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DRAWING TO LEARN SCIENCE: LEGACIES OF AGASSIZ

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ABSTRACT

The use of visual representation to learn science can be traced to Louis Agassiz, Harvard Professor of Zoology, in the mid-19th century. In Agassiz's approach, students were to study nature through carefully observing, drawing and then thinking about what the observations might add up to. However, implementation of Agassiz's student-centered approach has struggled with the conflict between science as a form of developing "mental discipline" in which mastery of scientific facts is the goal and science learning as a socially situated activity with an emphasis on the process of learning, not merely its products. Present-day attempts to have students draw to learn science often succumb to these same conflicts, limiting their full realization.

In a sophomore molecular biology laboratory class I work with at MIT, in one assignment students study the development of mutated zebrafish. A key pedagogical technique is to have students draw pictures of the developing zebrafish embryo at several time points. Invariably, some students complain about this seemingly low-tech and elementary technique. Why can't they instead take digital photos, they ask, and assemble a slide show? And what is the value in the tedious process of drawing? This isn't an art class, after all!

What students might not realize is that they are taking part in a tradition of teaching science—and studying the natural environment—that can be traced to Aristotle, one of the first leading "naturalists," according to Louis Agassiz [1, p. 1]. Agassiz himself was one of the country's pre-eminent naturalists of the mid-19th century, and in his classroom and laboratory at Harvard, Agassiz, in his words, “taught men to observe” [as cited in 2, p. 1]. Such observations were often accompanied by drawings, and from these observations Agassiz implored his students to make connections and develop general principles, for, according to Agassiz, “Facts are stupid things [. . .] until brought into connection with some general law” [as cited in 3, p. 370]. Students as experimentalists meant learning by discovery, by experiencing the natural world and drawing the lessons it had to offer, just as any scientist would do. As described by W. L. Poteat of Wake Forest College, the “essential feature of the laboratory method of instruction is that it brings the student into direct contact with nature. He does not study about nature; he studies nature” [4, p. 287]. Thus, Agassiz and his like-minded colleagues were offering disciplinary training, not mere mastery of content devoid of context.

This tradition of student-centered learning, however, has never been quite fully realized in the science classroom or laboratory. Most colleges and universities are not set up for the kind of time- and resource-intensive teaching that true inductive learning entails. More important, however, the task of—and resistance to—drawing to learn science reveals a long-standing tension between the theory of mental discipline or students mastering a body of scientific facts and constructivism in which students create knowledge through social interaction and opportunities to do the work of real scientists.

This clash between 19th and 20th century ideas is still with us as instructors in 21st-century science classrooms and laboratories struggle to embody Agassiz’s goal of imparting a sense of science as discovery and reconcile itself to the need for students to master foundational knowledge. As recently as July 2006, a *New York Times* editorial asserted that “the horrendous state of science education at both the public school and university levels” could be improved by giving students “early, engaging experiences in the lab—and much more mentoring than most receive now—to maintain their interest and inspire them to take up careers in the sciences” [5, p. A14]. The struggle is both old and new and old again. Old is the long-standing tendency of science education to fall back on cramming students full of scientific facts and figures, even when visual communication is the method for students to convey those facts and figures. Also old, as shown by Agassiz’s example, is the realization that science and the scientific method are about learning processes, ways of thinking, and problem solving. New, however, is a return to visual forms for students to learn science. In the specific area of biochemistry, Schonborn and Anderson argue that “the pedagogical importance of visual literacy and visualization in the education of biochemists has been ignored for far too long” [6, p. 101]. However, the struggle continues between learning science as mental discipline and learning as discovery, between mastering facts and understanding processes, between drawing to render and drawing to learn. Agassiz’s legacy points to the possibilities of learning science as a dynamic, meaningful process, but also to the conflicting forces that have prevented his ideals from being enacted.

LOUIS AGASSIZ AND LEARNING BY OBSERVING

Born in Switzerland in 1807, Harvard Professor of Zoology from 1848 until his death in 1873, founder of the Museum of Comparative Zoology [7], Louis Agassiz embodied an approach to studying nature in his classroom and laboratory at Harvard and later at his summer institute on the island of Penikese that would influence many subsequent leaders in science and science teaching [8, p. 664]. For Agassiz, science was not necessarily a discipline to be learned by close study of texts and mastery of static knowledge. Instead, science was to be experienced firsthand in order to counter a problem with the then-prevalent teaching methods that Agassiz decried: "The pupil studies nature in the schoolroom, and when he goes out of doors he can not find her" [as cited in 9, p. 119].

Agassiz was not formally trained in these teaching methods but instead seemed to offer his students the evidence from his own experience as testament to the powers of observation and drawing. Agassiz biographer Edward Lurie describes Agassiz's childhood in Switzerland as filled with experiences in nature [10, p. 8]. Even when Agassiz had started formal schooling at age 10, according to Lurie, "Vacations at home were spent adding to collections of insects, birds, fish, and small land animals. [. . .] He wanted to know the underlying reasons for the phenomena he observed, to discover relationships, to understand general concepts. In this quest, young Agassiz proceeded to educate himself" [10, p. 8]. Essential to this method of self education was recording his observations. As Lurie describes,

> From the age of eleven until he was nineteen, Agassiz kept minute and detailed accounts of his natural history observations, set down in fine script in a series of notebooks, with subjects classified and divided carefully under proper subject headings. The importance with which he regarded this activity is revealed by the fact that Agassiz carefully preserved these notebooks, treasuring them as intellectual landmarks of his first scholarly efforts in natural history [10, p. 9].

