemning it as "unrealistic" and not true to the actual specimens it was depicting. It was considered frivolous and fanciful by many scientists and academics, who probably had little knowledge or skill relating to the arts and could not envision the synergy of both processes. Haeckel deliberately created art with a particular style that was beautiful, flowing, and popular to showcase biological forms and generate interest in Darwinian evolution through that beauty (88). The drawings are also composite images of multiple specimens, where observed differences and morphological characters were emphasized (88). I have included exploring Lion's mane jellyfish's image as an example **(**see Figure 9). Haeckel named this jellyfish after his first wife, who passed away. He eternalized her memory through this particular species and had great sentiment woven into his work. The flow of the jellyfish' tentacles was rendered to be both accurate in dynamics and beautiful to observe. This itself is reflective of nature. *"Obtaining accurate kinematic data of animals is essential for many biological studies and bio-inspired engineering* (95)." Bell kinematics of large jellyfish are difficult even today to analyze, and movements are replicated with computers and high-tech visual cameras. Swimming cycles of multiple species would have recorded and averaged coordinates to calculate and to create a model of the way jellyfish swim (95). The bell moves through varying contraction stages and relaxation, but this is contingent upon the current, the particular organism, and other factors.

Haeckel, of course, did not have access to any of these modern devices and would have to infer contraction and relation of the bell based on descriptive drawing techniques and an averaging of the morphology. He may have also created animation through a step-by-step analysis of the movement-based observing live jellyfish. The final drawings would be an average of morphology and movement. Sketching would proceed with drawing, which would proceed lithography. The lion’s man jelly's oscillating motion was clearly depicted in even the static images Haeckel created. From his many drawings of class Scyphozoa, the propulsion mechanism, the radial mesoglea fibers, rowing, jetting, and the transition of the vortex during contraction are visible. Haeckel also retained the jellyfish's original geometry in his image and rendered it in the up-and-coming art nouveau style.

To depict this would be no trivial matter, as he would have to understand the anatomy in great detail: the bell’s flap, apex, mesoglea, exumbrella, sub umbrella, central disc circular muscles, and radial muscles (96). In the series of drawings, I have deconstructed Haeckel's lithograph to reveal some of his thought-technique. To create a lithograph of this degree of complexity, Haeckel would have created many focused drawings from actual specimens and thoroughly dissected and identified all structures. His process of being in nature to observe and draw organisms was similar to DaVinci and Boveri. Figure 8 is an illustration that might have been made of Lion’s mane jelly before Haeckel’s fanciful creation. Those drawings and observations would serve to inform the final piece of art (97) which we see in Figure 9. I created the sketch alongside the lithograph, which an artist would have to make before committing to the print. Haeckel collected specimens often, sketching and drawing and analyzing their morphology, but those Jellyfish washed up or caught would be amorphic jelly-like blobs. Volume, buoyancy, and rotational changes in structures of a relatively formless invertebrate’s bell would have to extend to its tentacles and any potentially moving structure, which Haeckel depicted to reflect dynamics in his images. Understanding the movement of jellyfish or the dynamics of the movement would greatly involve the artist in both living organisms and deceased ones. The drawings in Figure 10 may accompany a study and involve creating a storyboard or implied animation of the bell and tentacles.

2.4 Case Study IV: Santiago Ramon Cajal (1852-1934)

Santiago Ramon Cajal was most notably remembered for his groundbreaking Neuron Doctrine that posited many fundamentals about the neuron's form and function as the cellular unit of the nervous system (98). Cajal and the discovery of the neuron's behavior and underlying connectivity and individuality directly related to his artistic skills, love of the natural world, and his ability to use metaphors and words to describe his discoveries (99). Two aspects of the early 19^{th} century also played a role in Cajal's major neuroscientific discoveries: the development of light microscopy and the improved anatomical research methods. The cell as an individual unit of life from Schwan's work also emerged as an underlying principle (20). Cellular staining techniques created by Cajal's contemporary Camillo Golgi provided new visualizations of cellular morphology and relationships. However, Golgi did not see the same forms and relationships as Ramon Cajal (100). Was it Cajal's artistic eye that observed a different architectural pattern in neurons? Cajal did not abstain from new methods and instead experimented frequently with them, and upon returning from a brief experience in the army as a surgeon who used pathology images as part of his duty, he emerged with a new interest in the microscopic world of the neuron (101). Before that, Cajal documented all of this anatomical research with photography and drawing as photography served as a tool to capture structure (101). Cajal, as a boy, was intent on becoming an artist through painting but was dissuaded by his father and instead went to medical school. Throughout his scientific career, Cajal would use art and the written word to explore what he deemed the "neuronal forest (102)." The words we use today in neuroscience are directly attributed to Cajal's romantic description of nervous system cells and seeing the microscopic neuro-world as an actual forest (102).

Cajal's observations of the nature around him and the nature within the human body and his love of writing and drawing enabled the transformation of the discipline (Otis 2001). The relationship between man and the rest of nature was common throughout DaVinci's work 400 years before Cajal. Most scientists made drawings of their work because they had to, as there was no one else to do it. This closeness of research, drawing, and observation is apparent in a wide variety of pivotal discoveries (103). For example, the Reticular theory's underlying concept claimed that there was no distinction between nerve cells. The system was a continuous syncytium from the spinal cord to the brain (104). In Cajal's understanding of the staining technique and the concept of the forest, with its distinct trees but intimate connections, a different view emerged, one of a continuum and a network with individuals creating the effect of a continuum. In Figure 13, cross-sectional drawings of the spinal cord by Cajal are placed alongside an image I created of the spinal tracts. When Cajal discusses the branching of trees and forests, he also suggests the connections in the forest. The spinal column with its relay center of interneurons demonstrates how distant connections can occur throughout a system, similar to that of a forest, trees, and even underground fungal mycelial matrices and associations also exhibit this quality. Cajal ultimately established the neuron as the nervous system's anatomical, physiological, genetic, and metabolic unit based on the forest metaphor he eluded too often (102).

Nature provided many polymaths, perhaps, even all polymaths, with a foundation upon which art and science could be mutually appreciated, used and synthesized, or fused to evolve an understanding of life as well as express a personal relationship with it (93). The patterns biologists and other life scientists seek are the patterns of nature. Cajal was no different in that he demonstrated an exquisite sensitivity and depth to his investigations towards nature. This aspect of his character, that is, to have deeply perceptive feelings for all things beautiful in the natural world, was fundamental to his scientific knowledge. *"The essence of the sage was embodied by the enticing architecture of nature, where he satisfied his profound aesthetic feelings and modeled his artistic soul, thus giving birth to scientific creativity* (102)." Our current or modern understanding of the nervous system is based on two principles that were established in the 19th century. They were the functional localization and the neuron doctrine (104). The "reticular theory," posited by Golgi, was insightful but did not uncover the neuron's interdependent and individual nature. Without this, an understanding of neuronal communication, synapses, neurotransmitters, disease process, cognition, and learning could not be appreciated (20). How did Cajal's use of language and his continual, astute focus through drawing manifest these ideas?

Golgi had provided the method, which Cajal improved upon and, through that visualization, provided penetrating insights (105). The language of Cajal was not just important to the future of neuroscientific understanding and communication. However, it painted a visual picture of the emerging data as the artist experimented and drew. *"The actual forest of nature was so obvious to him that he applied the vocabulary of this to his historical findings, e.g., 'ivy,' 'creeper, 'mossy,' 'tuft,' 'nest,' 'glade,' vegetation,' 'bud,' 'pyriform,' 'elegant, 'leafy tree,' 'spikes,' 'climbing vines,' 'pinkish efflorescence's,' as a* *few examples* (Cajal 1899) (Cajal 1913-1914). (102).” These terms, along with very terms like *arbor vitae* and *dendritic,* are now commonly used vocabulary in neuroscience. However, the romantic approach to studying and describing the brain is not acceptable in modern descriptions, which have become largely technical (102).

One may say that objective language is technical and only attends to the observable facts, but the passionate use of romantic language may lie in nature's visualized frameworks. The scientist/artist can develop a sensitivity to the subject. A completely technical approach may stifle the imagination and limit what we perceive. The very way of writing Cajal developed to formulate the neuron doctrine would not be permissible in today's academic world, which ironically accepts that doctrine and Cajal as the “father of neuroscience.” It cannot be denied that in the romantic application of metaphor emerged scientific ideas. Since nature is infinitely creative and variable, developing the ability and interest in applying metaphoric or romantic language with drawing may help the student and/or the researcher conceptualize their work.

Cajal’s notebooks are filled with detailed descriptions of preparations, dissections, and revisions of already existing methods. His robust and detailed descriptions may be arguably sound non-scientific; however, they are directly attributable to his discoveries (102). Is there an advantage to charmingly seeing biological forms and phenomena? The language of an artist would normally be dismissed in scientific research today. However, the polymaths presented in this work reveal the history of where our current ideas come from- and they come from a combination of imagination, experimentation, and visualization. A century ago, abbreviations and numbered identifications were less likely to be used. Describing genes as PAX, BAD, or BAX may not be as beneficial as giving them a fuller, more revealing descriptor or character, which Cajal was successful at. Therefore, he serves as a model for the scientific metaphor. It is important to clarify that his metaphors are not just “fun” labels without thought but rather lifelong observations of nature marinating in his research as Cajal wrote, described, experimented, and interpretively illustrated processes regularly.

Cajal used words that evoked images that allowed contemplation of the phenomena and how they occurred interdependently. Abbreviations and numbers may not evoke the same passion, comparison, contrast, and complexity the way more romantic terms do.

Students may benefit from the observation of nature, the development of a vocabulary, and the relationship of that vocabulary with the biological process. Students often seem disconnected from the subject matter, often missing the biological process's connection to nature itself (106). The disconnect and lack of integration become apparent upon comparing the methods of the past and learning experiences in present-day biology courses. This also holds true for biology teachers who must dedicate more time to technology and less to creative skills and content knowledge. Cajal's interest in words extended far beyond the metaphors he created. He also wrote a novel entitled "*The Corrected Pessimist*" in 1905 (107). Through this fictional work, he reveals some of his scientific thought, including the importance of the scientist in placing themselves in the right point of view of a subject (20). Cajal described the methods he engaged with to reveal nature's mysteries in his writings and used the fictional novel as another artistic device to channel his ideas. Creative writing is not typically considered in the modern biology classroom, but Cajal presents us with a strong case for its development in general biology classrooms.

Like Haeckel and Boveri, Cajal utilized their artistic knowledge and skill to visualize and enhance their perception of the phenomena. *"Cajal adopted a complex methodology based upon a multiplicity of procedures. Ranging from staining and drawing to photography and animations, they complied into manifold skills"* (20). Methodological multiplicity in experimentation and image techniques creates an illustrated synthesis that can be revised, just like a mathematical proof. In terms of visual-spatial skills, scientists like Cajal were not merely able to visually rotate an object but instead applied two dimensions of visualization simultaneously to histology. I attempted to illustrate the concept of the brain's dimensional perspective and sectioned images in Figure 11. Drawing a section with an entire structure may help reveal form and function. Cajal made structures inside the three-dimensional object visually available and salient for further investigation. At the same time, these realized spatial dimensions were transferred to a two-dimensional drawing.

"Cajal's method combined not only different ways of observing, but also manifold routes of rendering objects and observations visible (20)." From the art-drawing view, three-dimensional objects can be flattened if they are of little value, and two-dimensional objects can be transformed into three and four dimensions in a drawing if they are deemed

significant by the scientist working through observation as a problem to be solved or an observation that inspires greater interest. *"Thus, to make visible the neuronal structures in a thick section of the human cerebral cortex, and to show,"* as Cajal states, their *"precise arrangement and their relations with other, extracellular structures, the histologist has to employ or find some staining method that is highly selective for the "framework referred to(108)."* This requires that the artist be fully engaged with the science of the investigation continually, as the content, observations, are constantly changing and are accessible at such a personal level that art becomes part of scientific knowledge in the context of continual investigation (102). Cajal was criticized for these methods by other neuroscientists because, like Haeckel, the images did not resemble exact duplications of the reality observed but rather were sorted, selected, grouped, and combined in ways that were suitable for synthesizing a body of knowledge into a workable theory over time and those techniques were not standardized but unique to the individual scientist. Without that personal skill set and method, what is visible would not have been visible otherwise. As scientific visual proofs and documents, the drawings could undergo revision (20). For Cajal and others like him, the "right point of view" would enable this exploration. The eye and hand were guided by the scientist's aesthetic dimension and constrained by an individual's visual curiosity. Cajal gives us an example of a biological-art drawing heuristic that has the potential to be applied today, and that is both unique and part of STEAM but functions at a much more sophisticated level. In his autobiography,

Cajal discusses his discovery of Golgi's staining techniques and the visualization of neuronal forests: "*The second path open to reason is what, in biological terms, is designated the ontogenetic or embryological method. Since the full-grown forest turns out to be imperceptible and indefinable, why not revert to the study of the young wood, in the nursery stage, as we might say? Such was the very simple idea which inspired my repeated trials of the silver method upon embryos of birds and mammals* (109)." Cajal then discusses how he plans to publish his results; *"From my hands emerged six lithographic plates which were included (for publication)."* Cajal speaks of his laws in his neuronal doctrine as revelations suddenly from staining, drawing, and studying what he was physically observing, noting that the laws were purely an inductive outcome that which manifested from studying the morphology and structure of the cerebellum and comparing them to the forest; *"How were the laws discovered?"* Cajal asks in his autobiography, and then he proceeds to answer; *"Repeating a simile already used, it was cause of finding out how the roots and branches in these trees in the gray matter terminate, in that forest so dense, that by refinement of complexity, there are no spaces in it, so the trunks, branches and leaves, touch everywhere* (110)."

From an artist's perspective following a forest metaphor, Cajal reveals that a lack of space around the neurons must mean that their touching allows for direct communication. Observing a lack of negative space leads him to conclude the following laws, which he states; *"1. The collateral and terminal ramifications of the axis cylinder end in the gray matter, not in a diffuse network as maintained by Gerlach and Golgi, and most other neurologists, but by free arborizations arranged in a variety of ways (baskets, nests, climbing branches, etc. 2. These ramifications are applied very closely to the bodies and dendrites, the tree-like out growths from the cell body, a contact or articulation established between the protoplasm and the ultimate axonic branchlets. 3. Since the final rootlets of the axis cylinders are applied closely to the bodies of the dendrites to the neurons, it must be admitted that the cell bodies and their protoplasmic processes enter into the chain of conduction, that is to say, that they receive and process the nervous impulse, contrary to the opinion of Golgi, according to who these parts of the cell perform a merely nutritive role. 4. The continuity of the substance between the cell and the cell begin excluded, the view that the nerve impulse is transmitted by contact, as in the junctions of electrical conductors, or by the induction effect, as in induction coils becomes inescapable." Cajal notes that the two physiological corollaries sprang from his laws and from the observations and depictions of the formed branches. The one-way transmission of impulses from dendrite to axon, a discovery of function from the drawing and understanding of the beauty of form* (111)." In Figure 12, a section of the hippocampus reveals considerable time on drawing those dendritic forms. Alongside this slice of the hippocampus, I illustrated the entire structure. A continual consideration of the entire structure and function would help Cajal solidify his theories.

If Cajal is considered the father of neuroscience, then his contemporary, Harvey Cushing, would be the father of neurosurgery. Interestingly, both of these men, who lived and worked in the same time period arrived at their discoveries as physicians, scientists, and artists. *"Both men (Cajal and Cushing) were pioneers of their time, using their tremendous insight to challenge and modify the flow of thought among their contemporaries* (112)." Both men had early inclinations to using drawing as a discovery process in science. Both had realistic, descriptive drawing skills, with Cushing's art emerging as exceptionally realistic and descriptive in a way different from Cajal's. Both also had unique drawing skills, one quite unlike the other. Harvey Cushing's drawings were influenced by one of the greatest scientific illustrators of the century, Max Brodel. Brodel's influence was so enmeshed with Cushing that they knew each other's discipline at an expert level (112). Although both men led distinctly different lives in terms of education, class, and culture, Cajal and Cushing shared drawing as a discovery process. Cushing once said that *"Neurosurgery was 20% science, 75% artistry, and 5 % community benefit* (113)." While Cushing was not at the mercy of an artist's interpretations but rather enjoyed his collaboration with Brodel, most other scientists in order to advance or publish their findings would be. *"Scientists were often forced to illustrate their own observations by means of their own drawings* (98)." Had technology existed, would they have made such groundbreaking discoveries and remained close to their respective disciplines? Would they have had the time and intimacy in our modern world even to develop such skills? These pioneers of the drawing discovery model chronicled their work through varied, realistic interpretations. They became more intimate with their area of study due to a dependency on personal skills that illuminated and described their findings.

Cushing contributed multiple overlapping clinical procedural changes through his illustrations and through collaboration with Brodel. Many of his most tedious and complex surgeries were illustrated with sketches and perfected along with the final drawings and images. There is evidence that surgical procedural skills and drawing of the actual procedure produce the same brain activity, enact the same pathways, and have a haptic similarity (112). Similarly, Cajal also had a large influence on modern neurosurgery. With Cajal's observant eye, he distinguished different types of cells, from identifying the patterns of different cells, such as astrocytes, oligodendrocytes, and microglial cells, he was also able to categorize and classify brain tumors (114). Both Cajal and Cushing were applying similar techniques and taking laboratory work to actual applications of that work.

Unlike today's disciplines, Cajal worked with a wide range of biological subjects, with the unifying theme of drawing. His work from the gross anatomical to the cellular was chronicled by observing the continuum from macro to micro perspectives (20). To understand how he may have arrived at the neuron as the fundamental unit, we will explore images he may have experimented with and constructed and the patterns he may have recognized using his artist's vision. In the 19th century, neuroscience was at its infancy. However, many people were contributing to a body of knowledge that would establish scientific views, "romantic" science established the idea that in the complexity of nature was also simplicity, that there were "highest" and "lowest" organisms. *"The task of the biologist was to identify the simple type and a given structure and to trace its progressive elaboration in the scala naturae, culminating in its fullest expression in humans the ganglionic nature of the vertebrate brain referenced to three specific forms of evidence, one of those was comparative anatomy, this was done experimentally on "lower" animals as an analogy to man's nervous system. Like evolution, also in its early stages, was the use of embryology, and lastly the concept that the nervous system consisted of a serial nature, and that it was continuous* (115)." The observed bifurcations, fracturing patterns, and subsequent branching appeared to be continuous to most observing it, and it was not necessarily a wrong view. It just did not identify edges and boundaries. How would Ramon Cajal come to see this web of branches as individual cells? Some physiological mechanisms of obvious "parts" of the nervous system were easily distinguishable. The cerebellum had clear anatomical divisions, and the cerebral hemispheres were the most obvious in their separations; however, the system was connected. By 1840, the respiratory centers were established, and brain localization of various functions began to emerge (115).

Morphologically distinct divisions and subdivisions allowed for experimenting with loss of function and revealing the nervous system's distinct properties. The cerebellum's role was designated as motor function. Those established roles, which were also viewed as fixed and unchangeable, remained basically the same in anatomy textbooks into the 20th century, the knowledge almost entirely based on vivisection (115). Cajal explored his neuron doctrine through the cerebellum, and his illustrations may have followed a different pathway of thought that still utilized dissection. However, alongside art and staining techniques, he was able to extract more about function. He also explored the hippocampus, which I have decided to analyze visually through drawings of my own based on isolated illustrations by Cajal.

2.5 Case Study V: Linus Pauling (1901-1994)

Although Linus Pauling is considered a chemist, his study on wide-ranging subjects from the structure of water to anesthetics and proteins is significant to the biological sciences, particularly biochemistry, molecular biology, and proteins' evolution. Pauling is important in this work to appreciate and understand how the creative visualization process shapes and contributes to an understanding of the dynamic processes of the biochemical and molecular worlds. There would appear to be little in common in Linus Pauling's work with the romantic illustration practices of Haeckel and Boveri. However, variations of the drawing heuristic and be seen in Pauling's exploratory processes. Pauling's sketched out theories and notebooks of his experimental work reveal that drawings need not necessarily be beautifully drawn or illustrated to reveal scientific ideas or assist in their discovery. Sometimes a simple cartoon can suffice and can demonstrate the flexibility of the drawing heuristic. The narrative and transitional drawing method of storyboarding is such a fundamental foundation of conveying action. It is almost shocking that it has not been used in biological investigations or biology education, and Pauling's storyboard confirms this.

Storyboarding, cartooning, or planning dynamic sequences is another dimension in the multi-pragmatic use of drawing for discovery. It is also part of my biological -art drawing heuristic. While not considered an artist, Pauling employed geometry, structure, form, complementary shapes, and storyboarding to synthesize, visualize, and communicate his hypotheses of antigen-antibody complexes. He was also a proficient model builder and had a particular methodology for building models. His expedition was through the model building experience combined with experimental evidence that produced the alpha helix and the beta-pleated sheet of secondary protein structure. How did Pauling deduce these fundamental building blocks, structures that would become the foundation of tens of thousands of proteins? How did and why did Pauling's model building illuminate the geometry of structure where other models had failed? The actual construction of models is essentially an offshoot of sculpting, except that Pauling was using experimental data to inform his molecular sculptures and collaborated with chemist Robert Corey to develop a specific type of model building.

Pauling's sculptures or models were molecular, but they still followed the naturalist's vision of nature. The natural landscape of the molecule was Pauling's specialty. The sculpture is a common practice of classical drawing, and both are often practiced together. Models are basically physical structures representing spatial arrangement. In Pauling's case, the spatial arrangement and physical structure or sculpture were atoms, molecules, and crystals. Their theoretical representation, that is, the model itself, was attempting to account for the properties of matter at the molecular level (116), and storyboarding combined with model building provided this chemist with a dynamic two-dimensional platform to test his ideas (storyboarding) and a static three-dimensional platform (models) to visualize them.

The storyboard provided the dynamic, the model, the form. He could then examine and speculate further, offering exceptional insights into the stereochemistry of proteins. One of the key aspects of proteins is their dynamic structure as a functioning biological entity, interacting, reacting, and evolving. Perhaps, it is that dynamic of a protein and its shape-shifting ability or the ability to morph and accommodate other molecules in intimate associations captured in both artistic processes. For biological molecules, the structure also maintains and influences the orientation of functional groups in a chemically dynamic bio network (117). Pauling recognized that structure and function were independent and that modeling just one protein binding interaction in a complementary albeit flexible way could represent nature's underlying process. The form and function of a property could be experimentally revealed but could not be seen or experienced, and the two morphing two artistic processes may have facilitated this. In his elucidation of the sickle cell anemia mutation, Pauling concerned himself with the effect of oxygen on the shape of the cell, envisioning the geometry and contour of hemoglobin and combining that mental model with his knowledge of the electric charge of globin proteins. He concluded that the difference was a matter of amino acid changes (118). To take this kind of knowledge and transform it into three-dimensional molecules, even in the mind's eye, suggests that Pauling merged his art form (models) with his experiments in a typical artistic-scientific fashion.

Illustrations of molecular models are and were widely used to study molecular structure and to teach chemistry. Models and illustrations work together with metaphor to produce a hypothetical world or stage of molecular interactions and properties as suggested for proteins (119). *"A metaphor must be employed, since we are generating synthetic images of objects that are far smaller than the wavelength of light. The most effective metaphors use lines to represent covalent bonds or ribbons to represent protein chains, capturing the relevant aspects of molecular structure and function"* (120, 121)." The drawing heuristic in biochemistry and the molecular world's hidden complexities may play a significant role in how students and scientists think about the unseen, unknown, scaled-down lively, energetic world of molecules. For instance, each representative art form captures a different subset of molecular processes, such as ribbon portions of molecules capturing folding and lines capturing bonding (122). In Pauling's drawings and sketches, he captured interaction with a representative, simplified form, which does not deal with other qualities of proteins such as their bulk, topology, or surface complexity but may be added later, altering the drawing.

From Pauling's cartoons to early, hand-drawn ribbon models of proteins, we can observe that artisanal skills carry through to a molecular domain and play a significant role in biochemistry's visual literacy. Once again, artistic skills historically demonstrate their essential and untapped potential for biology education and research today, keeping in mind that it is still nature that the biochemist is exploring. Moreover, if we revisit Boveri's "natural experiment," we see processes revealing themselves through the art. Pauling's contributions to immunology were significant because of his almost innate understanding of structural chemistry and three-dimensional, rotational spatial temporality of protein molecules (123), which employed basically the same principles developed by DaVinci 500 years earlier that make up the treaties of scientific illustration; rotation, transparency, and transverse section.

The specificity of antigen and antibody complementarity was sketched out and reasoned with the construction of mental and physical models. One visualization or cartoon of the antigen-antibody interaction reveals how storyboarding and creating even the simplest drawing can synthesize the theoretical nature of a significant scientific idea. *"All biochemists would readily agree that visualization tools are essential for understanding* *and researching the molecular and cellular biosciences* (122).” Evaluating and constructing an invisible world that is diverse, dynamic, and ever-evolving requires many complex perspectives, including reasoning and connecting many organization levels (124). Students starting with familiarity and sensitivity to the natural world’s forms, shapes, patterns, and relationships through a drawing skill set may be better prepared to tackle the layered, abstract world of general biochemistry and proteins.

Biochemistry has relied on various arts-based visualization techniques, some actual research methods, like x-ray diffraction, others visualization tools such as molecular models, photographs, micrographs, pictures, illustrations, diagrams, metabolic maps, analogical and metaphorical illustrations, drawings, and animations (122). However, all of these methods do not typically involve the researcher or student in a visual synthesis, such as what was achieved through Pauling’s work on antigens and antibody complexes. Some studies with high school students demonstrate the benefits of visualizing molecules through visual and tactile methods, but this practice in high school and college today is rare (124). The designer of protein software for animations of molecular processes or the medical illustrator would have access to the process of drawing and developing a model from start to finish without the loss of integration. However, unlike Pauling, they would lack the actual experimental experience. They also would probably lack the content investment and intimacy with the quantifying techniques that Pauling also employed.

What is important about Pauling is that he offered another example of engaging the artistic processes of sketching, storyboarding, and model making to solve dynamic structural puzzles. Pauling applied sketching and cartooning, combined with methods like gel electrophoresis, to visualize protein structure/form and protein-protein interactions in ways that are not practiced today (125, 126). Today, illustrations of molecular models and animations are widely used to study and disseminate molecular structure and function without the level of integration and originality of Pauling’s era. Pauling had to think about, visualize, and conceptualize both structures and their activities or mechanisms, develop theories, like the chemical nature of the bond and build on them, making the behaviors all part of his domain knowledge. Advances in imaging techniques have helped reveal the molecular world in greater detail. However, a sketch, drawing, and model remain a personal investigational tool for a biochemical and molecular holistic reality (Kemp 2008).

In the article, *"Arguing with Images: Pauling's idea of antibody formation became a collimation of his experimentation and knowledge* (123)." the author asserts that it was Pauling's understanding of the three- and four-dimensional quality of proteins and molecules that generated his complementarity hypothesis. He was combining knowledge of energy (charges/ions) with the transformation of matter (models/sketches). The approach of building models was a 1950's methodology for understanding molecular structure and was also quite common and, therefore, acceptable. With model building expertise, Pauling had a different view, a different perspective, and could add his original thoughts to the model. As Cajal proposed, creating something that was more akin to nature rather than the flat, static view was a major function of the art. The model was also a thing of beauty and had a visceral feeling of attractiveness, one that was physical and relatable and presumably pleasurable to work with.

Pauling was transforming stochastic mental models through the molecular models' physical construction and haptic enterprise, which may have also enabled him to consider various outcomes of the molecule and its interaction before an experiment. It may have guided the experiment. He was constructing and continually rebuilding his visual-spatial world (116). In the article, *arguing with Images*, the authors revisit what they consider to be a neglected aspect of Pauling's work; the visual dimension (123). *"Pauling's contributions in this field (immunological biochemistry) include empirical work-detailed chemical analysis of antigen antibody reactions- but also theoretical synthesis namely, his "template," or "instructions" theory of antibody formation* (123)." Understanding how forms change (protein evolution), vary, fold, and interact involves an appreciation of complementary forms dynamically existing in space and time (116). The artistic cases of sculpting, negative space in drawing, storyboarding, composition, and origami, to name a few, concern themselves entirely with the interactions of form and transformation of the form (116). Pauling's work and articles were introduced and enhanced by conspicuous theoretical drawings, which presented his thought processes on applying structural chemistry to the problems of protein-protein interactions. Pauling used drawings and models not simply for a show but as visual arguments (123). This application of drawing/art was very similar to what many visual scientists had accomplished before Pauling.

Visual arguments are typically based on experimentation and theoretical synthesis. They can be worked out for the scientist's use or to present work in public, such as Louis Pasture, who was known to have been a classical painter with a strong artistic background. Some suggest that it is through his understanding of spatial relationships and form, painting portraits and assessing them through the mirror, along with experimentation, that he reasoned out the concept of chirality. It was common for portrait artists to hold the portrait up to a mirror and evaluate its symmetry. Even though many scientists before him, with far more experience, attempted to study tartaric acid and its mirror image molecules, Pasture discovered the rotations of the acid's rotary and dextrorotary nature. *"He (Pasture) understood that (+)-TA and (-)-TA were non-superimposable-mirror-image molecular forms of each other through the examination of crystals of paratartrate and manually separating the two different forms, and this resulted in the discovery of chirality* (127)." Gal suggests that the discovery of molecular chirality was also influenced by Pasture's use of a common and complex art technique, lithography, which is a printing process.

As mentioned previously, lithography was also used extensively by Earnest Haeckel and Boveri and involved etching on a smooth limestone surface using oil or wax, then acidifying the stone surface, the areas not protected by the fat were etched away by the acid, following this, the ink was applied, and the image transferred to a paper surface to produce a positive image on paper (128). *"Given the nature of the transfer process, the final print on the paper is the mirror image of the original on stone* (127)." What also may be of significance to Pasture's discovery was the artisanal practice or experimentation with materials, both his science and his art employed acids, fats, and other biomolecules. The use of naturally occurring or naturally based materials was the hallmark of artisanal knowledge transitioning into scientific experimentation within Western science culture (19). Pasture, like many other artisanal scientists, would have become very familiar with the properties and processes of both their art and science through the use of natural materials that were essentially biological in origin (19) and throughout the rest of Pasture's scientific life, he would remain intimately connected to the arts (127).

In Pauling's case, specificity was dictated by the diversity of protein structure, which was dictated by the amino acid and its charges, creating interactions, and folding and providing a signature behavior or a defining property of biological molecules, in particular, enzymes defining the physiochemical nature of living systems (129). Three-dimensional structures and conformational changes of those structures constituted communication between molecules. Although the first ribbon models of proteins were conceived through hand drawing (121) and ultimately replaced by computer-generated ribbon models and smoothed off molecular animations, the idea and design were works of art. Without them, there would be no computer ribbon models. From start to finish, the ribbon model was essentially from a protein scientist's sketchbook (130).

How impactful is visualizing and drawing in conceptualizing the molecular? How much influence does a drawing have on those who create it and those who view it? The simple drawings produced by Linus Pauling’s from experimentation and studies of form/structure was a deep problem as it addressed the “the basis of life,” according to Pauling (131). The size and shape of molecules accounted for their biological properties. While DNA instructed the sequence of amino acids, it was ultimately the folding of proteins and their visual, dimensional nature that brought the x-ray diffracted, modeled DNA’s chemical script to life. The visual dimension, the picture or model relating to some phenomenon, was Pauling’s heuristic (123). This would imply that the drawing, sketching, and model building aspects of scientific inquiry would lead to discoveries in the molecular realm. The structure determined relationships at the molecular level ascending to organisms, populations, and communities. Pauling, intent on conveying his three-dimensional nature of life in molecules, drew out his sketches and then worked with an artist named Hayward to illustrate them in a series of articles featuring his complementarity theory. Pauling wanted the drawings to be in a narrative layout and illustrate the dynamic nature of his hypotheses (123).

Pauling’s sequential, step-by-step storyboard of antibody-antigen interactions emerged from a mental model he developed from laboratory research. This essentially created both an evidence-based model and a tangible artifact of that evidence. The visual narrative of function was a comic strip and almost resembled the comic strip layout you would see in a weekly newspaper. The “lock and key” concept of antibodies and antigens was a metaphor borrowed from Emil Fischer. Both Pauling and Paul Ehrlich shared the hypothesis of antigen and antibody complementarity and was the key concept portrayed in the drawings (129). Pauling was interested in arguing his point with illustrations and capturing the dynamics of protein-protein interactions. The illustrations served to reveal this vital and principal mechanism, and a temporary visual conclusion was literally drawn. The dynamic, static, energy-driven process logically could only be portrayed in storyboarded formats. This comic book style page layout and composition were becoming popular in Pauling's time with the advent of Marvel comics (132). They can be used today in classrooms to consider new problems or questions about DNA the genome.

Scientists were influenced by the art genre of their time period and culture. While a rise of Modernism was occurring, comic books were still accurately or realistically illustrated. Pauling may have taken some artistic license with the images produced, particularly in later professional drawings of the same antigen-antibody complex. Pauling's sketches and three-dimensional thinking regarding "molecular geometry" carried over to mental models about how proteins interacted and determined biological function. Pauling noted: *"The characteristic specific properties of native proteins should be attributed to their uniquely defined configurations*(123)" Geometry, folding, and dynamic form, which DaVinci explored, and used by classical artists, became a vision of complementarily-shaped substances to understand that subatomic quantum-mechanical interactions determined their unique bonds and attractions. The functionality of those protein relationships would follow, and in this way, Pauling's speculation became a visual hypothesis (123).

Pauling, who collaborated with geneticist Max Delbruck, suggested that protein synthesis was a process of complementary molecules and weak forces (123). The scientific process may have been converging and interrelating between electrophoresis experiments involving antibodies in blood serum, mental models, and the production of a series of sketches which was the only way to document that mental and experimental model of complementarity of proteins. The cartoon could be combined with more experiments, more drawings, and collaboration with an artist who understood the work. The drawings show stages of serum globin forming and then six stages of dynamic formation of an antibody (123). Surprisingly, more scientists did not combine the storyboard technique with model building. In a time before prefabricated computer models, computer-generated graphics, software-generated charts, and a host of easy access, downloadable visual images, scientists such as Pauling, Cajal, and others were forced to create their visual data, often by hand, which was previously mentioned and brings up the point that technology may hinder innovation. The intimate cognitive exchange, personal cross-pollination of subjects, and a serious commitment to developing a skill that would bridge their experiments, is missing and has not been seriously taken up by the STEAM curriculum.

It appears that this type of evolving research and discovery of natural phenomena within an individual has tremendous value and fosters a deep and unique bond between the scientist and their work with that natural phenomena, inspiring so-called creative genius, something that may be bypassed when outside sources provide the image-making process. (Arbor 1954). This may induce a homogenizing effect on the discovery process itself and those viewing the final work. Similarly, the focus on science to produce attractive computer graphic images also creates a bias that implies living systems at the molecular level are simple, smooth, and perfect. These are highly professional-looking visuals, layouts, and publications that completely bypass intermediate output (such as sketches, ideas, and hand-drawn mechanisms), generating an illusion of extreme simplicity.

2.5.1 Protein transition and slowed action

The nature of proteins, that is, their variable, flexibility, folding, bonding, and evolution, make them ideal for the artistic layout process of storyboarding and the drawing heuristic. They are also an excellent opportunity to create detailed art of proteins and possible interpretations of their probable appearance. It is also an opportunity to build a curriculum with practiced and challenging skill sets both general and specific to a domain. Examining molecules at this level through storyboarding would enable students and possibly researchers to consider the unique and changing features of a protein molecule. Pauling's "lock and key" concept is probably one of the first storyboarded protein narratives and can be seen in Figure 14. Drawing out the allosteric states, unstable and stable positions, repulsive and attractive dynamics, and other contacts and interfaces would allow students to internalize these concepts. Again, the landscape and the spatiotemporal structural environment are viewed mentally on the picture plane, created as another world with its molecular and subatomic narrative, echoing out its micro-dynamics from the variables of its conserved genetic directives and its scaled-up events of the cellular, environmental world. This parallels with Cajal's perspective with his eyes functioning as he fictionally writes "*as the microscope* (20)." The animators of protein dynamics have the experience of storyboarding these theoretical, experimental visualizations. While visual molecular animations have helped observers conceptualize the protein's world, the intermediate experience of interpreting the data, visualizing the data, and creating the animation is gone. Herein lies another dimension of the drawing heuristic, the creative process: a "tight feedback loop" is achieved by drawing and making internal dialogue possible. This would create a need for students to develop drawing skills early on in their biology career, equipping them with a malleable skill set. This would create greater diversity in visualized output and gives rise to competing, complementing, and diverse hypotheses on the same data and biological or biochemical phenomena.

2.5.2 Teaching applications from Pauling's storyboard

While biochemistry and molecular biology employ a wide variety of methods and kinetics and mathematical models, students still have to visualize and conceptualize what molecules look like and how those molecules behave (133). Detached from actual experimentation and from experiences with nature and an onslaught of possible graphics and visual representations, the difficulty in conceptualizing abstract molecular ideas becomes more and more challenging (133). Simultaneously, students are required to move from a broad view to a narrower view but have no way of grounding the molecular world's abstraction (122). *"In addition to the levels of organization and abstraction, a further possible source of confusion for students is that of educational representations, which also differ in terms of mode of representation. Abstract biochemical phenomena are represented in a range of different modes including two-dimensional and three-dimensional modes, and multimedia modes* (122)."

To teach students about the dynamic nature of three-dimensional molecules, or rather the temporal, interactive nature of three-dimensional molecules, several pedagogical methods and experiences are presented in the classroom and lab (125). These methods are largely based on educational theory, and educational theorists have taken up educational psychology, the importance of visual literacy in the biochemistry curriculum. Students are exposed to an ever-increasing number of diverse and confusing educational representations of biochemical molecules and processes. However, these theories are neither developed by scientists/artists or by scientists but by educational specialists who may not see into the content (133).

Pauling recognized that molecules are in sequential geometric states (123). Even the modern imaging and software that creates models renders them as if they were scaled up to the larger world, we live in. From an artistic and scientific view, light may not create shadows in these atomic worlds that may look quite alien in reality. We scale things up to accommodate human perception. The underlying theories of dual-coding (134) and visual-spatial theories often do not account for these physical unknowns. The researchers are technically "outside" the hypothesis and not internalizing it deeply enough to address the complexity of the content of biochemistry, the properties of atomic and molecular environments, and structures or the biology of multiple human cognitive capabilities. Aside from this, merely viewing animations, molecular pictures, and drawings do not allow the student to develop strong sketching and model building skills, enabling them to visualize their interpretation of the multidimensional nature of biological molecules. The most important part of biology is its energy transformations and shape changes, which can be difficult to imagine through PowerPoint presentations, which are overused in the classroom (135). Added to this confounding problem are teachers who may not be visually literate or skilled in discerning more appropriate visual experiences and representations, either because of limited content knowledge or limited drawing/art skills or both (136). *"It has been shown that there are often large discrepancies between experts' and novices' abilities to interpret and learn from educational representations. Experts have a greater conceptual knowledge, whether it be biochemistry or artistic skill sets but it has been shown that artists look at things differently and think differently about images than novices* (137)."

Pedagogical goals and structured experiences may not have as great an impact on the way a student's views the molecular world, so much as that student handling and building models, making sketches, and envisioning their haptic/visual experience through drawing discovery in a slower time frame, allowing for assimilation and speculation (138). In her paper on ribbon models, Jane Richardson, who drew some of the early ribbon models of proteins by hand, describes the process; *"Making these drawings was a fascinating* *process. First, the structures are very aesthetically pleasing- especially for me, the varied and elegant curves of Beta sheets. Second, making a drawing can change one's scientific understanding of a protein, sometimes revealing a preferable structural classification and once even correcting a chain tracing. Third, defining the conventions of representations was surprisingly complex and interesting* (139)." Richardson goes on to elaborate on how much thought she gave to the details of the drawings, including the peptide plane orientation, which is the basis of the model, the direction of the vectors, the loops, and the thickness of helices. Her description of the drawing process of ribbon models reveals the difference between a drawing heuristic process and casual viewing of someone else's interpretation of a model. Removed from the creative process, students can only be casual observers. They may not gain the intimacy, engagement, ` and understanding of form/structure/ and the application of specialized vocabulary necessary to appreciate what they are attempting to learn.

What if Pauling was alive today in the age of genomics? Can we imagine how the storyboard and the model-making might be applied? Would Pauling's interest in shapes, hands-on model building, molecular morphology, and geometrical thinking initiate an inquiry into DNA's more subtle shape configurations? Would this give insight into genetic codes into the evolution of proteins? Would he revise the molecular clock? How would Pauling address noncoding and coding DNA sequences? What models would he build, what point of view would he take? Would the storyboard and the model of DNA changes in minor grooves or nucleosome positioning become molecular morphology problems suggesting physical conformations as critical to the genomic function and DNA's evolution? What kind of experiments would he carry out to complement his artistic techniques? Could the artisanal skill set inform current sequence data and evolve new methods?

Furthermore, what of selective pressures? Would Pauling view these from a storyboarded perspective with subatomic super-positioning and hidden alternate codes for these dynamic processes? Perhaps Pauling would be interested in the proximity and shape of genes with nucleotide content in a model that would guide a storyboard of gene regulation. Shape and form evaluation might shed light on unknown encryptions in noncoding genes and move genomics or evolutionary thinking in another direction. Would

Pauling build a model with various degrees of plasticity to study regulatory sequences and then storyboard possible outcomes? Could he take this information of DNA shape changes and combine them with nucleotide sequence identification? What kind of picture would emerge of these systems? Could his model be building and storyboarding illuminate more dynamic perceptions of the epigenome or even the microbiome? Would these methods then make it into the classroom as standard practice? It would seem that the storyboard, the physical model, cartooning, sketching, and classical art would continue to be a good fit for dynamics in the modeling of nature. If we consider the methods of the polymaths of the past in the present, we may find that their flexible, well-developed artistic skills carry over quite effortlessly into the questions of today's biology. Perhaps even molecular naturalists would emerge as a new discipline. Similarly, Cajal, Boveri, Haeckel, and DaVinci – like attitudes and skills regarding nature and life may advance or revise our current views of many biological domains. This makes the Bio-STEAM initiative considerably relevant today.

2.6 Figures

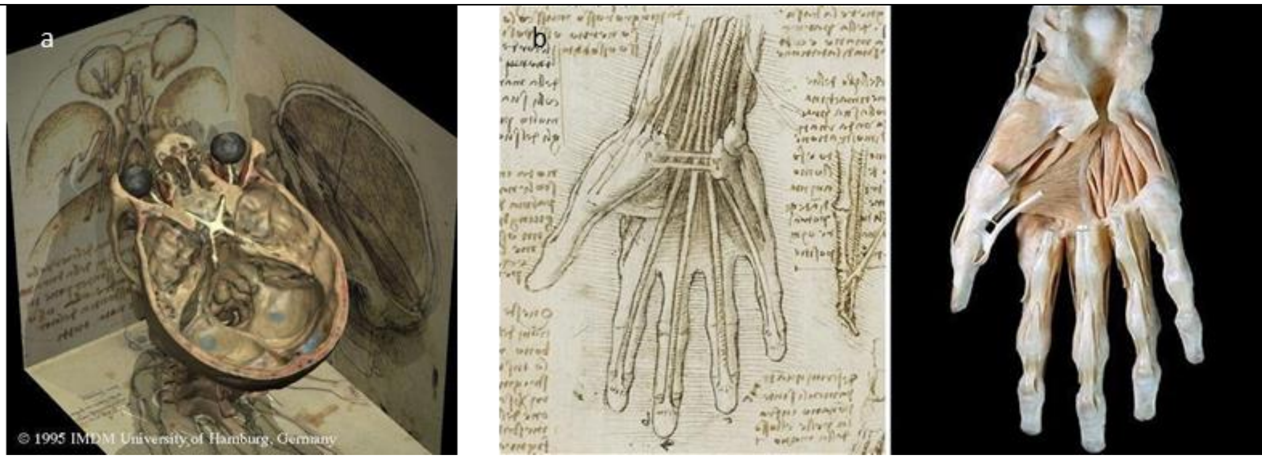


Figure 1. (a) Leonardo DaVinci Analysis I: Modern CT scan of the human brain with an almost identical anatomical match to Leonardo DaVinci's drawings of the skull and brain. (b) The modern anatomical model compared to DaVinci's anatomical drawing with identical, detailed structures. https://www.dailymail.co.uk/news/article-2383273/Leonardo-da-Vincis-drawings-100s-years-ahead-time.html.

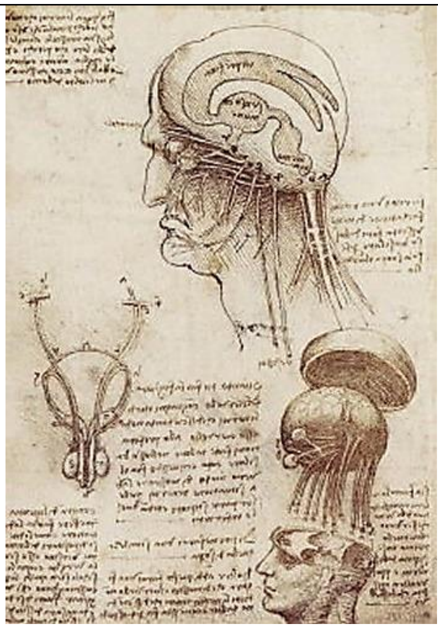


Figure 2. Leonardo DaVinci Analysis II: DaVinci's use of rotation, transparency, and the transverse section as well as basic geometry to illuminate a deeper understanding of structure. Source: https://www.leonardodavinci.net/drawings.jsp

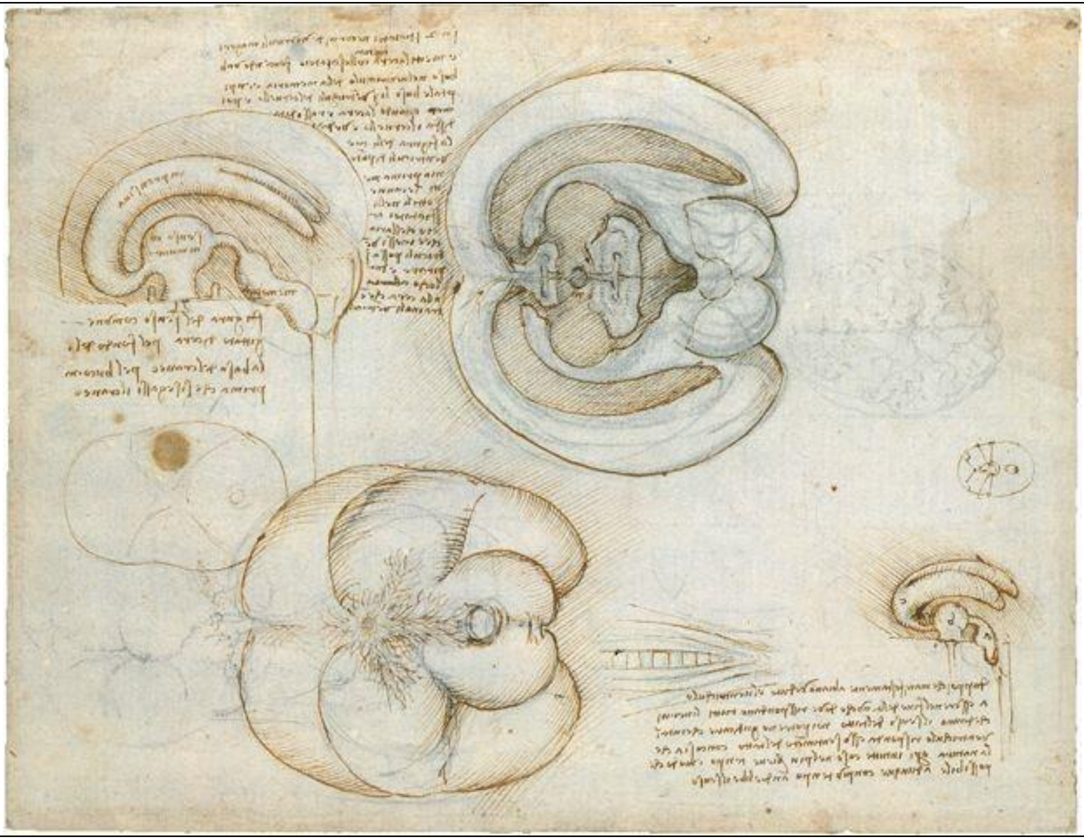


Figure 3. Leonardo DaVinci Analysis III: A view of the ventricles of the brain from DaVinci's notebook. This is part of his larger study of the brain and employs a different perspective but relies on transparency and sectioning. Source: https://www.leonardodavinci.net/drawings.jsp

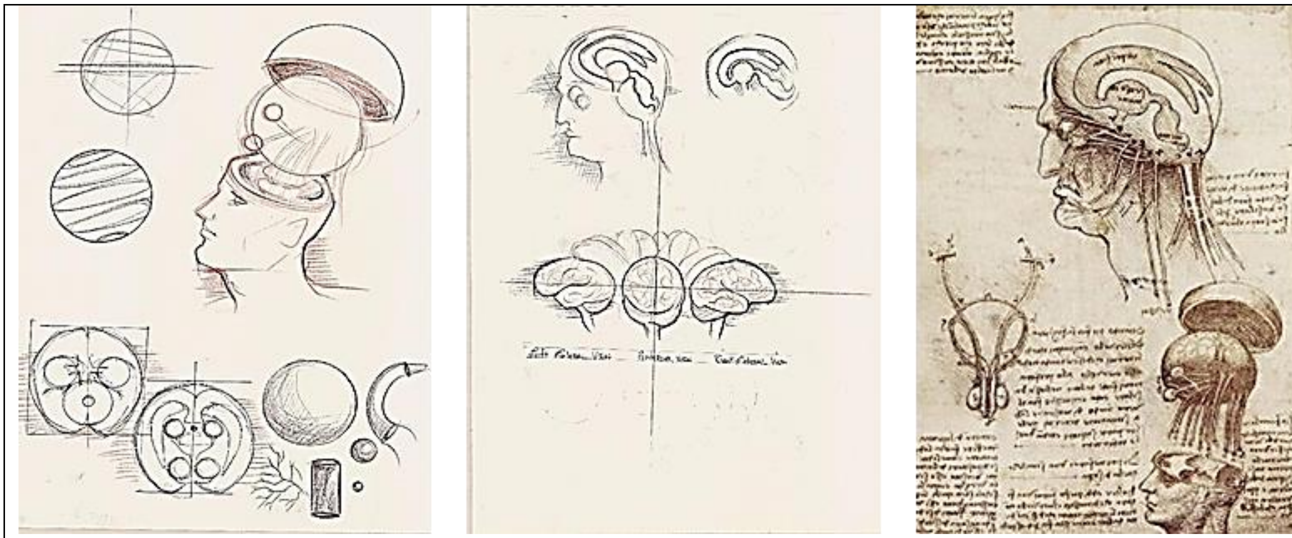


Figure 4. Leonardo DaVinci Analysis IV: The geometrical view that DaVinci may have applied in exploring the human brain's gross anatomy. Using his principles of transparency, rotation, and transverse section. DaVinci concerned himself with the shape and positioning of the anatomy from multiple perspectives.

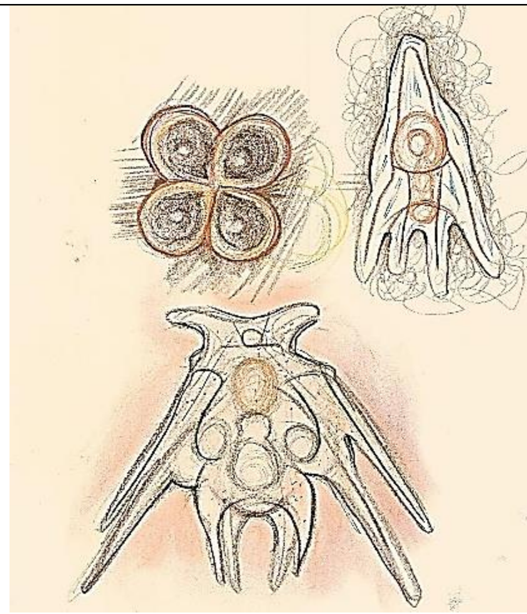


Figure 5. Theodore Boveri Analysis I: Boveri would have worked with entire organisms and ecologies before he embarked on tissues, cells, and pathways. The images I drew above, taken from Boveri's studies, along with actual ecologies from which they came, would be the precursor to drawing and observing any cellular processes associated with these organisms. Drawing the larger biology provides a framework for broad and narrowly based questions and provides a framework that students create themselves to visualize related biological questions.

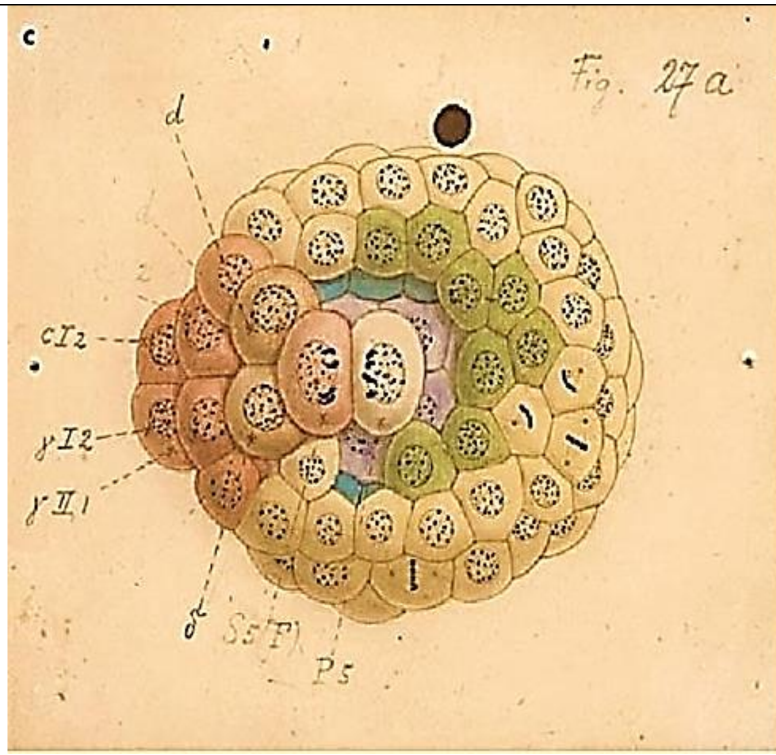


Figure 6. Theodore Boveri Analysis II: Boveri used colors to code different lineages. Source: https://ww.semanticscholar.org/paper/Theodor-and-Marcella-Boveri%3A-chromosomes-and-in-and-Satzinger/8a2e5468510bd4c191e66e0dfc41473c1c311e63/figure/1

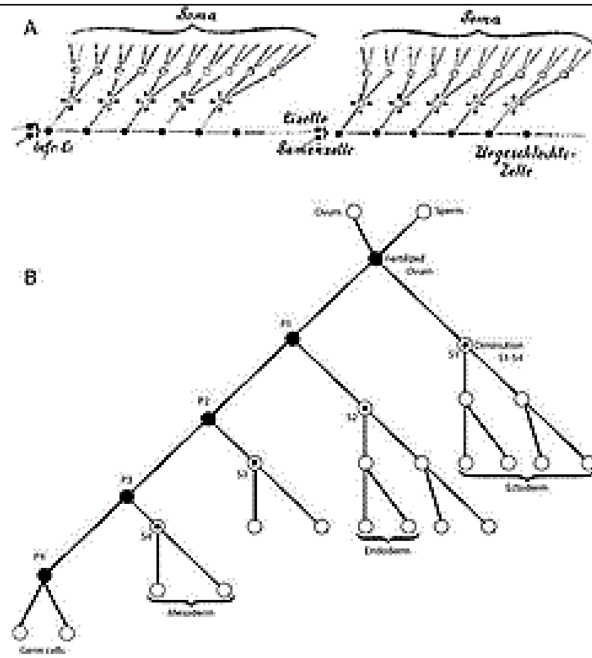


Figure 7. Theodore Boveri Analysis III: Boveri traced the different cell lines from fertilization to an embryo of 100 cells in completed illustrations. His watercolors and etchings of Ascaris were correlated with the Weismann and Haeckel stem cell diagram. From full illustrations to diagrams, Boveri hypothesized the germline contained complete hereditary information. https://www.alamy.com/stock-photo-chromatin-diminution

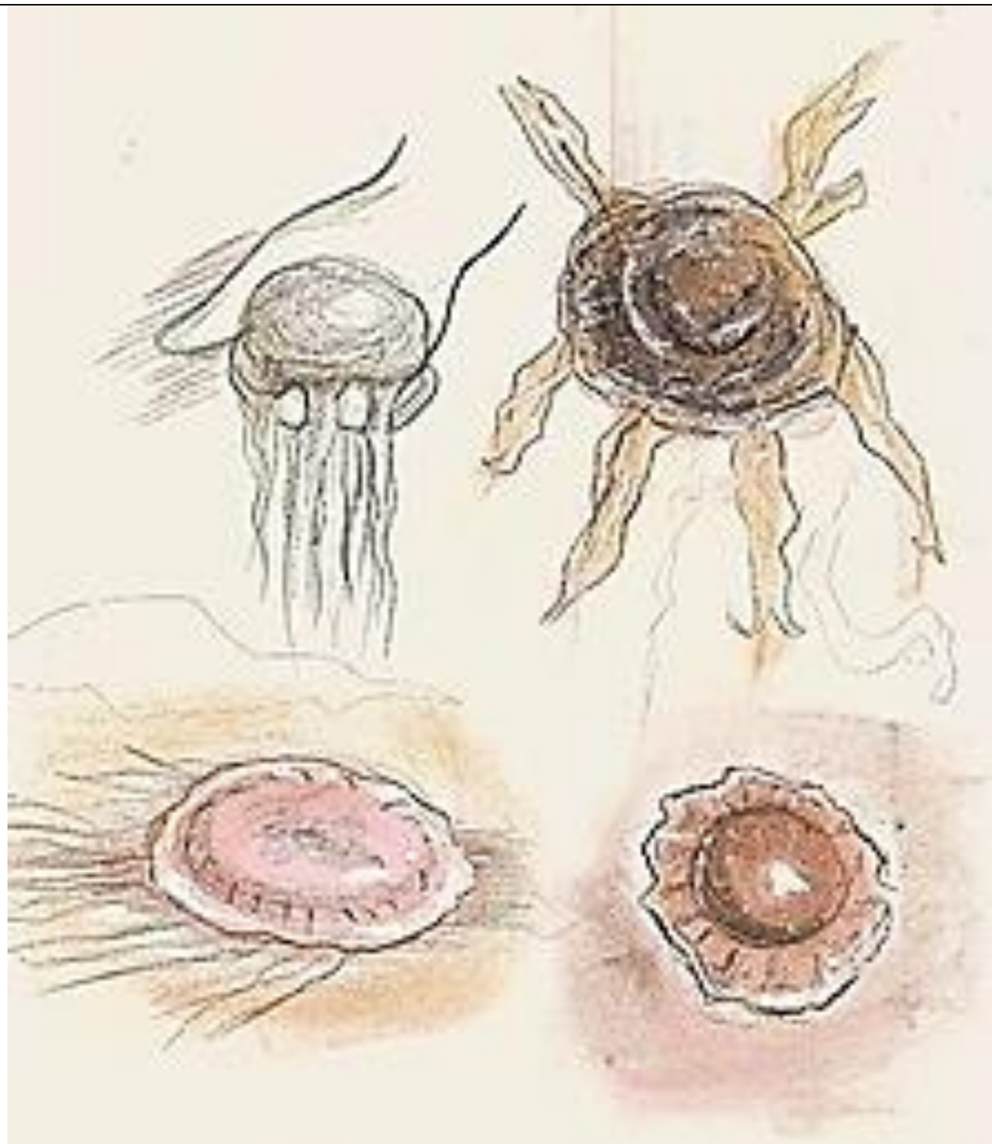


Figure 8. Ernst Haeckel Analysis I: This is what Haeckel may have started with, an organism (jellyfish), where there is no movement or definitive shape.

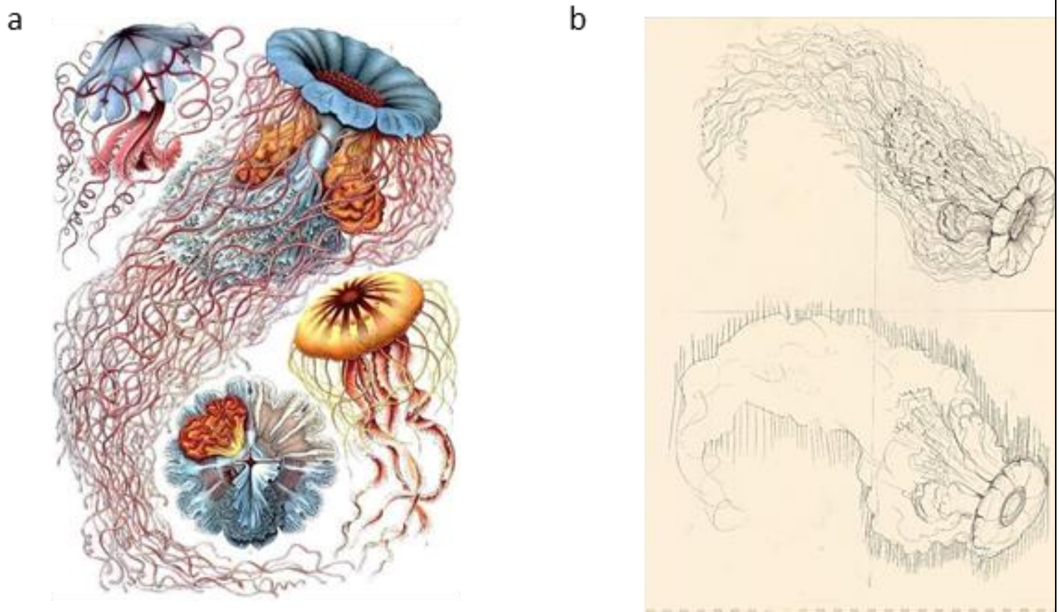


Figure 9. Ernst Haeckel Analysis II: (a) Lion’s mane jellyfish, *Desmoneama annasethe*, was produced through many studies and formalized into this lithograph. (b) Sketches I have made that would have been necessary as a study of movement in jellyfish. The finished image by Haeckel may appear stylized. However, his final art images' purpose was the promotion of evolutionary theory and appealing to general audiences.

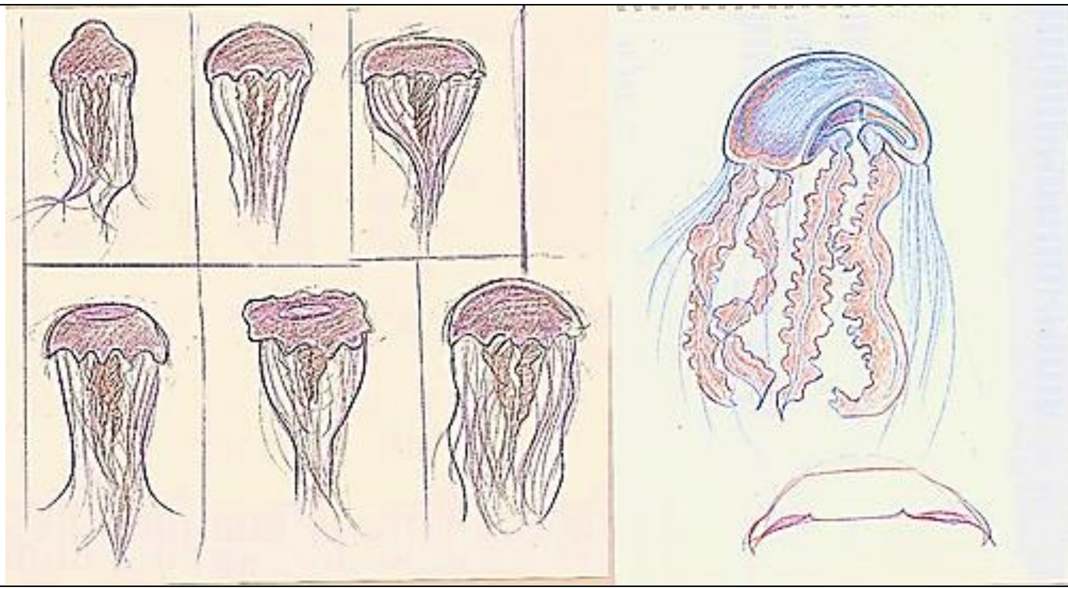


Figure 10. Ernst Haeckel Analysis III: Haeckel's study of anatomy is also evident in his images, with elaborate attention to various appendages on the jellyfish. This involved dissection and sequential analysis of the movement of the bell. A range of images would then be compiled, sorted, and redrawn to create the most salient and significant features of the species.

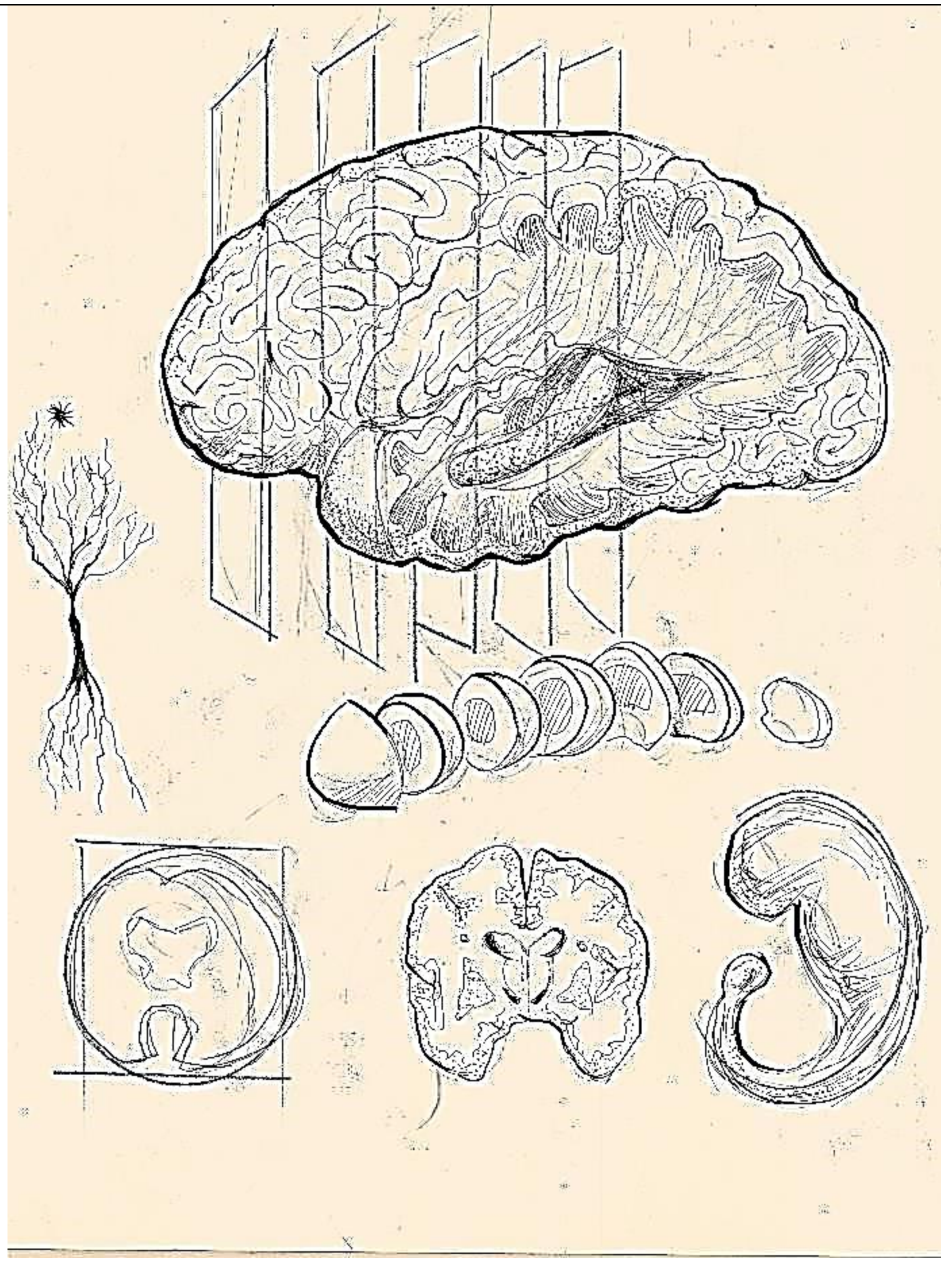


Figure 11. Santiago Ramon Cajal Analysis I: An image I created that would be an essential part of narrowing the focus on investigations on neurons. Cajal would have to start with the brain's entire structure to isolate and stain neurons and arrive at the metaphor of a "forest." This image involves DaVinci's concepts of rotations, transparency, and transverse sections. Cajal's love of nature helped develop a vocabulary that assisted in his anatomical conceptualizations.

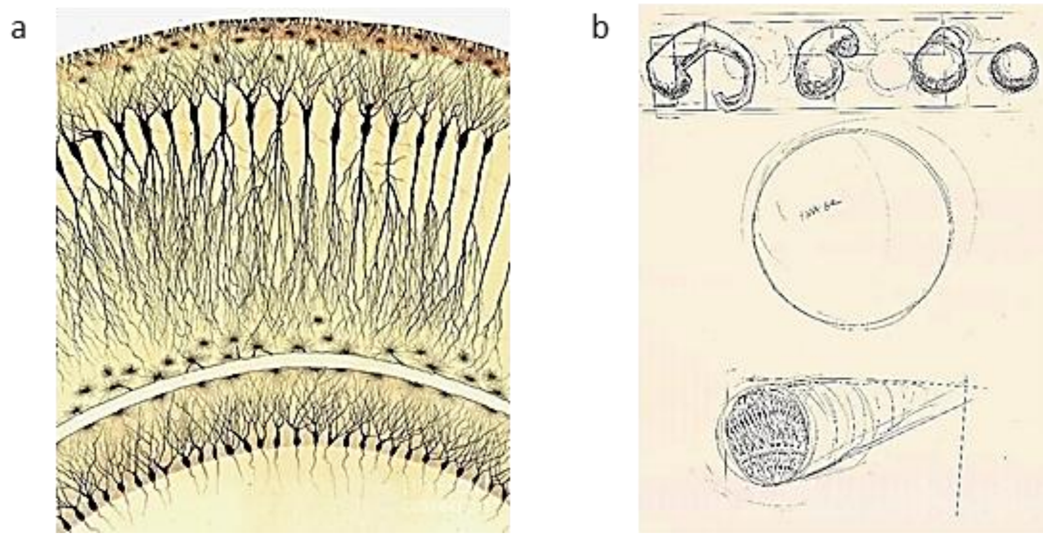


Figure 12. Santiago Ramon Cajal Analysis II: (a) A slice/section of the hippocampus drawn by Cajal. This image depends on broader observations and a coherent view of natural forms and functions, together with art skills. These enabled Cajal to form complete rather than fragmented concepts about the nervous system. (b) My illustration of how that section may have come about.

Figure 13. Santiago Ramon Cajal Analysis III: The multiple images on this page were created from Cajal’s two cross-sectional drawings of the spinal cord and nerves. For this, I show multiple views that may have been considered in the process of exploring neuronal communication. This would include the anatomy, the pathways, and the neuron’s physiology. My drawing of the full pathway (large left drawing) would be a schematic of the process that Cajal may have observed in his dissections and then reduced to a simplified format. The lower left-hand schematic is by Cajal and shows this technique with a vertebra and its sensory/interneuron connection. In this case, I created a more detailed version that Cajal would have reduced down for this schematic (upper right). Drawings as scientists present them may or may not display every step of the process, and as complex concepts, they may reconstruct, deconstruct, and amplify important structures and elements.

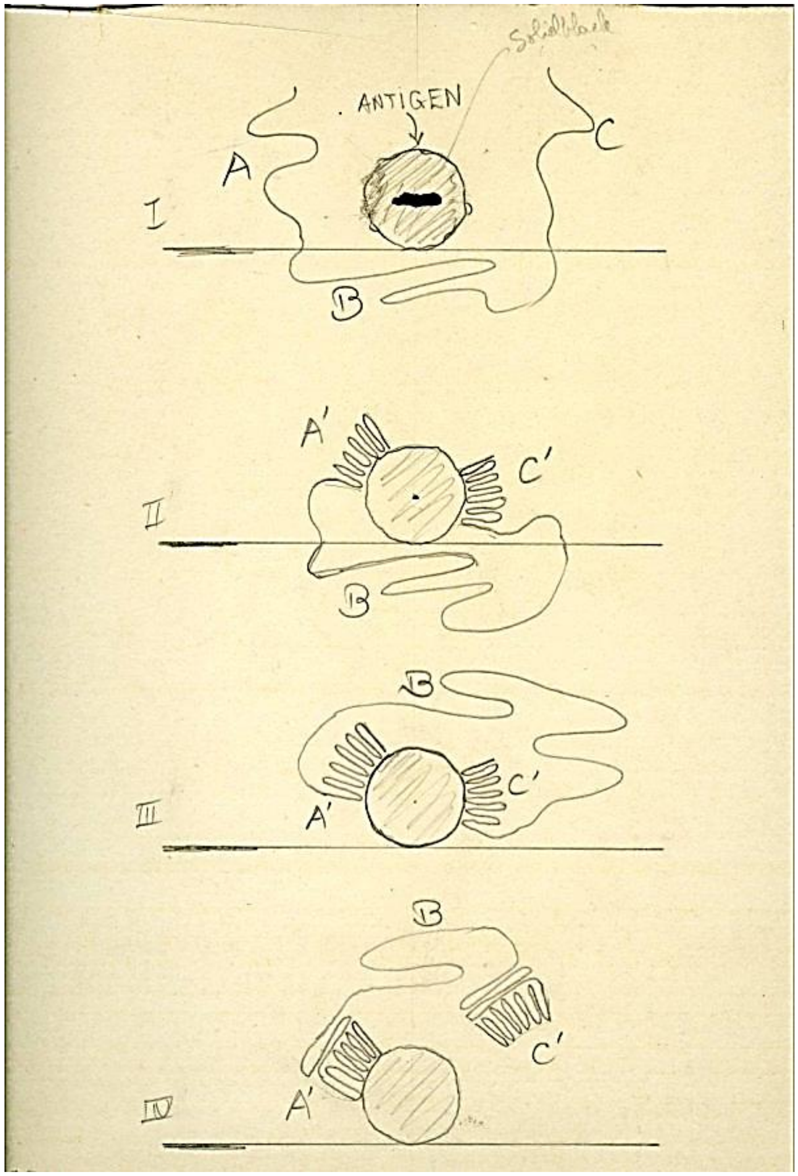


Figure 14. Linus Pauling Analysis: Pauling's storyboarded hypothesis of the induced fit model. The image to the left is Pauling's original drawing. Other images based on this cartoon were produced by a professional illustrator, with whom Pauling worked very closely. Source: http://scarc.library.oregonstate.edu/coll/pauling/proteins/pictures/sci7.001.5-drawing.html.

CHAPTER 3: A DRAWING HEURISTIC MODEL FOR BIOLOGY

From an analysis of historical pioneers of the scientific-artistic method (see Table 1), we can discern a variety of important teachable skills in a modern classroom. These skills require that we reevaluate the way we teach today. The analysis (rubric of skills) and its corresponding assessment tool (Table 2) scores those skills. In the following section, I have outlined those important qualities of the biological-art drawing heuristic and developed a teaching and research tool that I applied to my experimental classes.

Scientific drawings from direct observation are representations of reality. Drawings do not present the actual reality and can only convey conceptual and inferred realities (1). Drawings can omit qualities that are present and enhance salient qualities. They can also distort or inadequately represent reality. This is also true of computer simulations and computer-generated models and images. It should also be noted that preserving organisms, fixing organisms (or cells) to slides, interfering with biological systems, cells, populations, and individuals alter their form and shape from which we infer function. In the study or collection of data capturing images of biological phenomena, we also distort the reality of such entities as those entities respond and distort in reaction to the degree or type of interference. The distortion of the shape or form may mislead the inference of function.

An even larger problem exists in assessing biological systems and their continuous transformation and interfacing interactions in time and space, both microscopically and in geological time. Therefore, scientific theories start as imaginations, continue with observations and questions, and follow with experiments to become informed conceptual ideas. Theories contain speculation and require hypothesis testing to shore up and confirm their speculation. They must continuously do so, particularly with rapid and dynamic systems, to reflect some of the dynamic nature. In this way, drawing is similar to scientific methodology concerned with understanding biological systems. Unlike ecological studies or neuroscience, drawing does not disrupt the biological system or distort it; it is noninvasive. Its potential distortion may lie in the descriptive nature of its process. However, latent and possible reasoning and analysis can illuminate and visualize the biological mechanism or process of interest within that descriptive landscape.

Drawing biology, or drawing to understand biological systems, is complex and has historically functioned alongside and entangled in and with scientific research, the research itself, embedded in the culture and environment. All parts of this complex network of creative biological inquiry are equally important as they influence each other.

For my study, I had to limit my focus to one component of this scientific endeavor system that was testable within the university's academic space. For that reason, I focused on the method of scientific inquiry through drawing and sketching, which I called a drawing heuristic. The drawing process can simply be recording observable phenomena. It can become a heuristic of discovery, speculation, and inference, leading to more observation, drawing, and new questions and ideas about biological systems. This, however, requires expertise in both drawing and the content knowledge of the biological phenomena to date. Obtaining subjects with both of these characteristics is very difficult. Obtaining subjects with little or no drawing and biology content knowledge is much more achievable; developing a descriptive pattern of "how to draw for biology" is more feasible. This drawing heuristic, or for this work the "biological-art drawing heuristic," is the most fundamental, mechanistic element of the scientist-artist paradigm. It is also the most testable. Heuristics attempt to apply an approach to problem-solving or follow a self-discovery pathway that employs a practical method of attaining an objective. It has often been a matter of applying trial and error to problem-solving. "*The representative subjective assessment of probability resembles the subjective assessment of physical quantities such as distance or size* (4)."

Drawing directly from an object is more likely to give accurate results in the replicated image, providing all the data and information are present. However, in biological living systems, this is less likely to be the case. Those who "discover" through biological drawing must employ a degree of speculation, regardless of how accurate the drawing is. No living organism is static. As a result, the probability of a function, character, or quality may have a degree of subjective explanation. The drawing employed by scientists in history was a personalized method of the drawing heuristic and therefore had an aesthetic dimension unique to the individual. While making detailed and astute observations and drawings, scientists who employed drawing alongside their work also inferred and implied conditions that they observed and implied functions and transitional stages that did not or may not have existed. Judgment was based on limited data, which was subject to change.

However, from continual interaction and association with their chosen biological organism or system, they developed insight through a drawing heuristic.

Since all biological systems are subject to change at any moment in time, data collected from them is also changing. This is why the drawing heuristic works well with dynamic systems as it changes along with them. The use of intuitive and predictive judgments was based on their confidence in a particular field of study. Artists depicting or describing natural phenomena interpret these phenomena through a personal lens creating and generating many drawings, ideas, and diagrams. *"The strategy of choice is to increase the odds of favoring creativity by being productive* (140)." Boveri's "natural experiment" was an example of this, as were Haeckel's and DaVinci's works. The observation of all of the polymaths presented here indicates that art has some pivotal role in the transformation of knowledge and that they had, through the art, created something new by transforming ideas on paper into questions (141). This involves designing experiments, observing changes, recording changes, imagining or visualizing processes, and predicting outcomes. In interpreting data through an evolved specialist's lens, the drawing becomes both a valuable process and artifact of discovery. Scientific experimentation in independent investigations provides a degree of objectivity to refute or support that hypothesis. The "fewest assumptions" model of parsimony becomes the criterion of a good theory.

Another characteristic afforded to scientific investigations is that the theory and its hypothesis continue to encourage and inspire new concepts and questions regarding the phenomena through a heuristic conceptual construct. This quality to the theory provides ongoing investigations into the principles proposed, leading to discoveries. Finally, as part of this investigative continuum, a unity of knowledge should emerge. "Parts" and components of a discipline should correlate and be verified by consistency in other disciplines. In other words, the knowledge that is "true" should synchronize with additional systems and the knowledge generated from them for the phenomena.

Throughout history, the Drawing Heuristic contains within its domain a consistent correlation with scientific analysis and discovery of natural phenomena, a preoccupation with advanced and specific drawing skills, and a continual aesthetic perspective. It has been suggested that both in art as in science, the brain seeks elegance, which is the parsimonious and evocative description of pattern to clarify a confusion of detail (142). We observe things that look dissimilar. We compare and find patterns. We distance ourselves and create abstractions, laws, systems using transformations, mappings, and metaphors (143).

The Drawing Heuristic comes from the root of that underlying process of discovery and interpretation. Drawing typically makes an accurate representation of the visual world to express form upon a clear plane surface. This replicative and repetitive-based skill was central to the Western world visual arts from the early Renaissance until the beginning of the 20^{th} century (19). There was a dramatic shift when the genre of Modernism approached—before this period, drawing as a heuristic was prevalent and necessary to understand form. Its application to anatomical sciences, biology, and a host of other sub-disciplines in biology cannot be overstated. Drawing, after Modernism, however, became unfashionable, and having excellent draftsmanship skills was not artistically favorable. This trend has continued to present times. Drawing before Modernism was a skill for visual problem-solving. The Victorian artist and theorist John Ruskin proposed rules for drawing well as many art instructors of the classical method did and saw drawing as the foundation of expanding art mediums such as painting and sculpting. He proposed that drawing was an investigative method into nature and used it himself to explore botanical specimens (144). Excellent drawing skills that could replicate the form and imbue energetic qualities were highly desirable. Ruskin noted that "*drawing forces the artist to look at the object in front of him, to dissect it his mind's eye and put it together again*" (144). Artists with good drawing skills applied them to a variety of non-artistic practices such as design, medicine, engineering, and scientific practice (19). Some professions required technical accuracy and needed artists who could commit these practices to the profession.

3.1 Defining a biological drawing heuristic

The drawing that I will be referring to in this work is confined to the drawing principles before the Modernist movement in art. Most drawing in an artistic context involves looking at an object and then looking away to work on the drawing. It involves short-term memory and holding or visualizing the object, or aspects of it, for brief amounts of time in the mind to transfer that mental "capture" onto the media (4).

In some situations, photography is used to support the accuracy or to converge with the exploration of the object so that it is rendered with the most precision. If done repeatedly applying geometry principles, this practice of drawing in real-time develops the ability to draw (145). While drawing is inherent in the human species, development and refinement require practice and experience. These principles are still considered to be the classical foundation of realistically based fine art. They are also the principles applied to the method of descriptive, scientific illustration still used by paleontologists, medical, and scientific illustrators. Although these professions themselves are narrowed to the degree that the artist/ practitioner does not participate in the discovery process or the illumination of the biological phenomena, it is not even a collaborator, let alone a self-contained polymath in the past. Central to what was considered academic drawing practices is a need for accuracy. Drawing accurately, precisely, and interpretively are the actual method used to explore, navigate, and describe biological phenomena. Accurate drawings require an innate or cultivated construct of visual geometry, angles, planes, and rotation of those planes on x, y, and z coordinates. Leonardo DaVinci established principles of drawing scientifically and anatomical rendered images by positing his treaties of scientific illustration in the 1500s, advocating that scientific art must explore phenomena from three important perspectives: (a) Transparency, (b) Rotation, and (c) Transverse Section.

While most artists did not appear to adhere to DaVinci's Treaties, the concepts are critical for rendering and understanding the form being examined for scientific investigations and are visible in the artist/scientists presented in this work. For the most part, the case study artist/scientists drew accurately, but what is drawing accurately? Moreover, why is drawing accurately important to life science research and student achievement in the life sciences? The Biology-Art Drawing Heuristic, that is, the synergistic, interrelating, and coinciding skill set of those like DaVinci, I propose to serve the individual as self-reflective, self-correcting, self-teaching, and a self-evolving system of exploration, discovery, experimentation, further exploration, validation, resolution, which looped back to a similar exploration, and a repeating, revising process. This internal/external unity through interaction with nature and the "self" creates a network of knowledge within the individual and integration with the surrounding world.

Below I have listed the major components of the Bio-Art Drawing Heuristic (applying Table 1 and assessing with Table 2):

1. Observational Sketching
2. Evaluation of sketches
3. Planned page
4. Geometry in space
5. Shapes of Life
6. Distinction of organic property from induced property
7. Rendering
8. Evaluation

3.2 Methods and models of the bio-art drawing discovery

I have used Leonardo DaVinci's principles to design to provide the foundation of the method I will call the Biology-Art Drawing Heuristic. Rotation, transparency, and transverse section are part of the skill development, followed by aesthetic noticing, lateralization in observation, and resampling of sketches of biological organisms and preparations normally found in an organismic biology course. While this is far from what I had originally proposed, it is a small but critical piece of the larger occupation of the polymath artist-scientist of the past. I hypothesized that if students applied, experienced, and observed this, although very briefly experiencing it, they would inculcate some rudimentary aspects of the drawing heuristic and improve their test scores. I tailored the method to fit the random time frames and limited time frames of the lab. I had anticipated that I would run into several difficulties regarding the administration of it. Ideally, the drawing heuristic would be conceptually created from the analysis of five historical, scientific artists presented in this work. Table 1 provides a summary of the drawing methods of five scientist-artists and the chosen techniques. This conceptual model allows the teacher/student to reframe the concept, experiment further and ask new questions.

Examples how a student my proceed in the drawing heuristic are given in Figure 15 where an amoeba is depicted as a living, moving, changing subject with distinct morphology. Following this drawing analysis of the amoeba, a student or teacher can then continue to apply the drawing heuristic to dynamics, which can be seen in Figure 16. A further example of the fundamental principles of rotation and variable appearance and how one might approach it with a biological-drawing perspective can be seen in Figure 17.

3.3 Assessment of basic biological drawing

1. Students will develop tactile, haptic, and sensorimotor skills to build layered concepts.

2. To imply through tactile and visual drawing skills the dynamic characteristic of organic systems.

3. To engage the observer in a sequential, step-by-step methodology that more closely examines properties of biological systems.

4. To increase noticing skills in life sciences.

5. To cultivate fundamental skills of scientific drawing as a research tool with varied applications.

6. To increase student outcomes on biology lab exams.

7. To encourage a sense of self-learning and discovery through the drawing skill set.

8. To enable the evaluation of drawing in biological science.

9. To cultivate a dynamic process-based perspective regarding static specimens and images.

10. To develop a dynamic, process-based visual-spatial skill set.

11. To provide a foundation for inference into biological processes that are not directly observable.

12. Acknowledgment/understanding of living forms morphological forms go through change or process and cannot always be identified. It may be part of stages, cycles, environmental flux, and change due to genes' environment and expression.

13. Through drawing, learn about living systems as adapting, changing form, and populations evolving.

14. Starting with basic geometry and going beyond that to recognize and internalize form, variation, and complexity.

3.4 Ideal student drawing assessment criteria

1. Primary sketches of organism/observation encourage students to explore live specimens or observe nature (field studies),

2. Translation of those sketches focusing on geometry and spatial placement on the page. This takes the observations (sketches) and allows analysis and synthesis (combining live protozoa observations with slides). It also encourages the incubation of phenomena and consideration of what was observed.

3. Transparency: Attention to the effects of light: does light pass through it, reflect off of it? This allows observers to distinguish properties of living things, including irradiance, the density of matter, and variation in perception. It also encourages depth of subject or 3-dimensional quality of the subject.

4. Rotation: what is this organism's position/structure in space, and can the observer rotate this? Rotation develops multiple views of thinking. It considers that one may be observing any possible position of an organism or structure.

5. Transverse section: can the observer visualize and draw the form associated with this section? This technique employs both rotation and transparency and encourages the active synthesis of many dimensions of the subject.

6. Variations of this organism or structure: In the drawing's details, can the observer detect differences or variations and distinguish adaptations from variations?

7. Planetary forces: distention, desiccation, expansion, condensation, decay. Can the observer in their drawing distinguish these effects as they will be present in prepared slides, embalmed animals, and dried objects? The observer should consider the added distortion of preserving specimens and not observing living forms unless, of course, they are living, such as a flower on a plant, an emerging seed, or a bird in flight. In the case of natural distortion and decay, these parts of metabolism and change. Slides are stained, and specimens are distorted. Microscopes alter the appearance of an organism as well.

8. Inferring function from the observations (a later part of finished drawings with notes).

9. Inferring subsequent forms (so-called intermediate) from the one observed (next stage of developmental form, growth, change, or a continuation of the initial observational drawing).

10. The presence of any of the above qualities in a drawing is scored by a "0" or "1," where 0 = quality absent in drawing/sketches and 1 = quality present in drawing/sketches.

11. Drawings are then evaluated based on a visual key representing the quality and scored 1 through 5.

3.5 My BioSTEAM model in comparison to other frameworks

To many in the educational field and the STEM field, STEAM provides another dimension to the integrative paradigm of STEM. This dimension, at its core, focuses on what is commonly referred to as "the arts." The arts span a large number of experiences, processes, and domains. The amount of literature in this area is quite large as art can mean dance, theater, writing, and visual art, from all cultures worldwide and throughout history. That includes all the variations of these general disciplines dating back to man's earliest ancestors (146). A literature review for STEAM, in general, may also consider perspectives from the following disciplines; interdisciplinary studies, transdisciplinary studies, education, psychology, sociology, the life sciences, medicine, physics, environmental science, chemistry, geology, and cognitive science.

Along with these disciplines, there are many STEAM articles where educators try their "hand," so to speak, at implementing the arts in their classroom or developing the arts into research. This results in many publications that do not seem to fit into any category. To narrow down the enormous variation in the literature, I have chosen to report on several papers that reflect some similarity to my BioSTEAM framework. Although my BioSTEAM model incorporates facets of writing, storytelling, and theater (exhibition space), I am mainly concerned with the visual arts. The visual arts themselves are vast and broad, and I will focus on STEAM models that mirror some aspect of my BioSTEAM curriculum relative to the visual arts in this review. A summary and comparison of the BioSTEAM framework alongside related STEAM objectives can be seen in Table 3. Sample articles are listed alongside the most associated characteristic shared between BioSTEAM and STEAM, showing the similarities and the differences.

Some studies in the STEAM movement point to drawing as a source of observational skills, with several models and articles published on the benefits of drawing for science in general (147). Drawing as it relates to observations in biology has also been presented as part of the STEAM initiative. An example of this, "the drawing-to -know biology framework" proposed by Quillen, suggests that drawing enhances memory and observational skills (18). In other specific examples, such as the microbiology class, researchers admit that there is no quantitative method for scoring or evaluating student drawings once they are created. "Cell biology does not emphasize observation and quantitative analysis of microscopic images, and it is unclear how best to teach students these skills (148). In the study, "*Visual Arts Enhance Instruction in Observation and Analysis of Microscopic Forms in Developmental and Cell Biology,"* the authors propose applying "visual aesthetic approaches" to student drawings (148). However, they do not define what visual aesthetic approaches are sufficient to function in a quantitative role.

Along with visually aesthetic artifacts, the basis of their quantitative analysis involved taking measurements of images. The researchers had students use a representative photograph to draw from and then had students identify cellular structures. In another activity, they compared paintings and photographs with cellular forms. In each of these activities' students made their personal choices, applied some form of measurement to the image, drew some aspect of it, and wrote a narrative piece about it. These methods were taken as a quantitative approach to drawing and understanding biological images and suggested to the researchers that the inclusion of some type of aesthetic art would enhance the learning process. While the fundamental premise of quantifying student drawing related to biological images is present in some way, there remains no actual basis for this method or framework (148).

Historically, in classical drawing, a grid is sometimes used to assist the artist in seeing perspective. In the Renaissance, this involved new mathematical rules for turning a two-dimensional image into a three-dimensional image. In this article, there did not appear to be any grid method, and therefore, I do not know if this is what students were engaged with. Teaching students to use a grid to draw is problematic and requires a skill set to begin with. Furthermore, the students in this study were functioning as their own teachers, perhaps in an exploratory way, making choices about aesthetics without prior experiences, and like many STEAM papers and experiments, forming opinions on their isolated assignments. The teacher modeling of the process was not present, and therefore, there could be no genuine assessment of drawing skills, which may reveal the process of synthesis in the observation. Not all students will have or evolve the same skill. However, they will develop a basic skill set, which will allow them to explore and tailor their personal discovery of biology. In this research, there is no mention of the cytologists of the past who regularly synthesized their experimental findings with their drawing heuristic. In the BioSTEAM framework, the drawing heuristic is grounded in historical biology and teaches the basic biological drawing skill set.

The drawing methods from Leonardo Da Vinci, which enabled his detailed and accurate work in anatomy, are applied in a step-by-step method and exist concomitantly with sketching, dissection, a naturalist's experience, painting, sculpting, creative and descriptive writing as well as a visual metaphor. The methods of Theodore Boveri, specific to the cell and embryology and genetics, may have been very suitable for exploring cellular drawings, providing they were teacher-driven, yet Boveri is never mentioned. Furthermore, there is no teacher instruction for students to develop a synchronized drawing-biological synthesis as a regular experience of classroom engagement. This synthesis could underpin their exploration and train the student eye to the biological forms and shapes of the cell and embryo during lectures. While the writing part of the STEAM experience in this work adds the literary dimension with imagination, it is highly personal and not necessarily a narrative that reflects the biological system or content of the course, but it provides an exercise in creative writing (148). reveal a lack of development and delivery of a definable method, even though this synthesis is chronicled in the history of biology. It also reveals that both visual art and biology sectors are searching for a quantifiable, functional, and methodical method of combining drawing and biology within the STEAM concept, one which my BioSTEAM and drawing heuristic presents, outlines, and defines for those teachers seeking to implement STEAM and willing to learn the processes themselves first. Therefore, one may conclude that the relationship between live teacher-initiated demonstration and historically validated STEAM practices is not well represented in the literature.

In another article, an example of what teachers might do to promote STEAM learning is presented in a book series entitled: *Informatics in Schools* (149) A conference paper from the book series on Informatics in Schools, "*Holistic STEAM Education Through Computational Thinking: A Perspective on Training Future Teachers* (149)." suggests the importance of training teachers in STEAM-based skill sets. In this work, computational thinking skills are the focus. Admittedly, the authors point to a "lag" in teacher education, and that computational thinking may be the approach that bridges the sciences to the arts, suggesting it is an integrating skill set that can be taught to teachers, suggesting training events of computational thinking, and structured modules on using computational thinking. Surprisingly, while the papers suggest how this program can be delivered, they make no mention of storyboarding and the storyboarding framework that may facilitate their computational model. While the computational skill set is suggested for many domains of science, it is perhaps best suited for engineering, which the authors allude to. However, there appears to be no mention of biology or the life sciences, which demand a different perspective. In my BioSTEAM model, the narrative of storyboarding, along with sketching and "fleshing" out ideas, is fully outlined, and examples are given. Even in engineering, the BioSTEAM framework can be applied and alongside computational patterns of thinking. That is, it can be modified to non-biological systems. This example is seen in Leonardo DaVinci's ability to switch from organic nature to mechanical drawings. This is possible because of the underlying drawing skill set. The computational thinking paradigm also suggests "unplugging" from technology. However, it offers no suggestions on how to do this when drawing, storyboarding, and sketching are "unplugged" activities, provided they are largely done by hand, which are inherent in the BioSTEAM framework.

Cartoons and comic books have become popular in the STEAM movement and throughout STEM, with various comics being produced to explain science topics (150). In the paper "*Humorous Cartoons Made by Preservice Teachers for Teaching Science Concepts to Elementary Students: Process and Product* (150)," comics and storyboarding are presented along with multimedia animations and a focus on animation in general. This is a common theme in cartooning and teaching with cartoons. Cartoons can be very educational, but this only happens when they are synthesized with the content or the concept. Cartoons and comic strips are the foundation of animations. Artists who have produced classic storyboards for such popular animations of the past, such as *Bugs Bunny*, *The Jungle Book,* and *Tom and Jerry,* actually study each character from every possible rotational perspective in many loose sketches. This is not only done to explore possible variations of the character but to define the dynamics and movement of the character. For example, the animals featured in the Jungle book are drawn anatomically correct, their proportions are studied, and their features modified. This practice is highly skilled and allows an authentic but fanciful depiction so that the character is clearly recognizable and fun to look at, which defines a cartoon image. In this way, the animating practice compels the artist to study, observe, and transform a subject. Therefore, its skill set is highly applicable to biology students.

Furthermore, the cartoon characters are set in backgrounds created distinctly differently from the character to entrain human binocular vision to the animation. The character is sharply drawn against a background, muted, soft, or fuzzy, similar to that of a scene with perspective, one that binocular vision naturally sees. While this may seem inconsequential or unknown to STEAM educators who endeavor to create comics, it is a very vital technique that makes certain features of the cartoon more salient and more like the "real world." Biological concepts are a natural fit for animation techniques because they also follow DaVinci's scientific illustration treaties and make a vast difference in how biological activity is perceived and experienced in a storyboard or animation. I did not see this level of consideration in the comic activities created and presented in this publication.

The BioSTEAM framework emphasizes storyboards from a different perspective and proposes that the storyboard not only function as an organizing principle of thought but as a reflective mirror of experimentation and contemplative activity, which should remain "unplugged." In this way, it functions to slow down and examine what one is attempting to evaluate. Its other dimension, contemplation, and incubation, involves the hand-drawn, thoughtful activity of drawing and focusing on transitional forms in a series of steps, which cognitively capture and examine dynamics. Most storyboards and animations made by novices also do not capture the motion of living things correctly or at all. Leonardo DaVinci's flight of birds and vortices of the heart and water demonstrate life dynamics and transmutational changes, which are important when exploring motion in living systems. Most living things do not move mechanically but produce aftermath images of an arc. Therefore, when sketching motion, the movements of the same object on the x-axis and y-axis reveal different movements and timing of those movements and should be illustrated differently in sequence to account for gravity and to suggest realistic motion. In this way, the artist and the viewer will see the arc of movement slowed down, and that dynamic can be studied. This specific attention may be useful when examining the peristaltic/segmentation action of the digestive system, a paramecium pursuing prey, or the collective motion or shoaling of a school of fish. Admittedly, these are challenging skill sets, but their challenge is partially responsible for the focus. If drawing were easy, there would be very little focus.

Most storyboards and comic creations for students are referred to computers and apps for easy access, which defeats the purpose of gradual and attentive exploration. The historical basis for BioSTEAM, though, is supported by Linus Pauling's use of the storyboard and sketching in his popular work on protein-protein interactions (123). In the article "*Arguing with Images*," the author, Alberto Cambrosio, points out that a cartooning process called "paving" was used to create a panoramic continuum of serum, suggesting that the view was broader and more contiguous than the small panel of the antigen/antibody being viewed by the reader. This minor artistic change results in a significant perceptual alteration in the creator and the viewer. It is doubtful that most STEAM efforts that wish for students or teachers to create cartoons consider these subtle elements following intricacies of the biological phenomena.

While the hype of graphic novels and cartoons has been around for decades, the storyboard does not appear to ever been used as a teacher-designed and driven activity. In my BioSTEAM curriculum and its related products of my past and current research, I have developed the storyboard and the graphic novel in activities that teach specific biological content. I have also included the storybook genre not only as a teacher produced example, but as an actual teaching tool in a lesson plan that contains activities for students to engage with drawing in biology. While it is unlikely that most teachers will not immediately develop strong animation, skill sets or drawing skill sets, the BioSTEAM framework can provide examples of what is possible. No such developed examples are given in any of the STEAM articles I have reviewed. These unplugged, interactive products for students are developed to continually engage the student with the content and have some drawing techniques of classical animation. In this way, the BioSTEAM storyboarding method and storybook development include a historical basis as well as teacher-driven and modeled activity along with attention to the dynamics of biological systems. In both molecular and macro-level biology, traditional cartooning and animation techniques can be experimented with and developed by the teacher, imparting some skill development on the student. The transitions of each cell (another term for frame) within a BioSTEAM storyboard or book are also developed from the current literature on specific biology subjects of interest and translated into overlapping narratives to reflect the complexity of biological systems while serving as hypothesis-generating, hand-illustrated vehicles. Furthermore, with an understanding of how classical comics are made, the teacher can create identifiably realistic comic images, which suggest action, motion, and change. In these manifold ways, BioSTEAM is unique from other storyboarding and animating STEAM activities.

Hadzigeorgiou and Schulz (93) present a compelling argument for the revivification of romantic biology. While this is not presented as a "STEAM" framework, it is a historical interdisciplinary biology model. In their paper, "*Romanticism and Romantic Science: Their Contribution to Science Education* (93). " the authors outline how the romantic era in Western biology possessed an inherent interdisciplinary structure that brought together aesthetics, ecology, evolution, and as they put it, "as a state of mind," that constituted a holistic experience in the biological sciences, promoting a sense of wonder as well as reaching or outreaching to the general public, therefore generating heightened interest in the natural world. Hadzigeorgiou and Schulz (93) discuss student engagement in the modern school curriculum and point to the current model of learning as an overly rational activity without emotional investment. They discuss the issue of detachment in our current models and state; "*It goes without saying that during participation in an activity, the object of study can be disconnected from the emotions of the student, which can arise mainly from participating in the activity as activity* (93)." The authors then propose that the romantic biology of the 18^{th} and19^{th} centuries could inspire a new framework for biology by focusing on the unity of nature with the man in the European view. As the authors propose, the underlying basis of romantic biology is the unity with nature and beauty, which naturally flows from science to society (151).

I agree with this approach, and it is reflected in my BioSTEAM model. The features of this romantic science model are rooted in a Eurocentric foundation, as is the drawing heuristic of BioSTEAM. However, BioSTEAM can be reflective of indigenous and traditional unity with nature and encourages cultural views from various ethnicities, tribes, and traditional societies in the form of oral storytelling, metaphor, and the individual student's ultimate development of their own unique creative approach, perhaps even based on their unique cultural experiences. The non-Western perspective can be particularly powerful in the biology domains of ecology and biodiversity, where poetry, art, and harmony with flora, fauna, water, rocks, mountains, and soil produces both a knowledge base and an intimacy with biodiversity that are in many ways far superior to Western models of ecology and biodiversity evidenced by the fact that those human-inhabited ecosystems remained relatively intact for thousands of years until colonialism (152). I intended to introduce the Eastern Mandala as a traditional art form and created mandalas around evolutionary and ecological knowledge, keeping with the purpose of the mandala as a "whole teaching" that embodied the cosmos in a circular universal paradigm (153). This was to be part of my BioSTEAM delivery and storytelling, but I could not display the work. An example of this kind of multi-cultural storytelling space can be seen in Figure 18. It is, therefore, a large component of the BioSTEAM curriculum and unique to it in many ways, including the cross-cultural artistic and scientific influence and the fact that the instructor created the mandalas specifically to teach biology and introduce the artform of the mandala. Along similar lines, my BioSTEAM initiative sought to explore various creative writing exercises coordinated with nature walks, employing one writing genre in particular; Japanese Haiku. BioSTEAM also involves storyboarding and nature journaling, employing several skill sets, including the drawing heuristic, sketching, and spending time in nature with the important inclusion of traditional knowledge and views on nature.

Hadzigeorgiou and Schulz (93) outline important ideas that underly engagement and society. However, they have no visible development of delivery methods or teaching tools, and while their work is historically based, it is not inclusive of other cultures. There is also no dissection or replication of the aesthetic and biology-based skill set that was the hallmark of the time periods they suggest as the model. The drawing heuristic in itself is an engagement promoting experience, one that can be both objective and personal and inclusive and diverse. The work on the romantic biology framework supports the BioSTEAM framework from a historical context, but romantic biology only has only the past products to inform the biology curriculum of today and does not add anything new. Some STEAM and some ecology-based curriculums employ sketchbooks and visual experiences, and there is an undertaking of ecologically based art or art for ecology (154).

This has some merit in learning and appreciating biology from this point of view, but again, this is another disciplinary area that is to spread out to be considered for this work.

Nature or ecological consciousness is another important dimension of STEAM as it is why all the sciences exist and it was the foundation of all arts in both a literal and figurative way. In the article, *"Recognizing aesthetics in nature with STEM and STEAM education,"* authors Basaran and Erol (155) present a pretest, posttest study that aims to examine the effects of STEM and STEAM based activities on 4th grade students regarding their attitudes towards environmental awareness. Their primary goal was to see if a particular protocol raised student awareness of the environment. Their conclusion was that current environmental education is not sufficient to raise awareness in students and that including aesthetics and arts could help. This is a very fundamental problem but also a complex one. Inculcating students to care about the planet, or become sensitive to other life forms requires a lifestyle and a focus where nature is not simply a backdrop for more important things or a pleasant experience during a vacation. The deeper issues cannot be discussed here, however, children and adults alike spend less and less time in nature experiencing the wilderness or the natural world (156). The term "nature deficit disorder," has been coined to reflect this problem. BioSTEAM addresses this at its core since biology is the study of life, and its historical foundations for the Western world are grounded in that focus. DaVinci's primary interest above all else in his investigations and notebooks was the sense of wonder about the natural world and a respectful and inspired relationship with it (157). BioSTEAM by integrating nature walks with observational drawing, metaphor, fine art, and storytelling automatically makes nature the focus. This in itself shifts a student's perspective towards living things. With an emphasis on the beauty of nature and form our innate sense of biophilia emerges (142). Therefore, a respect and appreciation of nature is an emergent property of the drawing heuristic, which focuses the student's attention back to the intricacies of biological systems.

Narratives and storytelling have become a popular focus in current educational practice and have been presented in a variety of ways within the STEAM paradigm. The storytelling experience has been dubbed, "a culturally relevant pedagogy (158). Storytelling and pictorial communication, are behind olfaction as the oldest types of communication in human societies and are ubiquitous throughout cultures from all over the world. There are multiple ways in which stories can be conveyed. According to Doniger et al. (158), teachers should be developing various types of storytelling activities through conferences, "*This innovative professional development approach had five segments: (1) storytelling examples, (2) infusion of the arts into STEM, (3) technology, (4) CRT and storytelling, and (5) participant worktime and showcase. The professional development was designed in a way that it unpacked the process by introducing techniques, procedures, methods and pedagogies using the arts; exploring STEM subjects in a creative way; and considering how CRT practices can be applied* (158)." The various presentations representing the multiple ways stories can be told intertwined some science with sociological issues in Doniger's work and while the article provided images of the activities, it had no specific way of measuring the results of these activities and suggest that they simply promoted "creativity," furthermore, these activities are primarily for younger grades as storytelling as a lecture format is rare in college or university settings.

In another article, "*Learning Biology Through Molecular Storytelling* (159)," the authors focus on the domain of molecular biology by researching and telling stories about molecules and provide molecular storytelling exercises, which involve computer-based experiences. This does consider higher grade levels and has a focused domain. While these two storytelling curriculums have a general and domain specific focus, they are quite different from the BioSTEAM storytelling experiences. In BioSTEAM, the teacher develops and produces the biological story and delivers it to the class. The story itself is based on research, the teacher's research, maintaining that teacher's stay current with the literature and employ the discovery process themselves or at least with their content and in this way the teacher focused storytelling is also self-teacher education. Without teacher modeled instruction, research, and development of the story, students have little example or guidance on how to construct their own story as it relates to the biology topic and will gain little from the storytelling experience in regards to the complexity of biological systems, which is the function of teacher developed graphic novels, stories, and storytelling, furthermore, the storytelling outlined in my BioSTEAM products are themselves, visually animated lectures, which offer impromptu question and answer and examples to teachers and students. Again, this focuses on teacher skill development and delivery. Consistent with this approach in BioSTEAM are the graphic novels generated from various topics like the microbiome, mitochondria, apoptosis, and epigenetics to name a few. Lastly, the storytelling of BioSTEAM is meant to inspire students and engage them in the content, which can take place in lab, lecture, outdoors, or exhibition space. Overlapping narratives, cutting edge research and deep questions about biological systems are woven into the text and drawings. Through these teacher-initiated activities students not only witness the creation of story but experience the content of biology and this is a foundation upon which they can develop their own skills and creativity further. It is also a foundation where teachers can deepen their skills and knowledge.

In the journal *Leonardo,* authors (160) introduce the similar argument that STEAM is in some ways confusing. According to Henriksen and Mishra: "*The term "STEAM" may leave educators struggling with open-ended possibilities, or they may wonder how to integrate art into science if they have no arts background (or vice versa)* (160)." They present this argument and go on to discuss how focusing on one aspect of the arts is limiting. They also discuss how the modern curriculum in institutionalized learning is perhaps too rigid to accept the creativity necessary to experience STEAM integration at its fullest. This is a very important point, if institutions are too rigid in their policies and curriculums, the development and execution of new and creative ideas is highly unlikely. The authors preface their article ideas by taking a broad linguistic perspective. They mention multiple science domains and introduce the idea of the metaphor. They also mention the biological domain by giving examples of metaphors, such as "*examples include seeing the heart as a pump, or viewing energy conservation as akin to balancing account books or considering DNA as the "code of life" to be "translated" into building proteins* (160)." They provide some nice visual metaphors of the chiasmata in meiosis and crossing over and a mandala- like illustration representing complexity, self-organization, and evolving networks of living systems. The article provides insight into the use of metaphors, their importance, and even an example or two, but it does not say how to introduce these metaphors or the linguistic dimension into the biology classroom and there is no teacher skill development aspect to the article. While it provides a few examples from the art world, it also makes no mention of the use of metaphor throughout the history of biology, which my BioSTEAM model does.

BioSTEAM recognizes the importance of analyzing the historical metaphors of biology that have shaped our biological thinking today. The five case studies of this thesis trace where metaphors for stem cells, chromosomes and individuals, the phylogenetic tree, the “microscope as eyes,” and the vast vocabulary of the neuron metaphor used by Cajal come from. BioSTEAM not only explores their origins but traces those origins to the nature experiences, drawings, and experiments of these individuals. The BioSTEAM framework suggests that metaphors are a domain that emerges upon exposure to nature, a close bond with it, and observation from it. The incorporation of the naturalist’s experience and the drawing are therefore essential to the development of the linguistic dimension and are an inherent quality of the bio-art synthesis and, therefore, an inherent property of the BioSTEAM framework. Other aspects of the linguistic domain, such as science fiction writing, are not sufficiently explored in the literature to be mentioned. However, BioSTEAM, through the storytelling genre, based on actual research, includes the development of fictional foundations in which to couch the biological content and explore it further, not just verbally but visually. This is not found in any other framework to my knowledge.

Lastly, philosophical research has been conducted to explore the historical nature and the aesthetic dimension of people like Santiago Ramon Cajal, Leonardo DaVinci, Ernst Haeckel, Theodore Boveri, and Linus Pauling. DaVinci’s life, in particular, has produced copious amounts of literature, in which his notebooks are examined in great detail. The articles by Erna Fiorentini are extensively focused on the artist-scientists like Cajal and his visual perspective. Cajal’s visual perspective is explored in-depth, and his philosophical mindset is presented in several papers offering insight into his images (145). In many, if not all of these cases, history does not go beyond history or philosophy, and it does not translate into an applicable practice to a biology curriculum. While Fiorentini and other writers have provided wonderful insight into these historical practices, none of these authors have dissected the actual art on paper, to my knowledge, to establish a potentially teachable model, and that was perhaps not their intent. BioSTEAM is unique in that it considers and values these perspectives of the historical, biological polymath and has further developed the historical practices, perspectives, and insights into a teachable framework. The literature on the history is extensive and cannot be fully explored in this work, and may in the future inform more teachable practices in the BioSTEAM framework, which align with biological synthesis.

In conclusion, the BioSTEAM model and the drawing heuristic possess deeply intertwined biological and artistic practices that converge on each other, enhance each other, and reflect both nature and the nature of human learning. Therefore, the art and the science of the past cannot be clearly separated. The teacher-driven synthesis experiences are unique to this work and supported by biology's rich past of an art-science fusion, which brought modern biological disciplines into existence today. Since both science and art are cultural constructs when taken from a historical perspective, they reveal a methodology that is adjustable and applicable in today's biology classroom environments, and they may alter the course of the biology class of the future.

3.6 BioSTEAM lesson plans implementing the Drawing Heuristic

I have developed and described four applications of the drawing heuristic within its larger framework of BioSTEAM, which are the basis of this thesis. They are published in four articles in the *American Biology Teacher* journal. These articles are summarized below, with attention to the unique and novel characteristics and specific skill development that define BioSTEAM as it relates to the topic of evolution. The drawing heuristic and the BioSTEAM framework were tested in the methods section of this work and are a similar version of the drawing heuristic and the concepts presented in the four articles. However, they are not identical. Rather they are variations and examples of BioSTEAM's adaptability to a biological domain for teaching.

In each article's description, components of the drawing heuristic and BioSTEAM that make it a novel framework are highlighted. Continuity and the thread of the historical framework that informed the drawing heuristic and BioSTEAM framework can be seen in the progression of each work and underscores its applicability to any biology domain. The articles are primarily designed for biology educators, although the drawing heuristic/BioSTEAM framework can be used by teachers, students, and researchers. Each article is unique and the illustrations created underscore the importance of biology teacher education in the area of the drawing heuristic. The papers also reflect the idea of the "visual argument" or "visual hypothesis," presented in Linus Pauling's published works on antigens and antibody interactions (see section 2.5). Therefore, the article designs are novel designs, where the teacher develops and creates their own discovery-based illustrations in relationship with the text. This writing style and illustration are also reflective of the historical work where scientists illustrated their own work. In these articles, the visual illustrations functioned in an experimental, investigative window into teaching evolution for the author and as a sample product of that teaching with the drawing heuristic. The images are narrative, metaphoric, and hypothetical, and this also underscores the BioSTEAM initiative and its inherently synthesis-based nature. General BioSTEAM Model Features covered in the above articles:

1. Teacher centered
2. Historically based
3. Bio-drawing skill development (drawing heuristic) (flexible for all sub-disinclines of biology)
4. Bio-drawing skill is transferable and measurable
5. Lessons move from scripted to non-scripted mirroring nonlinear, irregular time frames
6. Dynamic lectures reflect movement and dynamics in living systems
7. Contemplative experiences with biology
8. Authentic interdisciplinary synthesis
9. Biophilia enhancing
10. Measurable from teacher skill to student learning
11. Bio drawing skill is domain-specific
12. Authentic synthesis with biology teacher extending and developing original lesson plans
13. Authentic innovation and skill-based discovery processes that are measurable back to the original skill set and accompanying environment

14. Students become active participants and learners in the classroom, simultaneously acquiring bio-drawing skills and associated biological concepts and content

15. Increased skill in examining and generating visualizations

16. Developed by a biology teacher and biological artist

3.6.1 Time Travel and the Naturalist's Notebook

I have developed a lesson plan that introduced a scientist who was also an artist and a fiction writer, Vladimir Nabokov (161). Nabokov's life work with the blue butterfly (*Plebejus melissa*) becomes the mechanism by which biology teachers could introduce evolutionary concepts such as speciation along with the drawing heuristic within the framework of BioSTEAM. The specific expertise and proficiencies of the historical practice were created as a major component of the lesson plan by examining Nabokov's drawing methods. In Vladimir Nabokov's work, we see how the historic bio-drawing (heuristic) experience becomes Nabokov's drawing discovery process, and, in this article, an almost exact discovery process for students is outlined. Through the teacher's example, students will experience the heuristic of creating illustrations of butterfly traits and morphological characters on notecards, just as Nabokov did.

A chalkboard composite introductory drawing is given as an example for teachers to follow in their own chalkboard drawing presentation, thus initiating the BioSTEAM framework and demonstrating their mastery of a skill they expect students to develop. The chalkboard sample drawing is in a compositional format that creates a narrative environment for the teacher to ad-lib and builds a story of evolution through Nabokov, our artist/scientist example. In the chalkboard image, major areas of Nabokov's work are illustrated for the teacher to copy. Each smaller component of the chalkboard drawing is a mini evolutionary lesson to be told as a story. Taken together, they introduce multiple concepts in a single chalkboard layout. This generates a more innovative classroom experience and lecture and deviates from the standard PowerPoint presentations by introducing specifically tailored, hand-drawn innovative visualizations and a narrative style of lecture. This format provides immediate discussion, feedback, and a strong sense of originality. Storytelling becomes unique to each teacher and for each topic. Teachers become the storyteller through the illustrated backdrop they create, including images of Nabokov, biogeography, morphological characters, wing variation, and a phylogenetic tree.

A storytelling approach introduces Nabokov's life as a writer, illustrator, and lepidopterist, which provides background and a historical timeline. Then students recreate through their teacher's examples (provided and developed by the author) the actual note card process employed by Nabokov, with a detailed illustration of butterfly wings on the 3 x 5 cards or cardstock, mimicking the process whereby Nabokov compositionally rearranged his card drawings to detect patterns of variation and change in wings and reproductive anatomy, leading him into the direction of his hypothesis about blue butterfly evolution. Students are asked to take the point of view of "becoming" Vladimir Nabokov, attempting his methods and shadowing his life. The final component is computational and provides an opportunity for teachers and students to explore divergence times of butterfly species through the Timetree of life. Nabokov's hypothesis of the Polymmatus blue butterflies emerges through the drawing heuristic activity, while Nabokov's vision of the blue butterflies arriving in the New world through Asia over millions of years is confirmed by molecular methods in the present.

Moreover, at this point, teachers can introduce those modern methods and continue the narrative. Timetree serves to move the morphological descriptive art process into the computational perspective, giving students an easy introduction to using the software and some of the taxonomic terms behind it. In this work, students, through their teacher's demonstration, experience the following:

1. Synthesis as it was developed by an actual artist-scientist and writer
2. A slowed-down morphologically descriptive experience
3. Focus on not only species differences, but differences in morphological characters, and further variation within those characters
4. A focus on the natural world
5. Broad biogeographical views through art process and geological time scales (Nabokov's hypothesis)

6. Focused details of variation and development of bio-drawing skills associated with detailed observations
7. An appreciation of the role of fictional writing in the forming of hypotheses
8. A modern sequence-based computational experience that provides divergence times and geological time scales (understanding of the current sequence methods that confirmed Nabokov's predictions)
9. Extended discussions include migration patterns, loss of biodiversity, and even sequence alignment software to create phylogenetic trees of butterfly species.
10. Multiple perspectives, specifically developed bio-drawing skills, and creative writing around and about nature and evolution underscore proficiencies that educators should embrace to adequately appreciate and understand their student's drawings and synthesis of art skills and science process.

3.6.2 Adventures in Evolution: Trundlers in Time

In this article, I use a popular invertebrate, the Tardigrades, who were at one time "unclassified" in taxonomy and are still somewhat unresolved today (162). These interesting animals provided a sense of mystery and adventure. Because of their extremophile characteristics, Tardigrades have become somewhat of a cult organism and, therefore, make a unique experience for teachers to develop bio-art drawing skills around. The discovery of their existence goes back over two hundred years. Although biochemically complex, their underlying drawing scaffold is simple, and therefore, they make a good fit for introducing the drawing heuristic. This paper focused again on evolutionary topics, such as biogeography, morphological characters, speciation, divergence, variation, and horizontal gene transfer. Other biological topics connected to this include tardigrade anatomy and ecology. A variety of biology domains are explored through the umbrella of evolution. The "art" or BioSTEAM content and skill development again employs or provides opportunities to explore these animals through the drawing heuristic and places the Tardigrada in a storytelling, coloring book venue.

Taken from Theodore Boveri's use of chromosomes as "individuals" and organisms as "historical," tardigrades are given a name and seen as an organism with a persona. This anthropomorphic perspective is often viewed negatively. However, it is through the similarities to ourselves that we relate to other living things. Instructions on how to draw a "Tardigrade" chalkboard or whiteboard are given in the workbook, and so the workbook is for both teachers and students. Presumably, they will be experienced by the teacher first, and the skills presented from the teacher according to their own time frames and class formats. These articles are intended lesson plans on evolution; however, they can be delivered in other content areas such as invertebrates. They can also be combined with wet labs and encourage microscope use. I decreased the difficulty of the drawing heuristic in this work by creating the coloring book, which provides solid support for teachers, who, in most cases, have no training in the artistic areas but who wish to employ the arts or STEAM. In the storybook/coloring book, a "how to draw microscopic morphological features" also encourages teachers to learn how to draw tardigrades so that they can distinguish different morphological features such as claws or siphons.

Teachers take students through the story and the other bio-drawing experiences in the workbook, as well as some natural history. This finally culminates in an experience with the Timetree of life. By using the computational skill last, we not only follow the historical progression from natural history and bio- drawing and microscopy to current technologies, but we also build a tangible, bio-drawing experience that solidifies the organism within an eco-evolutionary perspective, which examines the concept of a niche. In this experiential progression, a teacher drawing heuristic flows to students who have become personally acquainted with tardigrades and can explore them further in the abstracted computational realm. Having multiple perspectives, skills (natural history drawing and computational exercises), and experiences may assist in accepting and understanding the evolutionary process. In this work, students, through their teacher's demonstration, experience the following:

1. Synthesis through storytelling, drawing heuristic, metaphor, and humor
2. A slowed-down morphologically descriptive experience
3. Focus on not only species differences, but differences in morphological characters, and further variation within those characters
4. A focus on the natural world
5. Broad biogeographical views through art process and geological time scales
6. Focused details of variation and development of bio-drawing skills associated with detailed observations of tardigrades

7. An appreciation of the role of storytelling in following an organism in its habitat
8. A modern sequence-based computational experience that provides divergence times and geological time scales (understanding of the current sequence methods that confirmed Nabokov's predictions)
9. Extending discussions that may include HGT, speciation, and even the use of MEGA software to create phylogenetic trees of tardigrades and their unresolved close relatives
10. These multiple perspectives, specifically developed bio-drawing skills, storytelling around and about nature and evolution, underscore proficiencies that educators should embrace to adequately appreciate and understand their students' drawings and synthesis of art skills and science process.

3.6.3. Molecular Memories of a Cambrian Fossil

In this article, the focus was a specific time period, the Cambrian explosion, which provides a large geological time frame, theater-like experience with a fascinating array of animals, and the "burst" of segmentation, adaptations, and novel structures, such as the compound eye (163) This allows for exploring the regulatory genome, hox genes, evolution of predator/prey relationships, and their associated structural changes and variations in vision, coloration, and co-evolving adaptations. This subject introduces the property of flexibility and expansion in a BioSTEAM lesson plan; that is, it can easily branch into other biological areas, from ecological to molecular, introducing connectivity in a truly interdisciplinary way via the drawing heuristic. For example, with the large Cambrian art image, all of the above topics can be introduced and illustrated to create the feeling of evolution, interdependency, and change, which underscores biological behavior. The same can be said of a gene. If the teacher illustrates the gene or many genes (such as Hox genes), the idea that they interact and communicate with each other in a network-like way automatically becomes apparent. This is very different from an isolated view of a gene as a genomic element out of context that exerts some control on something, and so, the Cambrian explosion is also a setting for introducing the gene, if so desired. In this work, I also wanted to utilize the drawing heuristic in another tangible and frequently used practice;

paleontological drawing. Fossils would be useful for this, but even pictures of the fossils can serve the purpose. Through drawing from a fossil into a living hypothesis, students may come to appreciate the reconstruction of the past as they focus on structures that may seem similar to structures today. The unusual animals provide insight into present-day adaptations and set the "stage" for storytelling and metaphor. I also had a whiteboard composition of a reconstructed Cambrian environment, but it did not appear in the article. I wanted to include a larger image of the Cambrian artwork, but images were limited. It is, however, visible in the corner of the first page.

Providing original artwork that synthesizes complex biological topics can be inspirational to teachers and students. Teachers themselves are encouraged to create some of the materials for this lesson and draw the animals of the Cambrian and modern arthropods. A rule borrowed from phylogenetic tree building, the parsimony principle, is introduced into the drawing heuristic. I saw a similar pattern in the drawing heuristic in my exposure to computational methods for making trees. Since teachers and students will be applying the drawing heuristic to reconstruct a living version of a Cambrian animal from fossil evidence, the fewest drawings method may be applied. In this way, students and teachers do not deviate from their observations but rather select the visual "facts" to construct the drawing. Often, non-artists include items they are not observing and go off the visual path in an attempt to make a more elaborate drawing, but this does not necessarily make the drawing "better," it simply becomes less descriptive.

To achieve a realistic depiction, there are many steps and transitions in a drawing. As the artist, you want to limit these steps but execute them solidly to produce an image that captures the visual facts and the biological essence. Along with these steps, students would produce multiple drawings and choose the one that best fits the fossil. This is based on experience with extrapolating and extruding three-dimensional shapes, which is essential for understanding fossils and slides. In this lesson, today's arthropods are also illustrated and compared against those of the Cambrian, and a comparison of similar features is recorded. Through visual recognition and understanding of animal appendages and segmentation, students learn to differentiate and focus on observations. The final culminating piece is using the Timetree of life to "play" with divergence times.

1. Synthesis through the broad narrative of the Cambrian explosion, drawing heuristic, and metaphor
2. A slowed-down morphologically descriptive experience
3. Focus on not only species differences, but differences in morphological characters, comparisons of features from extinct ancestors and living animals
4. A focus on the natural world
5. Broad biogeographical views through art process and geological time scales
6. Focused details of variation and development of bio-drawing skills associated with detailed observations of the animal phylum
7. A modern sequence-based computational experience that provides divergence times and geological time scales to put animal evolution in perspective
8. Extending discussions that may include food web and eco-evolutionary relationships
9. Multiple perspectives and flexibility of lesson plans that are teacher-centered and focused

3.6.4 How to Build a Super Predator: From Genotype to Phenotype

In this article, through the charismatic Pleistocene animal, saber-toothed cats, teachers can develop their bio-drawing skills around cat anatomy with a focus on precision-biting adaptations, dentition, jaw, and face changes that lead to the apex predator's success through time and evolution of a powerful bite force (164). The story of the saber-toothed cats and the modern feline makes for interesting questions and hypotheses about the origins of today's cats and their amazing predatory skills. Teachers develop their drawing and presentation skills by observing variation in smaller cats and larger cats and are encouraged to observe and draw cats, make sketches, and become familiar with sketching and sketching living things in motion. The important BioSTEAM activity of developing a comic book character also employs imagination and exploring the dynamics of transitional forms through the storyboard. The storyboard is an excellent organizational framework for the transitional changes in morphology and can be created alongside protein and nucleotide investigations. Specific changes in morphology can be introduced through this method and created with evolution-based topics such as tetrapod limb evolution and evolution of the inner ear in vertebrates. While this article looked at large phenotypic traits like ears, tails, coat color, its other focus was to introduce protein evolution. The large anatomical traits are contrasted with the protein myosin, which is introduced through a drawing presented in work. This moves into a discussion on how computer software and genes can build phylogenetic trees of extant organisms.

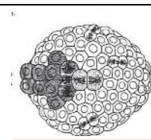
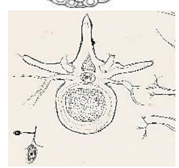
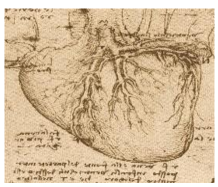
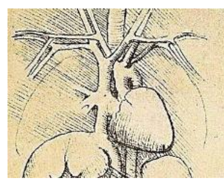
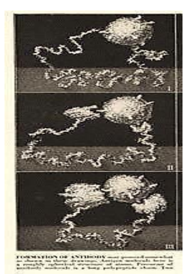
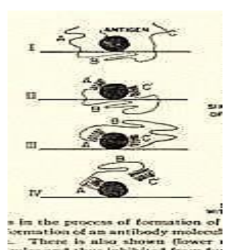
The concept of genotype to phenotype is another difficult and complex topic to develop in introductory biology. So, the genotype-phenotype question serves as a platform for our building of the super predator, which carries us into the world of protein evolution. For most teachers, the terms genotype and phenotype are not explored beyond their definitions, and the drawing heuristic would assist in visualizing their deeper meaning. My purpose in this area of genetics and evolution was to have teachers visualize the genotype-phenotype question through the broader environment- adaptation idea and the concept of genomic plasticity. To facilitate teacher drawing, I provided a "prototypical" predator that could be "morphed" through drawing into a predator that is best suited for its current environment. These combined concepts are also linked to ecological networks in nature through a systems model of biological plasticity. Students and teachers explore drawing skills to flesh out the future of a predator while engaging with the computational software MEGA, which introduces students and teachers to nucleotide changes in the protein myosin. Students are not expected to use MEGA but can actually storyboard the use of MEGA. In this way, the storyboard also serves as an organizational framework for understanding a computational program's functions and creates a sense of familiarity with the software. Along with a computational investigation into the myosin family of genes, teachers are encouraged to draw the protein's shape and explore the isoforms of it, bridging the computational experience to the bio-drawing experience and the molecular realm.

1. Synthesis through the broad narrative of the Pleistocene, drawing heuristic, comic books, storyboards, and imagination
2. A slowed-down morphologically and molecular descriptive experience
3. Focus on not only species differences, but differences in morphological characters, comparisons of features from extinct ancestors and living animals
4. A focus on the natural world

5. Broad biogeographical views through art process and geological time scales
6. Focused details of variation and development of bio-drawing skills associated with detailed observations of the animal phylum
7. A modern sequence-based computational experience that provides divergence times, sequence alignments, phylogenetic trees, and geological time scales to put animal evolution in perspective and show relationships
8. Extending discussions that may include food web and eco-evolutionary relationships
9. Multiple perspectives and flexibility of lesson plans that are teacher-centered and focused

3.7 Tables and figures

Table 1. Rubric of Historical Scientific-Drawing Synthesis Skills. This visual guide table summarizes the art technique, its simpler form or schematic, and the possible questions and line of inquiry that scientist-artists may consider from the drawings they make.

Artist/Scientist	"Art" created (detailed replication with the aesthetic dimension"	Schematic with essential characteristics and elements	Concepts emerging	Questions
Theodore Boveri			Drawing detailed realism and moving to a schematic	Can we learn the different processes in black and white vs. color?
Santiago Ramon Cajal			Perspective and perception of observed phenomena (where and how the observer is positioned, point of view, entire structure/part of a structure)	Does a detailed drawing increase observation? Does a schematic enhance the important features?
Leonardo DaVinci			Rotation, Transparency, and Transverse section. This includes foregrounds and backgrounds	Does the point of view or perspective change the way we depict or analyze an observed phenomenon?
Earnest Haeckel			Multiple concepts conveyed using many specimens. These specimens are averaged into an "ideal" drawing	Does drawing multiple versions and exploring variation in an organism form help derive an understanding of implied movement
Linus Pauling			Animated, storyboarded, action and process, creating an analysis of isolated interaction	Does storyboarding using frames to imply motion reveal functionality?

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https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2845060/
http://scarc.library.oregonstate.edu/coll/pauling/proteins/pictures/sci7.001.5-drawing.html

Table 2. Assessment Rubric for historically based scientific-drawing synthesis skills. To be used as self-evaluation for teachers or for student evaluations.

Drawing Elements	**Poor (1)**	**Below Average (2)**	**Average (3)**	**Good (4)**	**Excellent (5)**	**Present/Absent +/-**
Sketches (visual observations)						
Geometry (fundamental forms)						
Transparency (light qualities)						
Rotation (3-D properties) reveals the true shape						
Transverse Section (anatomical visual-spatial)						
Natural Variation (present and represented						
Forces identified (stages of change due to growth, decay, disease)						
Inferred function of identified morphological characters						
Inferred continuation/evolution/change						

Table 3. BioSTEAM vs STEAM Literature. Some literature examples distinguishing BioSTEAM and STEAM characteristics

BioSTEAM	STEAM	Literature Sample
Drawing heuristic, biology content, and biological qualities and drawing merge in an active synthesis.	Drawing but without a specific skill set for the biology of synthesis. Not modeled by teacher in context with content.	Quillin K, Thomas S. (2015). Ezin M, Noravian C, Mahomed A, Lyle A, Gill A, Elul T. (2020).
The teacher presents a live demonstration, live question and answer, visually executed. Uses DaVinci's principles	Some models suggest teacher skill sets but few details and no historical background.	Pears A, Barendsen E, Dagienė V, Dolgopolovas V, Jasutė E. (2019).
Historically based, developed, constructed, and consistent with biological discovery and art process from which authentic art/science skills emerge.	Historical context from the "romantic period" but no teachable skill sets generated	Hadzigeorgiou Y, Schulz R. (2014).
Includes storyboarding to develop ideas that develop drawing skills simultaneously with storyboarding specific to biological dynamics and processes, traditional animation techniques.	Focus on cartoons and comic books, but no procedure on producing them or foundation of drawing animation skills.	Rule AC, Sallis DA, Donaldson JA. (2008)
Biology content conveyed through storytelling (along with live drawing) Student engagement through biological narrative.	Introduces storytelling through the computer. Not modeled through the teacher. Domain-specific, but this is not often the case.	Dutta S, Eswaran S, Sanelli A, Bhattacharya M, Tempsick R. (2018).
It takes the naturalist's approach, focuses on nature's processes, emersion in nature, and the aesthetic dimension as part of educational experience. Teachers build art/biology portfolios and can provide examples.	Nature and wilderness presented in opinions without integrated experiences with drawing from nature. No teacher modeling of aesthetic relationships in art and nature.	Başaran M, Erol M. (2021).
Environment and classroom focus with exhibition space, biological art, culturally diverse art, ancient & traditional cultural views of nature (mandalas, textiles, scrolls, stone, sand art).	Scattered genres of art forms introduced in STEM, primarily for lower grades (K-6). Not necessarily incorporated into learning spaces or biology-specific use of diverse traditional non-Western art forms.	Stankiewicz MA, Krug DH. (1997). Hunter-Doniger T, Howard C, Harris R, Hall C. (2008).
Develops metaphors from the subject. Focus on creative writing (poetry, fiction, Haiku, etc.) specific to biology	Introduces writing, uses some metaphors but not domain-specific and not teacher modeled.	Henriksen D, Mishra P. (2020).

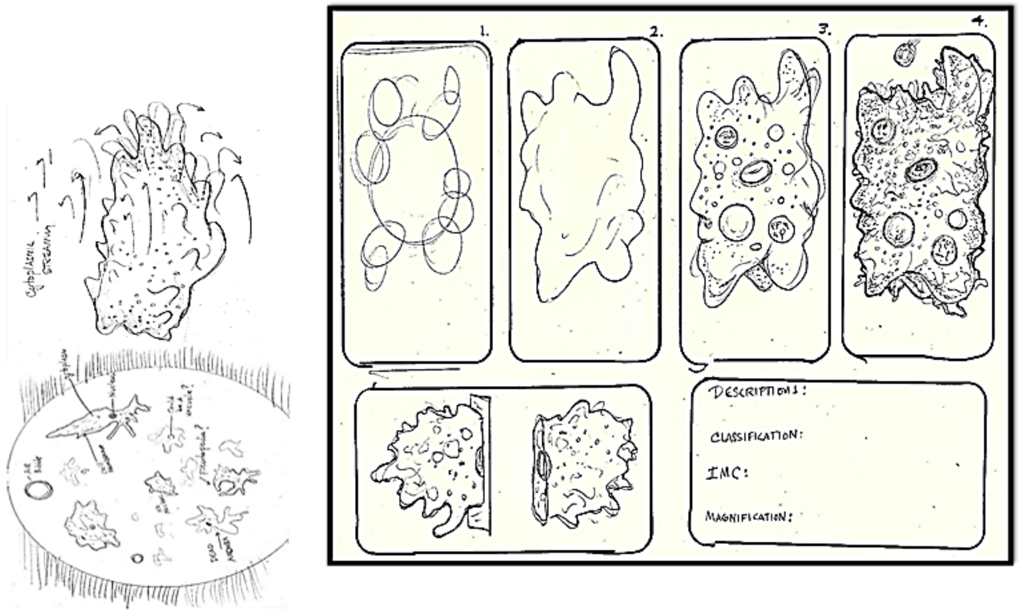
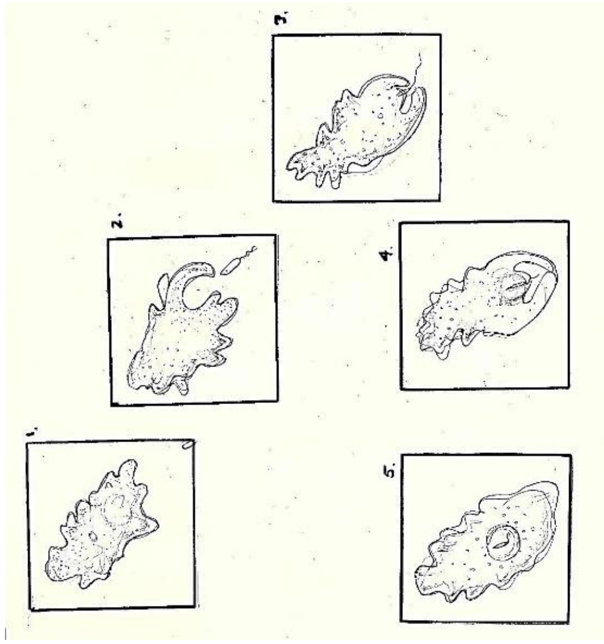


Figure 15. Storyboarded Amoeba I. Visual storyboarded rubric for students to emulate. These images show multiple aspects of the organism, the ameba's shape, movement, structure, and spatial sections. Students will draw pseudopodia and the ameba in relation to other organisms in pond water.



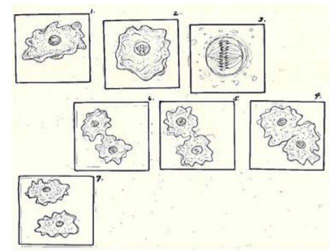


Figure 16. Storyboarded Amoeba II. Drawings of storyboarding amoeba in motion. This is a process that students would observe under the microscope and follow as the teacher drew these animated steps on the board.

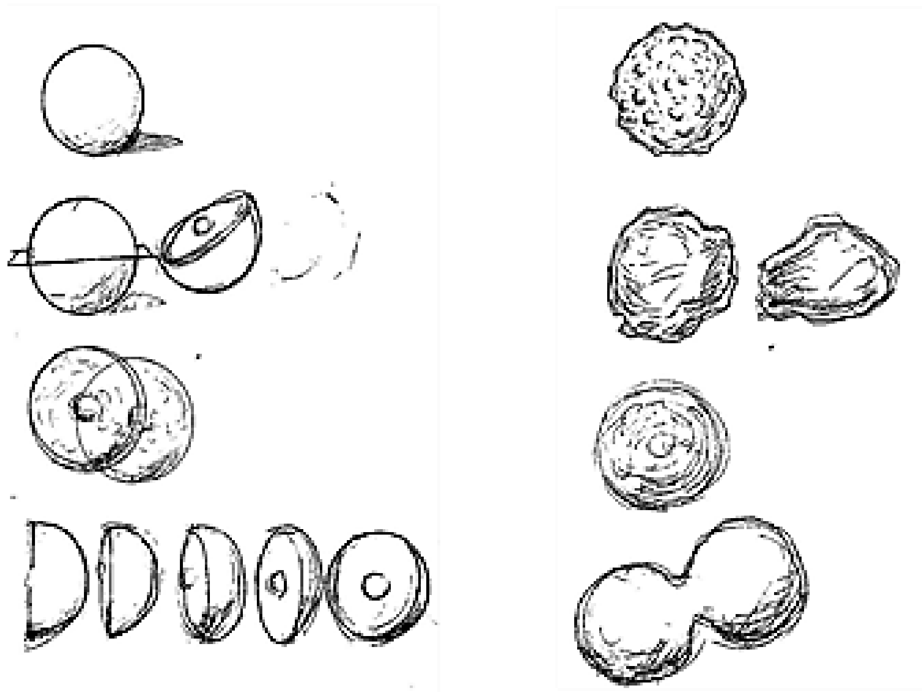


Figure 17. DaVinci's Treaties Simplified. A simple visual assessment student would attempt to draw to understand transparency, rotation, and transverse section.

Figure 18. Biological Notebooks & Exhibitions for BioSTEAM. A sample page of a scrapbook or biology notebook with embellishments students can create for fun and to enhance their learning style. Below the idealized exhibition, art environment students would have had access to and lecture to complete and inspire their work.

CHAPTER 4: EVALUATING ART IN BIOLOGY TEACHING

4.1 Introduction

The purpose of this study was to examine how the art strategy of the drawing heuristic, utilized historically to make discoveries in the life sciences, implemented in two biology courses, would affect or facilitate an understanding of biological and evolutionary concepts in first and second-year biology tracked students. The practices employed decades and centuries ago worked concomitantly with scientific investigations into Nature to facilitate a deep understanding of living systems. The artistic component became a synthesis or discovery protocol for students pursuing a biology track. This work consisted of assessing the past, synthesizing a new teaching method for discovery using the arts and classical drawing. My dissertation sought to develop a synthesis of the processes of drawing/art skills and biology to answer the following questions: Does the art/drawing discovery process increase practicum scores for a basic biology lab? Does the instructor's art/drawing discovery process motivate interest in a basic biology lab?

No such methodology exists for testing the unified and demonstrable concepts of drawing discovery that existed in the past. Therefore, I developed a general protocol and adjusted the protocol's original design to fit the current teaching model and the specific courses involved in this research. My thesis relied on the data accrued from available courses at Temple University for me to teach. I created the teaching materials for all the courses and study materials for students utilized in this study. Following Temple University’s Institutional Review Board guidelines and course syllabi, I significantly adjusted the protocol to those courses' conditions and content. I administered the protocol developed for three sets of course lessons/curriculums over two semesters. I administered the methodology twice to Biology 1111 lab (Spring 2019 and Fall 2019) and once to Biology 3112 lab (Spring 2019).

These courses presented different implementation challenges, requiring different strategies for developing and administering the Bio-Art Drawing Heuristic or discovery model. Since no such model or a model of this merged synthesis exists in the literature, this was a completely novel undertaking. This made the choice of research design difficult.

I decided to use the simplest strategy of a 2-group experimental design and a modified Likert scale survey. Because the purpose of this study was to examine the model and the process, a quantitative and qualitative approach were the most appropriate choices. These strategies and/or methods are presented below.

4.2 Evaluating art in Biology 1111 lab teaching

4.2.1 Overview

To assess and modify the Drawing heuristic, I had to consider the format, structure, and environment of the biology lab and the content I was addressing. The Biology 1111 lab is an organismic-based lab course with an overarching theme of evolution and morphology. Students are exposed to a wide range of organisms, traditionally organized in a five-Kingdoms concept but with current classifications and taxonomy of three domains. Students are expected to draw approximately 40 drawings for the course, which are primarily microscopic. They are presented with phylogenetic relationships from the beginning of the course, with the most inclusive three-domain tree drawn on the chalkboard on the first day of class. Students are not required to do drawings for anatomy or gross anatomical structures, only microscope drawings. Students also follow the rule of placing several drawings on one page and not using a circle to frame the image but draw them without boundaries. There is no grade for drawing skill, although two sets of drawings are completed for the course. I took this opportunity to focus on the microscopic drawings introducing students to the drawing heuristic model in the live demonstration drawings.

I also used this opportunity to focus their attention on the biological qualities of living things as they would normally appear versus the changes in their biological properties once the specimens had been prepared on the slide. This live storyboarded transitional drawing demonstration from living to nonliving, sectioned, stained, and altered may enable students to identify and differentiate one organism and its internal structure from another. It may also enable students to recognize the variability of structure and form between individuals and species, which assists in conceptualizing morphological characters and their variation. This is important because phylogenetic trees are also part of this lab. The first half of the course was almost entirely focused on microscopic specimens. The second half of the course was more focused on gross anatomical features of specimens, of which I continued to draw but not as effectively due to limited space and time.

4.2.2 Hypothesis

My research question was: "Does the art/drawing discovery process or the drawing heuristic of the BioSTEAM framework increase practicum scores for a basic biology lab?" The null hypothesis was that the art discovery or "drawing heuristic" strategy developed for this study had no impact on students' performance. To test the null hypothesis, I designed a case-control experiment and conducted statistical tests (see *Method and Materials*). Naturally, I hoped that the art strategies would help engage students and have a positive experience with the drawing heuristic/discovery model. I also hoped that the experimental class would have an overall higher score than the control group. Of course, the primary focus was on testing the null hypothesis of no effect.

4.2.3 Method and materials

4.2.3.1 Participants

Participants were students who had registered for Biology 1111 lab in Spring 2019 and Fall 2019 semesters. They were freshman and sophomores on the biology track. For most of the students, it would be their first biology course since high school. I taught three lab sections in the Spring 2019 semester and two sections in the Fall 2019 semester for the Biology 1111 lab. Each semester, I randomly selected one section as the experimental group to receive the treatment (i.e., Art-Bio teaching) at the beginning of the semester. The rest of the sessions were control groups that received the traditional teaching strategy. I did not favor a certain group of students over another. Only students who had given consent were included in the study, none of the students declined in the experimental sections, and so all registered students participated.

4.2.3.2 Treatment

Making strong observations through drawing can help stimulate question formation, and the Next Generation Science Standards call for students to generate and investigate questions about the phenomenon. However, they do not provide a well-rounded experience for students at the college level, nor do they include any definable standards for drawing biological systems, which are inherently different from just "drawing." The literature also calls for strategies to help students ask questions, which I intended to do through artistic narrative and which is an inherent design of a biologically based drawing discovery process. The art strategy for this study would have incorporated drawing and painting into some outdoor science instruction to engage students in observing, noticing details, asking questions, and making relevant connections between what is being drawn on the page and what is observed in Nature (165). The strategy I used instead was to navigate the already existing course work of Biology 1111 lab and insert a biology-based drawing experience wherever I could. This drawing-based drawing synthesis (drawing heuristic) was to be the extracted skill set of the five case studies. I would be considering types of drawing genres from each artist-scientist as well as their literary contributions. This involved deconstructing the original drawings, that is, drawing and re-drawing experimentally related illustrations from the five case studies and evaluating their potential for a classroom delivery method. This process resulted in the drawing heuristic.

To infuse other elements into the teaching experience that were clearly part of the historical framework, I featured organisms in story-like discussions so students could get a better picture of their complex and intertwined lives (naturalist's approach). I spoke about the beauty (aesthetic dimension) of these living groups of organisms from an evolutionary framework (e.g., mimicry) and in an individual way (anthropomorphic). Along with this method, I selected videos that showcased particular organisms in their natural environments and followed this up with the drawing activity. While this had garnished some attention by students, I noticed that focus was scattered, and a more complete idea about the organisms could be augmented through a workbook.

Because I had taught Biology 1111 lab previously, I thought that a workbook would be the most inclusive and straightforward way of delivering the drawing heuristic with the limited time frame. I was also inspired to make the workbook because students in the back rows had trouble seeing me draw and were losing focus. I decided to create a BIO 1111 workbook in alignment with course content, following a format similar to that of the syllabus. The workbook that I created specifically for the Biology 1111 course found at this website: https://igem.temple.edu/downloads/MYBIOLOGNOTEBOOKPLANTS.pdf. Along with live demonstrations, the workbook would reinforce the synthesis of biology and drawing and would reflect the exact objectives outlined in the course. I could not offer extra credit or any credit for the workbook and instead relied on students to use it as they saw fit. Since it did contain both drawing exercises and coloring book exercises, I encouraged students to study from and enhance their lab experience. I suggested that the workbook be a contemplative activity, which would be both relaxing and functional. When time permitted or when a question was asked, I also provided step-by-step drawings before and during the lab in the live demonstrations and to individual students, and I offered brief lectures on evolutionary relationships among organisms, including morphological homologies and analogies.

In the first group of students (Spring 2019), I spent 10 minutes before class modeling the drawing of specific content for the lab and encouraging students to use the lab workbook. In my second group (Fall 2019), I still attempted to draw sporadically in class when it was useful and handed out the workbook I created for the course. I presented materials and topics to draw that was also on worksheets, such as the stages of development of the starfish, and discussed how students could focus on the quality, quantity, interactions, and descriptions of their drawings while making observations in the lab from slides and models.

For fourteen weeks, the class received the instruction stated above. I also emphasized difficult concepts such as phylogeny and morphological characters using narrative and drawing simultaneously. However, again this was extremely limited in terms of space (drawing space) and time. Such constraints are real for all attempts to bring "arts" to the science curriculum and standard classrooms. I relied on the historical background-based "rubric of skills" that I had developed from the five case studies to dictate the style of drawing and conceptualizations presented to students to keep the strategy as consistent as possible. The rubric was useful for me in breaking down specific steps and presenting them but was sporadically followed by students taking pictures and focusing more on finding the “right slide,” or topic that would be on the midterm and final practicum. I used all the historical content of the rubric of skills in the class and the workbook for most classes. Occasionally, I would tell students where the historical drawing skill came from, and some students seemed genuinely interested, but there was little time to explain it. Students may have picked up the step-by-step instruction just by the repetition alone, as over time, I was drawing multiple topics the same way. By the middle of the semester, my presentations were becoming more acceptable. That is, the style of drawing-explaining and narrative had become familiar to students, and they expected to come in and see drawings on the board. Some of them came early to copy images down or take pictures (which I tried to discourage) before class. I suspect that most students nowadays do not have teachers present material this way, so the technique initially seemed foreign. I often reminded them of DaVinci’s treaties when transforming a slide back into its whole image to highlight the points of rotation, transparency, and transverse section. A slowed-down approach seemed to help along with repetition.

While the drawing examples I give in this dissertation are based on microorganisms, I also included drawing for fungi, slime molds, plants, invertebrate animals, and vertebrate anatomy and applied the template of skills to all those areas of study. Sometimes I would take the actual specimen, such as the slime mold, and draw it as it appeared to the naked eye. I would then animate the life cycles (plasmodium and amoeboid). I would then zoom in and create a larger drawing of the cell type. I also intended to use the drawing process on the chalkboards to “work out” a visual problem such as the heart's development from a cylinder to four chambers or the mammalian heart’s pulmonary and systemic circuits in a whole heart with overlapping images and from a cross-sectioned diagrammatic heart. I drew slowly and explained the biological process and the drawing process as it was visualized on the board. I encouraged students to draw with me and periodically reminded them to do so, some did, but most were reluctant. As an example, the final lab topic, embryology or development, was created on the board largely before class with the illustration and transformation of the ovum and sperm into the zygote, followed by the morula, blastula, and gastrulation and leading into neurulation, which ultimately led up to a slide they would need to know for the final. When I got to that slide, I used DaVinci's treaties and "visually" prepared it as it may have been prepared from specimen to slide. I did this to accentuate this particular piece of knowledge. The process of fertilization is easy to draw, so some students did attempt it. By coming in and drawing on the board, I could erase parts of the drawing and focus on redrawing a particular section or area, which I often did to answer impromptu questions.

I could also compare and contrast the different types of development like starfish development and fetal pig development and accentuate the characteristics of those images. The formation of the blastopore, some gastrulation events, neurulation, and organogenesis would be redrawn several times **(**Figure 19). As I helped students with microscope viewing and identification, I could see where some had the most trouble, and I would focus on this problem by drawing it isolated and larger on the board. This was done in front of the class before students examining the slides and often after the slides. Students showed a positive reaction to seeing all the artwork, and some commented on how it benefited them but getting them to draw it when it was not for credit was problematic. I continually reminded students how the drawing would help them prepare for identifying specimens in the practicum and how it would benefit their conceptualization process. I also applied the larger BioSTEAM framework of eco-evolutionary storytelling by describing certain dynamics using metaphors to imagine physical and structural changes happening in real-time. This drawing-animation on the board is simply storyboarding without boundaries and is part of the drawing-biology synthesis, and while I drew these images for one class, they were left on the board for the control group. I could not move to a different class for the control groups, which would see the final drawings, some of which I had to draw around material that could not be erased. This was not my material but slide descriptions for all labs. However, the control group would not have the number of experiences of drawing along with the instructor or observing how to draw, including a storytelling narrative, interesting facts about the organisms, and ecological/evolutionary concepts. Ideally, I would have no drawing on the board for my control group, but the labs were back-to-back, and students came to the control class early and took pictures of it, which made erasing it problematic. The control group would also not have access to the workbook, which emphasized the drawing, the concepts, and the entire course in a non-threatening cartoon-like manner.

4.2.3.3 Instruments

The student's art pieces were originally intended as a measurement for evaluating student understanding. However, students did not adhere to or follow the procedure I outlined. Picture taking interrupted almost all activities in the lab and is permitted, which may have contributed to the lack of attention and often defeated the purpose of drawing demonstration with students following along with their drawing activity as I drew. This made the initial rubric that I created for this study essentially useless, and it shows the challenges of instituting a slowed down or contemplative practice in courses where students are primarily focused on grades and using cameras. My designed rubric may have identified major components of the student observations through their drawings had it been used, and these could have been scored. I have included the rubric of skills (Table 1) as a primary example of a bio-art synthesis, a historically based measurement instrument that defines and delineates artistic process. Unfortunately, it and its assessment could not provide further data for this work (see Table 2). One could also conclude that limited time was a factor in students not employing the procedure.

Further, student concern over midterm and final grades played a factor in the lack of attention to non-grade- based experiences. Therefore, ultimately, the performance quizzes and exams became the primary metrics of evaluating the impact of using "arts" in delivering basic biology to students. Essentially, I created the Biology-Art Drawing Heuristic sample with the rubric for the idealized process of a teacher-student driven activity, which would train a biology-drawing synthesis under conditions that allowed for its use. The rubric is designed to teach students or teachers, neither of which I was able to do. However, since I was using it as a teacher, it did serve that purpose.

While I did repeat the processes of the rubric on the board and in the discussion, it would have assisted students who had difficulty in deconstructing biological images, particularly under the microscope, if it had they had employed it. The students did see me, though, as the teacher did it, which meant that it could be effectively used if part of a required grade. This rubric considers DaVinci's treaties and other important criteria for strong observations through drawing practice: consideration of motion and movement, qualities of living vs. fixed or dead organisms, and the extrapolation of a flat slide into an extruded 3-dimensional structure or organism. Generally, student drawings are labeled, and the magnification is given, which is standard practice for everyone taking the lab. However, the observed phenomenon can be perceived in several different ways (20), and this is why student application of the rubric would have given insight into the specific method of the drawing heuristic. This is important because the structure, function, and entire living system are related and are conceptually significant. My method and model required that these facets of a living system are conveyed and replicated in the drawing as informed by historical drawing practice from the five case studies and that its creation is visible. While there are many and varied biological drawing synthesis examples, my rubric criteria were based on DaVinci's principles (rotation, transparency, transverse section), Canal's concept of perspective, Boeri's detailed and schematic illustration, Haeckel's averaged image, and Pauling's sequential cartoon as drawn in real-time. There is much overlap in all of these processes, and that overlap contains storytelling, fictional writing, poetry, metaphors, and animation techniques. It would be very difficult to include all of these in a rubric, so the rubric only serves to deliver the very basic extracted biological drawing processes to students but is augmented considerably by the teacher demonstration and narrative. The rubric, in other words, primarily serves as an assessment tool for teachers and self-assessment by students.

4.2.3.4 Data analysis

Simple statistical techniques were used to tabulate the results for this study. The primary data were analyzed with the average score taken for the entire class and the entire semester for experimental and control groups. Since no criteria exist for teaching and drawing biology in this method, I relied on the historical background and work of the scientists presented in this dissertation to construct the methods and dictate the style of drawing and conceptualizations presented to students. Since I could not use the rubric, I did not score student drawings themselves but included the rubric as an example of a possible assessment tool in the future.

I evaluated students' performance based on their scores in different exams: in-class quizzes, the midterm exam, and the final exam. I pooled observations from two semesters

(Spring 2019 and Fall 2019) to ensure a large enough sample size and improve statistical power in testing my hypothesis. Because effect sizes could not be anticipated and the number of lab courses one is allowed to teach was limited, a bigger study design was not feasible. I removed the students who dropped out of the lab, which resulted in 55 students in the control group and 39 students in the experimental group. I also removed all the in-class assignments from the analyses because they have no discriminatory power, as almost all the students get full points when they participate. Therefore, I used only scores in quizzes, the midterm exam, and the final exam in the analyses. There are nine quizzes (ten points for each quiz), two parts for the midterm exam (30 points for writing and 60 points for practicum), and two parts for the final exam (30 points for writing and 60 points for practicum). So, the full score for a quiz, midterm exam, and final exam is 90 points. I removed scores for quiz #4 in the Spring 2019 labs because it was canceled for one lab section. Fall 2019 labs have scores for all nine quizzes.

I calculated the mean value and standard deviation (SD) of scores for overall performance, quizzes, the midterm exam, and the final exam for control and experimental groups. The overall performance is measured by a score calculated using the sum of scores for quizzes, the midterm exam, and the final exam for each student. I conducted a two-tail *t*-test for the mean values and a two-tail *F*-test for variances to examine whether the difference observed between the control and experimental groups was statistically significant.

To eliminate the impact of outliers, I removed the students with the highest and lowest scores from control and experimental groups in calculating the mean values and SDs. This resulted in the removal of approximately 5% of the data. I also conducted the same statistical tests on the means and variance calculated using no-outlier data and compared the results with ones calculated using the full dataset.

4.2.4 Results

I found that the overall performance of the experimental group was slightly better than the control great when assessed using their mean scores. The experimental group's mean of 63.7 is ~7% greater than the control group's mean of 59.5 (Figure 20a). Although the experimental group received a slightly higher mean score for the overall performance, the difference was not statistically significant at $P < 0.05$. Interestingly, the SD of the overall score was much lower for the experimental group (7.0) than the control group (11.7). This 40.2% difference was statistically significant ($P < 0.05$, Figure 20b). Therefore, while students in the experimental group had more similar overall scores than those in the control group. The significantly lower dispersion of the experimental group scores suggests that the "drawing heuristic" strategy reduces learning inequality among students compared to the non-arts classroom.

I then looked into the mean values and SD in each type of exam (i.e., quizzes, the mid-term, and the final exam) to see whether the overall score pattern is consistent with individual components. There was no significant difference in the performance of experimental and control groups in the in-class quizzes, even though the mean score was higher and SD lower in the experimental group compared to the control group (Figure 4.2c and d). So, while the direction of change was the same as the overall trend, the actual difference was smaller, as the mean was 2.5% higher and SD was 18.2% lower in the experimental group. Therefore, the observed overall difference is not due to better student performance on quizzes administered during the class period that could have been a potential source of bias.

Interestingly, the mean score and SD in the experimental group were significantly different from those in the control group for the four quizzes before the midterm ($P < 0.05$). The mean scores (SD) were 24.9 (6.7) and 28.7 (4.4) for the control and experimental group, respectively. However, the differences were not significant after the mid-term. Therefore, the heuristic drawing strategy seems to have helped students understand the content much more before the midterm than after the midterm. The midterm consisted of mostly microscopic slides representing prokaryotes through plants and fungi. The second half of the lab was largely focused on animals, and there were fewer slides and more dissections. The lab supervisor suggested that students have an easier time with animals. Regardless, I applied the same drawing techniques to both content areas before midterm and after the final.

The midterm exams were the same for all the course sections (including sections not taught by me). Again, the mean score in the experimental group was higher and the SD lower, consistent with the overall pattern (Figure 20e and f). However, only the SD was significantly lower (9.2 vs. 15.1) and statistically significant ($P < 0.05$, Figure 20f). Interestingly, both the mean and SD of scores for students in the experimental group were significantly different from those in the control group in the final exam ($P < 0.05$, Figure 20g and h). Therefore, there is some significant evidence that the introduction of "arts" during teaching helps students.

These patterns are similar to what was observed in the overall performance (Figure 20a and b). It is also worth mentioning that, unlike the quizzes that were created by the lab instructor (me), midterm and final exams were set by the lab coordinator independent of me. Therefore, they can be considered as an external examination of the art heuristic teaching strategy. However, it is possible that outliers caused the observed difference between experimental and control groups. Therefore, to examine the impact of outliers, I removed the students with the highest and lowest scores from the control and experimental groups (approximately removing 5% of data). I found that each exam type's overall performance patterns were very similar to those from the full data (Table 4).

4.2.5 Discussion

Historically, nature drawing and chalkboard biological discussions were used to introduce younger students and lay audiences to the larger world of Nature and biology (27). This teaching strategy and the drawing heuristic developed from the historical figures served as a novel approach towards a new synthesis of the artist-scientists of the past. The skills extracted from the five cases studies needed to operate within the boundaries of the courses, IRB approvals, and the time constraints in introductory biology classrooms, which severely limit the application of an "arts" protocol and the use of the instruments and the collection of various types of data. Some behavioral and physical problems may have affected the delivery of the "arts" treatment, such as many of the blackboards were not visible, students were unable to access the drawings because carts and materials were blocking the chalkboards. The computer obstructed the central chalkboard, and the monitor and students could not see at the back of the room. There was often little or no space to draw on student desktops, and because the chalkboards were so high up, I had to stand on a chair to make drawings periodically. Therefore, the drawing attempts were confined to a small area that students from the middle to the back of the room could not see. These are real classroom constraints, as most contemporary classrooms are not built or designed to accommodate student drawing or teacher visual storytelling. So, my experiments' results may be more relevant to current conditions in the classroom than an alternative situation in which "ideal" conditions for "arts" were created. Some modifications, however, would have made the delivery easier.

I was interested in exploring the questions posed in the framework of ecological/evolutionary narrative through art and nature in the form of an exhibition and a nature walk as these would have tied in with the biological drawing synthesis. They may have further engaged students in the lab and provided another perspective to the drawing experience. I could not create or meet my ideal experimental conditions, which may have impacted the results. This work's qualitative research outcomes in the form of questionaries considered the exploratory and investigative drawing discovery process in biology courses and were meant to help develop an initial understanding of this protocol for future research. Nevertheless, the questionnaires were sporadically completed by students and could not be used in the analysis, which will be useful for the future adopters of this approach.

While I would have liked to see statistically significant improvements in all student performances in the experimental group, it is heartening to see that students in the experimental group consistently received a higher mean score and lower SD in every course component. In all analyses, the SD difference was statistically significant, and the mean score difference was sometimes significantly different, which we find encouraging. In the future, experiments with a larger sample of students will likely reveal more interesting patterns that will likely be statistically significant about how greater engagement with the material through drawing practice can be useful.

That is, students may be more alert to the concepts, drawn to the teacher's lectures, or attracted to the drawings of their lab's content. One could speculate that the drawing heuristic, even without being fully presented, succeeds at stimulating and focusing student attention. When time, space, and rules inhibit fully delivering the focused drawing heuristic, storytelling and drawing even in small quantities is comparatively unique and engaging. Once students become familiar with this method of lecture (which became apparent after several weeks), they may expect to see biology presented in this more visually engaging way and, therefore, feel more comfortable with its processes. The overall increase in scores between control and experimental may be attributed to the following. (a) The method of teaching engages students more effectively with living systems and is active and highly visual, keeping student attention. (b) The drawing treatment may have increased memory or retention of names and terms. (c) The drawing treatment is non-threatening for a highly stressful course. Easing the distress of assimilating large amounts of information through a cartoon-style workbook enables poor test-taking students to remain interested and less discouraged. (d) The drawing treatment may have encouraged the latent skill set of drawing, which students enjoyed. Slight increases in scores for the various components that make up the total scores may also reflect the limited exposure. Would more exposure to the drawing heuristic and its complementary framework of art, nature, and narrative reflect onto greater increases in scores?

The slightly higher mean overall score and significantly lower dispersion of the experimental group scores suggest that the "drawing heuristic" strategy may significantly improve the performance of students who receive low scores in the traditional labs. This may also suggest that some students within a traditional classroom may struggle with math and memorization and may rely more on the visual or the drawing for their learning. Bio 1111 students are required to take upper-level math courses and chemistry along with the biology 1111 course and the drawing element, particularly from the teacher creates a different environment from math or even other science classes. Certain students may not be suited for math but still like biology and struggle with both courses. The drawing and storytelling may have mitigated stressful effects by adding variation to student experiences in learning at a college level, offering another way of approaching their learning and knowledge acquisition. This result also suggests that some students who score lower in exams may benefit from a different biology education style, employing the drawing heuristic.

A reduction on both sides of the distribution of scores causes a decrease in SD. So, one may also say that traditionally high-performing students, who may learn or study more efficiently, performed closer to average in the "arts" class. The lower variance resulted from the experimental group utilizing the artistic method across all levels of competency and studying skills, so the weakest scoring students did better, as did the mid scoring, and high scoring students, shifting the average to better overall scores. This directional shift suggests that students are acquiring a skill set, and the skill set is compressing the inequalities of learning into a more homogenous result. Since most classes use PowerPoint, it takes time to get used to a storytelling/drawing classroom. This may have been reflected in the mean mid-term scores not having significance. If we did a post-test analysis and further removed high-scoring and low-scoring students, mid outliers would be removed, and the distribution would change. In general, the protocol of art allows students to improve their scores, perhaps mitigating any possible impediments or handicaps to learning biology. Not all students succeed with the arts, though, and that art-based curriculum may hinder some normally high performing students, as they may have particular study habits they are used to and successful with and that most likely do not include art, but this would be not easy to establish with our current data as we did not have an identical group of students to test simultaneously to confirm this.

Overall, in this introductory study, the drawing heuristic and the BioSTEAM framework made a small but positive and consistent shift. It may be that only through repeated and larger experimental versus control group investigations a more significant pattern will emerge. This may ultimately also include all outliers, that is, high scoring and low scoring students. A preference or an option for students to take a course with art-based biology and with the administration of a standard exam may ultimately be more informative. Other considerations include a larger sample size. However, drawing instruction is typically done in smaller groups of students and often involves some critique of the entire class's work so that some room modification may be necessary. Drawing lectures need to be consistent throughout course work as they require repetition, particularly with a specific domain such as biology, to create the synthesis. Tracking student progress through courses over a biology curriculum that employs the drawing heuristic may also be revealing.

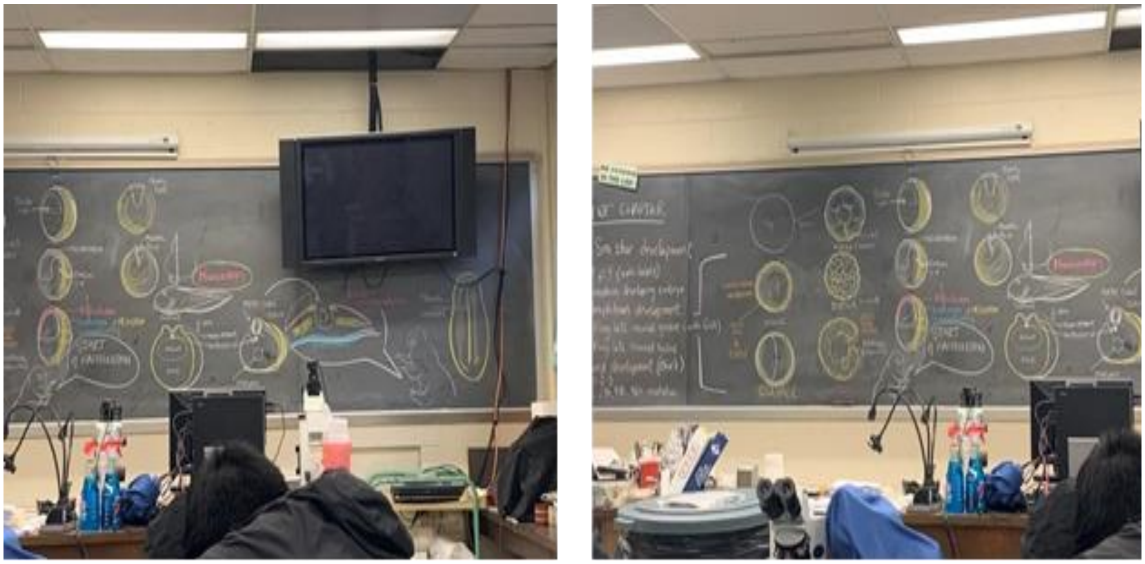


Figure 19. Teacher-Based Live Drawing Demonstration. The Biology 1111 classroom/lab with the weekly drawing presentation in the first 10 minutes of class. Students were asked to draw these images along with the lab instructor.

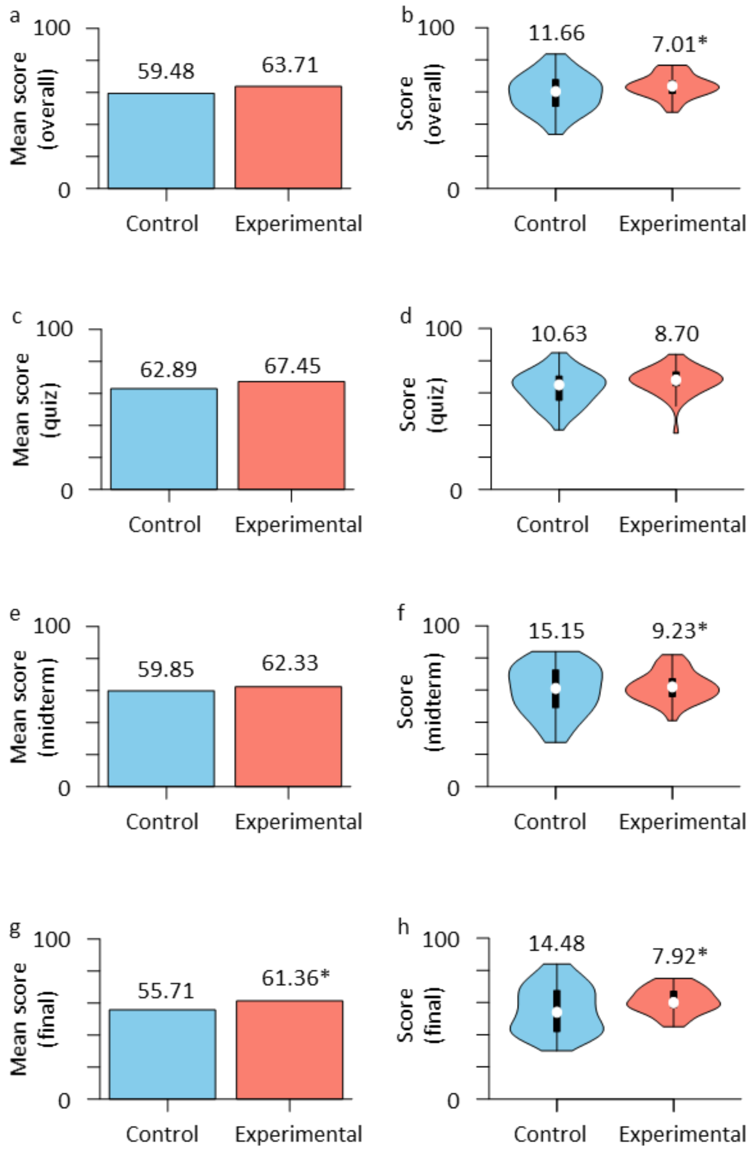


Figure 20. Performance of students in the Biology 1111 labs. Plotted are mean value and distribution of grades (percent scores) for overall student performance (a and b), quizzes (c and d), midterm exam (e and f), and the final exam (g and h) for control (blue) and experimental (red) group. Mean scores are shown in panels a, c, e, and g. Standard deviations (SDs) are shown in panels b, d, f, and h, and white dots are median values. The overall score for each student is calculated using the sum of scores for quizzes (9 quizzes, 10 points for each quiz), midterm (2 parts, 90 points in total), and the final (2 parts, 90 points in total), so the total score is 90. The control group contained 55 students, and the experimental group contains 39 students. If the difference between the control and experimental group is significant ($P < 0.05$), an asterisk is labeled.

Table 4. Comparison between results of full data and no-outlier data.

		Full data		Removal 5% outliers	
		Control	Experimental	Control	Experimental
Overall	Mean	59.48	63.71	59.51	63.81
	SD	11.66	7.01*	10.83	6.31*
Quiz	Mean	62.89	67.45	62.96	67.88
	SD	10.63	8.70	9.75	6.55*
Midterm	Mean	59.85	62.33	60.00	62.38
	SD	15.15	9.23*	14.38	8.16*
Final	Mean	55.71	61.36*	55.66	61.43*
	SD	14.48	7.92*	13.77	7.32*

*difference is significant ($P < 0.05$)

CHAPTER 5: OVERALL CONCLUSION

My exploration of the biological-art drawing heuristic resulted in a model and lesson plans on implanting the theoretical model. The historical overview of polymath scientist-artist reveals a complex haptic-visual, Nature-based conceptualization skill set that, in some individuals, underpins successes in biological science (31, 145). These complex sets of variables relate to a passionate pursuit of knowledge, beauty, and coherency to understand Nature and the natural world. This model's importance is that it underlies visual literacy in life sciences and, ultimately, STEAM practices that are visually based in biology. The model also touches on the complex nature of human perceptions of the natural world and how they become models of knowledge in science, which are subject to that time and place's culture. The analysis also reveals that emotional connection to Nature, appreciation of beauty in the natural world, and replication of it through drawing practice (aesthetic dimension) merges into the scientific observations and experimentations of certain individuals to produce a unique perspective on the phenomena. Several other important characteristics result from exploring the histories of these scientists-artists. One characteristic is contemplative knowledge, which is slow, passionate (engagement), and intimate association with the biological phenomena. A second characteristic that evolves is developing and using tools and skills in the drawing process that coevolve with research and learning to validate and review experimental results and theoretical constructs. It is the synchronicity of the neural motor and emotional skills that function within the construct of the culture as they relate to biological phenomena. These skills also shape the culture in which they evolve. Taken together, a simplified but more accurate model of STEAM learning emerges. A model where the human mind is assimilating a variety of sensory data, observing, being attracted to, and forming connections to that culture and biology creates a coherent synthesis or mental model of the apparent reality observed. It is the complex mix of culture, feeling, observation, skill, and knowledge in and with Nature that guides the scientist's research.

The implication of this model for life science education and biological research is manifold. From this model, we can see that at least a fraction of science teachers should be conversant with drawing in front of their students and modeling drawing biology to compare and contrast this method with others. This method presents itself as coherent and therefore requires a setting and environment most conducive to teacher -modeled biological drawing and student focus/engagement, which the STEAM movement suggests, by adding art to promote creativity in students (21). From one notable researcher on creativity in science and other disciplines (31), environment plays a critical role in the development of this type of individual in science, particularly if it contains beauty and complexity, the author notes; "*would the same works have issued forth even if their creators were confined to a steamy urban alley or a sterile suburban spread? One cannot answer that question without a controlled experiment. Given the fact that creative works are by definition unique, it is difficult to see how such an experiment can be performed* (31)." Currently there are no "experimental classrooms" that differ significantly from the present generic model. However, while campuses create more homogeny in classrooms, it is possible to create an "experimental" environment, classroom, and course, which can be tested with the entire model intact and compared. Such environments existed in the past, where students experienced their lectures in varied spaces. Literature also has discussed the so-called "stimulating learning environment" or the "interactive classroom." Some studies have been done comparing museum environment learning to classroom learning (166). I wanted to do this with an exhibition and a unique space, as I believe it would have had enhanced the drawing heuristic experience and potentially influenced the outcomes.

The literature (18) points to drawing-for-biology as a paradigm for increasing student engagement. However, the process and activity of drawing are fragmented from the niche of the artist and the naturalist. This includes everything from nature walks to classroom lighting and environment. These are differences that cannot be neglected in the biology discovery drawing practice or detached from it. Studies demonstrate that college students are more bored than ever with the college classroom experience in general (167) and that they feel disengaged and distracted through overuse of technology (168). This, coupled with the decreasing time in Nature (169), diminishes biophilia (170), and biophilia underscores passion as well as mental health (171).

My flexible and visually informative method combines with a narrative of the content to create a vision and a skill for students embedded in the mental health and creative benefits of a natural environment (172). The STEAM concepts of drawing as increasing visual literacy may hold. However, they cannot be adequately assessed or generated without instructor demonstration and attention to Nature, as this is the engagement factor. This model also points to a necessity of student exposure to Nature and visual intercourse with Nature and its abundant variety of form and pattern to develop a sense of ecological and evolutionary patterns. Without these experiences to draw upon, students have a little cohesive foundation upon which to configure biological vocabulary and concepts contextually. This is particularly important for ecology, evolution, and general biological knowledge. Notetaking, sketchbooks, and narrative also create a balanced engagement and focus on the biological world not as something exploited but rather in awe of (173). Students have little access to nature walks, pathways, botanical, pollinator gardens, insects, birds (except for those dying as they hit buildings), or animals. This makes their attachment to other living things superficial, and this may result in difficulty seeing important relationships between all life and human life. Biological concepts may make little sense devoid of these experiences (174).

My experimental results are the outcome of my attempts to fit a model to conditions that severely impaired its production and presentation. However, the modest and restrained administration of this model still appeared to have some measurable benefit in the Bio 1111 lab course. However, the experimental variable of the drawing heuristic should be done early in a biology student's curriculum and with the model fully intact within the content framework and classroom environments.

Lastly, many benefits potentially exist through this model. Medical schools are revising their curriculums, some quite modestly, others more boldly, to include narrative - in- medicine courses and drawing for surgeons and physicians have already been documented as valuable skills (175). So biological curriculums may consider doing something similar. Through the environment, teaching, and variation of the curriculum, a program can select for and offer students another perspective. Students that may not have been interested in biology or life science before may also gravitate to this "naturalist" approach. Without variation in the environment, teaching methods, or curriculum, there will be no possible way to measure such an approach's effectiveness. While content can remain relatively the same, modes of experiencing and presenting it can differ significantly.

History certainly offers a wealth of information on the success of so-called arts-based or romantic paradigms for cultivating an individual's desire to learn more about

Nature and our planet. That itself is evidence that has been largely ignored. Without the scientists/artists mentioned in the paper and countless others, we would not have the biology foundation we have today. Neglecting students who do not excel at math but are also attracted to the aesthetic should be considered potential biology students. Many would-be students with talent and potential, who are often creatively oriented, are not attracted to scholastic realms' rigidity. Yet, others struggle within the institutionalized learning model, which can severely dampen enthusiasm and creative potential (176). This is a loss to the diversity of the life science discipline, the university, the community, and the planet. The continual destruction of the natural world is evidence that intellect and scholastic achievements have not successfully abated ecological devastation. Biophilia exists as a concept but not as an ongoing process of experience, environment, action, or curriculum (177).

I have summarized possible broader impacts, particularly for selecting students who have a genuine interest or passion for the arts, beauty, and nature:

1. The development of an experimental classroom, curriculum, and/or course for premed and life science students that features visualizing and drawing biological phenomena before entering into a biology program.

2. A teacher education course that focuses on using the chalkboard/whiteboard effectively and develops skills for doing so, including drawing demonstration skills

3. Biology-art exhibition space in biology departments, medical schools

4. Greater ecological use of surrounding spaces where students can observe some form of intact natural systems.

5. The development of workbooks that foster these skill sets

6. Review and analysis of this or these types of courses over a 2-4-year period

For students: Contemplation (relaxation), “slow” and personal knowledge building of biological knowledge, and an environment to go without technology usage disrupting thought process and drawing skills. Incubation of concepts, ideas, and vocabulary, visual and written. The appreciation of scale and context in living systems through narrative and context. This is particularly important for the concepts of interdependence, in all levels from molecular to ecological and evolutionary. The very important concept of transition, motion, change, and time is of particular interest to all biological knowledge and evolution. This conceptualization can be accomplished through teacher demonstrations of transition, form, and DaVinci's Treaties of Scientific Illustration, which students come to learn through teacher demonstration and their drawings with an application to lab experiences and all morphologies and forms from anatomy, to microbes, to proteins, again within the narrative of the local and large ecology with the use of metaphor. This skill set will be personal, building self-efficacy, passion, and commitment to planetary well-being channeled through the student's own particular disciplinary interest in biology. For medical students, the drawing heuristic is significant, from learning anatomy and becoming visually literate in human form, to appreciating its embryological and evolutionary frameworks and narratives, as well as biochemical networks and the interdependence of microbial symbionts, as well as the human body as continuum and conduit of planetary cycles.

For science educators, this model will build a skill set that will allow them to personalize their classroom lectures, establish a visual protocol and display, reveal and exhibit the narrative for interactive classroom experiences. It will also allow teachers to become flexible in teaching a myriad of subjects, as the model drawing skills can be applied to anatomy, molecular, evolutionary, and systems biological thinking. Schools such as Johns Hopkins is employing curriculum aimed at developing PhD students who are more innovative and interdisciplinary by creating courses that create a wider lens on the scientific subjects and return to the philosophical views of natural phenomena, "Under pressure to turn out productive lab members quickly, many PhD programs in the biomedical sciences have shortened their courses, squeezing out opportunities for putting research into its wider context (178)."

Campus-wide programs that inspire and include biological art exhibitions, drawing, research, and mentoring; teachers may appeal to various students who never considered entering the sciences. The drawing heuristic techniques can help students and researchers gain insight into experimental design and data as they develop the aesthetic dimension of knowledge. Teachers can also develop their teaching materials to address their classrooms' specific concerns with students accommodating deficits or providing insights through new perspectives using drawing skills gained from drawing heuristic experiences and practice. Educators can use their drawing heuristic skills to inquire into their biology interests, transforming research into conceptual models and narratives. Lastly, educators can advocate for environments, buildings, classrooms, and local ecologies that build and support Nature and truly creative, STEAM-based skills on campus. This will enable schools and campuses to attract and transform students with a college experience that is stimulating, positive, and life-affirming, highly content-driven, and meditatively focused. In this way, and the Anthropocene, the campus, its student body, and faculty will evolve into a truly innovative and unique institution, rooted in creativity, emotional intelligence towards all life through the study of life processes and becoming a prototype standard for the future.

BIBLIOGRAPHY

1. Arnheim R. Visual thinking: Univ of California Press; 1969.
2. Ruskin J. Laws of Fesole, A joy forever, Our fathers have told us, Inaugural address: Bryan, Taylor; 1857.
3. Csikszentmihalyi M. Creativity: The work and lives of 91 eminent people: HarperCollins; 1996.
4. Tversky B, Hard BM. Embodied and disembodied cognition: Spatial perspective-taking. Cognition. 2009;110(1):124-9.
5. Van Meter P. Drawing construction as a strategy for learning from text. Journal of educational psychology. 2001;93(1):129.
6. Lowe DG. The viewpoint consistency constraint. International Journal of Computer Vision. 1987;1(1):57-72.
7. Mathewson JH. Visual-spatial thinking: An aspect of science overlooked by educators. Science education. 1999;83(1):33-54.
8. Schmeck A, Mayer RE, Opfermann M, Pfeiffer V, Leutner D. Drawing pictures during learning from scientific text: Testing the generative drawing effect and the prognostic drawing effect. Contemporary Educational Psychology. 2014;39(4):275-86.
9. Nersessian NJ. In the theoretician's laboratory: Thought experimenting as mental modeling.: InPSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association 1992 1992 Jan 1. Contract No.: 2.
10. Katz P. Drawing for science education: An international perspective: Springer; 2017.
11. Bolwerk A, Mack-Andrick J, Lang FR, Dörfler A, Maihöfner C. How art changes your brain: Differential effects of visual art production and cognitive art evaluation on functional brain connectivity. PloS one. 2014;9(7):e101035.
12. Wittmann B. Outlining species: Drawing as a research technique in contemporary biology. Science in context. 2013;26(2):363.
13. Bobek E, Tversky B. Creating visual explanations improves learning. Cognitive research: principles and implications. 2016;1(1):1-14.

14. Liu M, Horton L, Olmanson J, Toprac P. A study of learning and motivation in a new media enriched environment for middle school science. Educational technology research and development. 2011;59(2):249-65.

15. Ball SJ, Junemann C, Santori D. Edu. net: Globalisation and education policy mobility: Taylor & Francis; 2017.

16. Darden GF. Demonstrating motor skills—rethinking that expert demonstration. Journal of Physical Education, Recreation & Dance. 1997;68(6):31-5.

17. Kozbelt A, Seidel A, ElBassiouny A, Mark Y, Owen DR. Visual selection contributes to artists' advantages in realistic drawing. Psychology of Aesthetics, Creativity, and the Arts. 2010;4(2):93.

18. Quillin K, Thomas S. Drawing-to-learn: a framework for using drawings to promote model-based reasoning in biology. CBE—Life Sciences Education. 2015;14(1):es2.

19. Smith PH. The body of the artisan: Art and experience in the scientific revolution: University of Chicago Press; 2018.

20. Fiorentini E. Inducing visibilities: An attempt at Santiago Ramón y Cajal's aesthetic epistemology. Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences. 2011;42(4):391-4.

21. Yakman G, Lee H. Exploring the exemplary STEAM education in the US as a practice educational framework for Korea. Association for Science Education. 2012;32(6):1072-86.

22. Clapp EPea. Maker-centered learning: Empowering young people to shape their worlds.: John Wiley & Sons; 2016.

23. Yakman G. "STEAM education." Research on technology, innovation, design & engineering and teaching. 2008;19:1-28.

24. Milner-Bolotin M. Technology-enhanced teacher education for 21st century: Challenges and possibilities. Emerging technologies for STEAM education: Springer; 2015. p. 137-56.

25. Mishra P, Henriksen D, Group D-PR. Rethinking technology & creativity in the 21st century: On being in-disciplined. TechTrends. 2012;56(6):18-21.

26. Alters BJ, Nelson CE. Perspective: Teaching evolution in higher education. Evolution. 2002;56(10):1891-901.

27. Wylie CD. Teaching manuals and the blackboard: Accessing historical classroom practices. History of Education. 2012;41(2):257-72.

28. Bruhn JG. The sociology of community connections: Springer Science & Business Media; 2011.

29. Cavallaro MC. Sustainability champions: Role models in sustainability graduate education." Handbook of theory and practice of sustainable development in higher education. Springer,Cham. 2017: 329-42.

30. Dissanayake E. Homo aestheticus: Where art comes from and why: University of Washington Press; 2001.

31. Csikszentmihalyi M. The systems model of creativity: The collected works of Mihaly Csikszentmihalyi: Springer; 2015.

32. Keele KD. Leonardo da Vinci, and the movement of the heart. Sage publications. 1951:209-13.

33. Capra F. The science of Leonardo: Inside the mind of the great genius of the Renaissance: Anchor; 2008 Dec 2.

34. Todes DP. Darwin's Malthusian metaphor and Russian evolutionary thought, 1859-1917. Isis. 1987;78(4):537-51.

35. Schultheiss D, Engel RM, Crosby RW, Lees GP, Truss MC, Jonas U. Max Brödel (1870-1941) and medical illustration in urology. The Journal of urology. 2000;164(4):1137-42.

36. Udelsman R. Presidential address: Harvey Cushing: The artist. Surgery. 2006;140(6):841-6.

37. Hansen JT. Frank H. Netter, MD (1906–1991): The artist and his legacy. Clinical Anatomy: The Official Journal of the American Association of Clinical Anatomists and the British Association of Clinical Anatomists. 2006;19(6):481-6.

38. Lukhtanov VA. Nabokov ’ s scientific artistry. Nature. 2016;531:304.

39. Alexander VN. Neutral evolution and aesthetics: Vladimir Nabokov and insect mimicry. Working Papers. 2001;43(1996):144-50.

40. Bramly S. Leonardo. New York: HarperCollins Publishers; 1991.

41. Kemp MJ. Leonardo DaVinci and the Science of the Poetic Impluse. Journal of the Royal Society of Arts. 1985;133(5343):196-214.

42. Gross CG. Leonardo da Vinci on the brain and eye. The Neuroscientist. 1997;3(5):347-55.

43. Richter JP. The notebooks of Leonardo da Vinci: Courier Corporation; 1970.

44. Hale NC. Abstraction in Art and Nature Courier Corporation; 2012 June 19.

45. Clayton M. Leonardo Da Vinci: The Anatomy of Man. Plastic and Reconstructive Surgery. 1993;92(5):973.

46. Banerji R. BBC News. 2012 May 1.

47. Jack J. A pedagogy of sight: Microscopic vision in Robert Hooke's Micrographia. Quarterly Journal of Speech. 2009;95(2):192-209.

48. Orr DW. Earth in mind: On education, environment, and the human prospect: Island Press; 2004.

49. Pevsner J. Leonardo da Vinci's contributions to neuroscience. TRENDS in Neurosciences. 2002;25(4):217-20.

50. Barolsky P. Vasari and the historical imagination. Word & Image. 1999;15(3):286-91.

51. Kuligowski S. Leonardo da Vinci: Renaissance Artist and Inventor: Teacher Created Materials; 2012.

52. Bonaiuto P. Art, Science, and Humor: The Study of Humorous Experience at the Intersection between Psychology and the Art World. Empirical Studies of the Arts. 2006;24(1):3-41.

53. West JB. Leonardo da vinci: Engineer, bioengineer, anatomist, and artist. American Journal of Physiology - Lung Cellular and Molecular Physiology. 2017;312(3):L392-L7.

54. Jeanneret M. Perpetual Motion: transforming shapes in the Renaissance from da Vinci to Montaigne: JHU Press; 2001.

55. Shen T, Baker K. Venous return and clinical hemodynamics: how the body works during acute hemorrhage. Advances in physiology education. 2015;39(4):267-71.

56. Wildgen W. The phenomenology of spatial cognition and the relevance of topology for linguistics. La Lingüísticacomo reto epistemológico y comoacción social. 2009;1:187-207.

57. Bookstein FL. The study of shape transformation after D'Arcy Thompson. 1977.

58. Baltzer F. Theodor Boveri. 1964:809-15.

59. Laubichler MD, Davidson EH. Boveri's long experiment: sea urchin merogones and the establishment of the role of nuclear chromosomes in development. Developmental biology. 2008;314(1):1-11.

60. Satzinger H. Theodor and Marcella Boveri: chromosomes and cytoplasm in heredity and development. Nature reviews genetics. 2008;9(3):231-8.

61. Opitz JM. Annals of morphology THEODOR BOVERI (1862–1915) To commemorate the centenary of his death and contributions to the Sutton–Boveri hypothesis. Wiley Online Library; 2016.

62. Meijer GA. Chromosomes and cancer, Boveri revisited. Hindawi; 2005.

63. Boveri T. Zur frage der entstehung maligner tumoren: Fischer; 1914.

64. Cremer T, Cremer C. Chromosome territories, nuclear architecture and gene regulation in mammalian cells. Nature Reviews Genetics. 2001;2(4):292-301.

65. Müller F, Bernard V, Tobler H. Chromatin diminution in nematodes. Bioessays. 1996;18(2):133-8.

66. Cremer T, Cremer C. Rise, fall and resurrection of chromosome territories: A historical perspective. Part I. The rise of chromosome territories. European Journal of Histochemistry. 2006;50(3):161-76.

67. Coleman W. Cell, nucleus, and inheritance: an historical study. Proceedings of the American Philosophical Society. 1965;109(3):124-58.

68. Churchill FB. August Weismann: Harvard University Press; 2015.

69. Manchester KL. Theodor Boveri and the origin of malignant tumours. Trends in Biology. 1995;5(10):384-7.

70. Sathananthan AH, Ratnasooriya WD, De Silva A, Randeniya P. Rediscovering Boveri's centrosome in Ascaris (1888): Its impact on human fertility and development. Reproductive BioMedicine Online. 2006;12(2):254-70.

71. Maderspacher F, Mendel G. Essay Theodor Boveri and the natural experiment. Current Biology. 2008;18.7:279-86.

72. Bartholomew GA. Scientific Innovation and Creativity : A Zoologist ' s Point of View Oxford university press. 1982;22(2):227-35.

73. Deichmann U. From Gregor Mendel to Eric Davidson: Mathematical Models and Basic Principles in Biology. Journal of Computational Biology. 2019;26(7):637-52.

74. Dröscher A. Images of cell trees, cell lines, and cell fates: The legacy of Ernst Haeckel and August Weismann in stem cell research. History and Philosophy of the Life Sciences. 2014;36(2):157-86.

75. O'Connor C, Miko I. Developing the chromosome theory. Nature education. 2008;1(1):44.

76. Churchill FB. Theodor Boveri. Life and Work of a Great Biologist 1862-1915. JSTOR; 1968.

77. Lancaster C. A history of embryonic stem cell research: Concepts, laboratory work, and contexts: Durham University; 2017.

78. Goday C PS. The occurrence, role and evolution of chromatin diminution in nematodes. Parasitology Today. 1993;9(9):319-22.

79. Strickfaden H, Zunhammer A, van Koningsbruggen S, Köhler D, Cremer T. 4D chromatin dynamics in cycling cells Theodor Boveri's hypotheses revisited. Nucleus. 2010;1(3):284-97.

80. Reynolds AS. The third lens: metaphor and the creation of modern cell biology: University of Chicago Press; 2018.

81. Ramalho-Santos M, Willenbring H. On the origin of the term "stem cell". Cell stem cell. 2007;1(1):35-8.

82. Boveri T. On multipolar mitosis as a means of analysis of the cell nucleus. Foundations of experimental embryology. 1902;1964:74-97.

83. Holland AJ, Cleveland DW. Boveri revisited: Chromosomal instability, aneuploidy and tumorigenesis. Nature reviews Molecular cell biology 2009;10(7):478-87.

84. Ried T. Homage to Theodor Boveri (1862–1915): Boveri's theory of cancer as a disease of the chromosomes, and the landscape of genomic imbalances in human carcinomas. Wiley Online Library; 2009.

85. Hardy Pa ZH. Reappraisal of the Hansemann—Boveri hypothesis on the origin of tumors Cell Biology International. 2005;29(12):983-92.

86. Richards RJ. The tragic sense of life: Ernst Haeckel and the struggle over evolutionary thought: University of Chicago Press; 2008.

87. Hall BK. Embryos in evolution: Evo-devo at the Naples Zoological Station in 1874. Theory in Biosciences. 2009;128(1):7-18.

88. Breidbach O. Visions of nature: The art and science of Ernst Haeckel: Prestel München; 2006.

89. Thompson DW. On growth and form. On growth and form. 1942.

90. Rieppel O. Ernst Haeckel (1834–1919) and the monophyly of life. Journal of Zoological Systematics and Evolutionary Research. 2011;49(1):1-5.

91. Elinson RP, Kezmoh L. Molecular Haeckel. Developmental Dynamics. 2010;239(7):1905-18.

92. Reynolds A. Ernst Haeckel and the theory of the cell state: Remarks on the history of a bio-political metaphor. History of Science. 2008;46(2):123-52.

93. Hadzigeorgiou Y, Schulz R. Romanticism and romantic science: Their contribution to science education. Science & Education. 2014;23(10):1963-2006.

94. Stauffer RC. Haeckel, Darwin, and ecology. The Quarterly Review of Biology. 1957;32(2):138-44.

95. Villanueva AA, Priya S. Cyanea capillata Bell Kinematics Analysis through Corrected In Situ Imaging and Modeling Using Strategic Discretization Techniques. PloS one. 2014;9(12):e115220.

96. Satterlie RA. Neuronal control of swimming in jellyfish: a comparative story. Canadian Journal of Zoology. 2002;80(10):1654-69.

97. Farber PL. Finding order in nature: the naturalist tradition from Linnaeus to EO Wilson: JHU Press; 2000 July 10.

98. DeFelipe J. Sesquicentenary of the birthday of Santiago Ramón y Cajal, the father of modern neuroscience. TRENDS in Neurosciences. 2002;25(9):481-4.

99. DeFelipe J, Garrido E, Markram H. The death of Cajal and the end of scientific romanticism and individualism. Trends in Neurosciences. 2014;37(10):525-7.

100. DeFelipe J, Jones EG. Santiago Ramón y Cajal and methods in neurohistology. Trends in neurosciences. 1992;15(7):237-46.

101. DeFelipe J. The dendritic spine story: an intriguing process of discovery. Frontiers in neuroanatomy. 2015;9:14.

102. DeFelipe J. Cajal and the discovery of a new artistic world: the neuronal forest. Progress in brain research. 2013;203:201-20.

103. Evans CA. A Study of Goethe's Philosophy of Science. 1980.

104. Andres-Barquin PJ. Santiago Ramón y Cajal and the Spanish school of neurology. The Lancet Neurology. 2002;1(7):445-52.

105. Fields RD. Beyond the neuron doctrine. Scientific American Mind. 2006;17(3):20-7.

106. Abrams E, Southerland S, Cummins C. The how's and why's of biological change: How learners neglect physical mechanisms in their search for meaning. International Journal of Science Education. 2001;23(12):1271-81.

107. y Cajal SR. Vacation Stories: Five Science Fiction Tales: University of Illinois Press; 2001.

108. Garcia-Lopez P, Garcia-Marin V, Freire M. The histological slides and drawings of Cajal. Frontiers in neuroanatomy. 2010;4:9.

109. y Cajal SR. Comparative study of the sensory areas of the human cortex: Clark University; 1899.

110. DeFelipe J. Cajal's Neuronal Forest: Science and Art: Oxford University Press; 2018.

111. Llinás RR. The contribution of Santiago Ramon y Cajal to functional neuroscience. Nature Reviews Neuroscience. 2003;4(1):77-80.

112. Zamora-Berridi GJ, Pendleton C, Ruiz G, Cohen-Gadol AA, Quiñones-Hinojosa A. Santiago Ramón y Cajal and Harvey Cushing: two forefathers of neuroscience and neurosurgery. World neurosurgery. 2011;76(5):466-76.

113. Long DM. Harvey cushing at johns hopkins. Neurosurgery. 1999;45(5):983-9.

114. Jones EG. Santiago Ramon y Cajal and the croonian lecture, March 1894. Trends in neurosciences. 1994;17(5):190-2.

115. Clarke E, Jacyna LS. Nineteenth-century origins of neuroscientific concepts: Univ of California Press; 1987.

116. Francoeur E. Molecular models and the articulation of structural constraints in chemistry. Tools and modes of representation in the laboratory sciences: Springer; 2001. p. 95-115.

117. Rahman S, Abdur Z, Albert Y. An overview of protein-folding techniques: issues and perspectives. International Journal of Bioinformatics Research and Applications. 2005;1(1):121-43.

118. Pauling L, Corey RB, Branson HR. The structure of proteins: two hydrogen-bonded helical configurations of the polypeptide chain. Proceedings of the National Academy of Sciences. 1951;37(4):205-11.

119. Corey RB, Pauling L. Molecular models of amino acids, peptides, and proteins. Review of Scientific Instruments. 1953;24(8):621-7.

120. Olson WK, Zhurkin VB. Modeling DNA deformations. Current opinion in structural biology. 2000;10(3):286-97.

121. Richardson JS, Richardson DC, Tweedy NB, Gernert KM, Quinn T, Hecht MH, et al. Looking at proteins: representations, folding, packing, and design. Biophysical Society National Lecture, 1992. Biophysical journal. 1992;63(5):1185.

122. Schönborn KJ, Anderson TR. The importance of visual literacy in the education of biochemists. Biochemistry and molecular biology education. 2006;34(2):94-102.

123. Cambrosio A, Jacobi D, Keating P. Arguing with images: Pauling's theory of antibody formation. Representations. 2005;89(1):94-130.

124. Herman T, Morris J, Colton S, Batiza A, Patrick M, Franzen M, et al. Tactile teaching: Exploring protein structure/function using physical models. Biochemistry and Molecular Biology Education. 2006;34(4):247-54.

125. Roberts JC, Headleand CJ, Ritsos PD. Five design-sheets: Creative design and sketching for computing and visualisation: Springer; 2017 May 28. 1-333 p.

126. Atkins LJ, Salter IY. Using scientists' notebooks to foster authentic scientific practices. AIP Conference Proceedings. 2013;1513(January 2013):50-3.

127. Gal J. Pasteur and the art of chirality. Nature chemistry. 2017;9(7):604-5.

128. Beall KF, West FB. The Interdependence ofPrinter & Printmaker in Early 19th-Century Lithography. Journal of Source Art. 1980;39(3):195-201.

129. Pauling LC, HD., Pressman,D. The nature of the forces between antigen and antibody and of the precipitation reaction. Physiological Reviews. 1943;23(3)(3):203-19.

130. Dubois JE, Doucet JP, Yue SY. Computer molecular modelling and graphic design. Molecules in Physics, Chemistry, and Biology: Springer; 1988. p. 173-204.

131. Morgan GJ. Emile Zuckerkandl, Linus Pauling, and the molecular evolutionary clock, 1959-1965. Journal of the History of Biology. 1998:155-78.

132. Van Lente F. Comic book history of comics: IDW Publishing; 2012.

133. Roberts JR, Hagedorn E, Dillenburg P, Patrick M, Herman T. Physical models enhance molecular three-dimensional literacy in an introductory biochemistry course. Biochemistry and Molecular Biology Education. 2005;33(2):105-10.

134. Paivio A, Clark JM, editors. Dual coding theory and education. Draft chapter presented at the conference on Pathways to Literacy Achievement for High Poverty Children at The University of Michigan School of Education; 2006: Citeseer.

135. Slykhuis DA, Wiebe EN, Annetta LA. Eye-tracking students' attention to PowerPoint photographs in a science education setting. Journal of Science Education and Technology. 2005;14(5-6):509-20.

136. Pauwels L. On the nature and role of visual representations in knowledge production and science communication. Science communication: De Gruyter Mouton; 2019. p. 235-56.

137. Solso RL. Brain Activities in a Skilled versus a Novice Artist: An fMRI Study. Leonardo. 2001;34(1):31-4.

138. Barbezat D. Paying Attention. Contemplative Learning and Inquiry across Disciplines. 2014:151.

139. Richardson JS. Early ribbon drawings of proteins. Nature Structural Biology. 2000;7(8):624-5.

140. Nakamura J, Csikszentmihalyi M. Catalytic creativity: The case of Linus Pauling. American Psychologist. 2001;56(4):337.

141. Bartholomew S. Why we cannot afford to lose CTE in schools. International Journal of Vocational and Technical Education. 2014;6(2):7-12.

142. Wilson EO. Biophilia and the conservation ethic. Evolutionary perspectives on environmental problems. 2007:249-57.

143. Rothstein E. Emblems of mind: The inner life of music and mathematics. New York: University of Chicago Press 1995 Jan.

144. Ruskin J. The Laws of Fesole; A Familiar Treatise on the Elementary Principles and Practice of Drawing and Painting: Plaat Press; 2008.

145. Fiorentini E. Placing Oneself at an Adequate Point of View. Santiago Ramón y Cajal’s Drawings and the Histological Look. Graphing Genes, Cells, and Embryos Cultures of Seeing 3D and Beyond, Berlin: Max Planck Institute for the History of Science. 2009;380:133-42.

146. Spivey NJ. How art made the world: a journey to the origins of human creativity: Perseus Books Group; 2005.

147. Ainsworth S, Prain V, Tytler R. Drawing to learn in science. Science. 2011;333(6046):1096-7.

148. Ezin M, Noravian C, Mahomed A, Lyle A, Gill A, Elul T. Visual Arts Enhance Instruction in Observation and Analysis of Microscopic Forms in Developmental and Cell Biology. The STEAM Journal. 2020;4(2):8.

149. Pears A, Barendsen E, Dagienė V, Dolgopolovas V, Jasutė E, editors. Holistic STEAM education through computational thinking: a perspective on training future teachers. International Conference on Informatics in Schools: Situation, Evolution, and Perspectives; 2019 Nov 18: Springer.

150. Rule AC, Sallis DA, Donaldson JA. Humorous Cartoons Made by Preservice Teachers for Teaching Science Concepts to Elementary Students: Process and Product. Online Submission. 2008.

151. Esposito M. Romantic Biology, 1890–1945: Routledge; 2015.

152. Shiva V. Colonialism and the evolution of masculinist forestry: Bloomington: Indiana University Press; 1993 Oct. 22nd.

153. Babaian C. Visualizing biological networks as mandalas: with an Eastern spiritual symbol and some colored chalk, a biology teacher explores the interdependence and the evanescence of all living things. American Scientist. 2015;103(5):322-6.

154. Stankiewicz MA, Krug DH. Art & ecology. Art education. 1997;50(6):4.

155. Başaran M, Erol M. Recognizing aesthetics in nature with STEM and STEAM education. Research in Science & Technological Education. 2021:1-17.

156. Driessnack M. Children and nature-deficit disorder. Journal for Specialists in Pediatric Nursing. 2009;14(1):73.

157. Capra F, Luisi PL. The systems view of life: A unifying vision: Cambridge University Press; 2014 April 10.

158. Hunter-Doniger T, Howard C, Harris R, Hall C. STEAM through culturally relevant teaching and storytelling. Art Education. 2018;71(1):46-51.

159. Dutta S, Eswaran S, Sanelli A, Bhattacharya M, Tempsick R. Learning biology through molecular storytelling. The Science Teacher. 2018;86(2):28-33.

160. Henriksen D, Mishra P. Of Metaphors and Molecules: Figurative Language Bridging STEM and the Arts in Education. Leonardo. 2020;53(3):316-20.

161. Babaian C. Time Travel and the Naturalist's Notebook: Vladimir Nabokov Meets the TimeTree of Life. The American Biology Teacher. 2018;80(9):650-8.

162. Babaian C, Kumar S. Adventures in Evolution: The Narrative of Tardigrada, Trundlers in Time. The American biology teacher. 2019;81(8):543-52.

163. Babaian C, Kumar S. Molecular Memories of a Cambrian Fossil. The American Biology Teacher. 2020;82(9):586-95.

164. Babaian C, Kumar S. How to Build a Super Predator: From Genotype to Phenotype. The American Biology Teacher. 2021;83(3):138-46.

165. Kellert SR, Heerwagon J. H., Mador M. L. Dimensions-elements-and-attributes-of-biophilic-design.pdf. Hoboken, NJ; 2008 Jan.

166. Beal C, Mason C. Virtual fieldtripping: No permission notes needed creating a middle school classroom without walls. Meridian Middle School Technologies Journal. 1999.

167. Tranter J. Biology: dull, lifeless and boring? : Taylor & Francis; 2004.

168. Wood NT, Muñoz C. Unplugged: digital detox enhances student learning. Marketing Education Review. 2020:1-12.

169. Nielsen J. Americans spending less time in nature. NPR org. 2008;6.

170. Ulrich RS. Biophilia, biophobia, and natural landscapes. The biophilia hypothesis. 1993;7:73-137.

171. Gullone E. The biophilia hypothesis and life in the 21st century: increasing mental health or increasing pathology? Journal of happiness studies. 2000;1(3):293-322.

172. Maller C, Townsend M, Pryor A, Brown P, St Leger L. Healthy nature healthy people:'contact with nature'as an upstream health promotion intervention for populations. Health promotion international. 2006;21(1):45-54.

173. Tennessen CM, Cimprich B. Views to nature: Effects on attention. Journal of environmental psychology. 1995;15(1):77-85.

174. Balling JD, Falk JH. Development of visual preference for natural environments. Environment and behavior. 1982;14(1):5-28.

175. Charon R. Narrative medicine: a model for empathy, reflection, profession, and trust. Jama. 2001;286(15):1897-902.

176. Applebaum E. A Practice of Narrowing Options: How the Theory-Based Curriculum Destroys Creativity. Music Educators Journal. 1972;58(7):43-5.

177. Hauk M. Gaia emergent: Earth regenerative education catalyzing empathy, creativity, and wisdom: Prescott College; 2014.

178. Bosch G. WORLD VIEW Train PhD students to be thinkers not just specialists. Nature. 2018;554,7692.