Agassiz's influence as a teacher has been recounted by many former students. What is repeated in these accounts is Agassiz's strict adherence to having students learn on their own, rather than to be passive recipients of what Agassiz already knew. As noted by William James Beal, a leading naturalist of the 19th century, "It has seemed to me that the work with Agassiz helped me more than that of any other teacher with whom I came in contact, and yet no teacher ever told me so little" [as cited in 8, p. 664]. So what did Agassiz's teaching look like? In a widely anthologized essay, Samuel Scudder, a student of Aggasiz at Harvard in the 1850s, recounts his first encounter with Agassiz's methods:

> "Take this fish," said [Agassiz], "and look at it; we call it a haemulon; by and by I will ask what you have seen" [3, p. 369].

Scudder initially makes short work of this task, noting that in "ten minutes I had seen all that could be seen in that fish" [3, p. 370]. However, Scudder finds that Agassiz is not to be found to hear his report. Thus, Scudder finds himself with nothing left to do but look at the fish some more: "At last a happy thought struck me—I would draw the fish; and now with surprise I began to discover new features in the creature. Just then the Professor returned. 'That is right,' said he; 'a pencil is one of the best eyes'" [3, p. 370]. Scudder's initial report to Agassiz, however, was met with what Scudder describes as "an air of disappointment." Agassiz tells him, "You have not looked very carefully; why [. . .] you haven't even seen one of the most conspicuous features of the animal, which is as plainly before your eyes as the fish itself; look again, look again!' and he left me to my misery" [3, p. 370]. After several more rounds of this activity and the passing of a day, Scudder gave another report of observations to Agassiz, who responded with

> "That is good, that is good!" [Aggasiz] repeated; "but that is not all; go on"; and so for three long days he placed that fish before my eyes, forbidding me to look at anything else, or to use any artificial aid. "Look, look, look," was his repeated injunction [3, p. 370].

For Scudder and many others, by observing and drawing to learn, students would not merely be passive repositories of information, but active participants in the creation of meaningful knowledge. Essential to this meaning making was not merely observing, drawing, or recording, however, but it was making inferences from those observations. In Agassiz's words, "the ability of combining facts is a much rarer gift than that of discerning them" [as cited in 2, p. 67]. The naturalist's project of classification, then, of making connections between natural objects, was to guide the work of Agassiz's students. Agassiz saw a powerful simplicity in this process, noting about his own research,

> I have devoted my whole life to the study of Nature, and yet a single sentence may express all that I have done. I have shown that there is a correspondence between the succession of Fishes in geological times and the different stages of their growth in the egg,—that is all. It chanced to be a result that was found to apply to other groups and has led to other conclusions of a like nature. But, such as it is, it has been reached by this system of comparison, which, though I speak of it now in its application to the study of Natural History, is equally important in every other branch of knowledge [1, p. 8].

Thus, Agassiz was teaching his students to learn about nature as he learned about nature, from his childhood observations in Switzerland to his mid-19th century explorations in the Brazilian Amazon. As Agassiz told his students gathered on the island of Penikese for a summer of study in 1873,

> I do not wish to communicate knowledge to you, you can gather that from a hundred sources, but to awaken in you a faculty which is probably more dormant than the simple power of acquisition. [. . .] I am therefore placed in a somewhat difficult and abnormal position for a teacher. I must teach and yet

> not give information. I must, in short, to all intents and purposes be ignorant before you [as cited in 11, p. 73].

Accounts of Agassiz's teaching take on a sort of mythic quality, particularly given the often-unrealized vision of hands-on learning. Many writers look back at Agassiz as a pioneer, but with a not-so-subtle indictment of current teaching practices. In 1947, James David Teller engaged in this Agassizian process of observation and comparison:

> To Agassiz, the laboratory was not a place (as it has become in our schools today) for the verification of generalizations which the teacher suggests to the student. It was a place where the student would observe and compare and generalize for himself. Agassiz was a firm believer in the pedagogical principle of activity: we learn to observe by observing; we learn to compare by comparing; and we learn to generalize by generalizing. Merely observing the objects to which our eyes are directed; merely comparing facts which we have been instructed to compare; merely verifying the generalizations which the teacher has explained—are not methods of true observation, comparison, and generalizations in the sense in which Agassiz uses these terms [11, pp. 72-73].

Agassiz's teaching practices, then, have become an idealized goal against which the failings of contemporary practice could be contrasted. It is odd, in a sense, to read claims such as Donald Peattie's, offered in 1933: "It is safe to say that no American scientist has ever has as much influence on scientific education as Agassiz" [as cited in 11, p. 138]. The historical record of cycles of unhappiness with prevalent teaching methods in science classrooms would seem to indicate that Agassiz's influence has been minimal. Instead, looking back to Agassiz is a kind of longing for mythic days of yore. Such longing and it recurrence, however, reveals the conflicted nature of science teaching and learning in higher education: the real work of a real naturalist versus the artificial conditions that classroom and laboratory contexts often demand. As I show next, the history of science as an accepted course of study in higher education—and the attempts to realize active learning techniques such as observation and drawing—more often than not succumbed to these conflicts.

THE ACCEPTANCE OF SCIENCE IN THE LATE 19TH CENTURY

While the hands-off nature of Agassiz teaching might seem courageous by today's standards, at the time the approach was particularly revolutionary. In Agassiz's time, teaching in higher education was dominated by formal lecture and recitation, and the role of the sciences as accepted academic disciplines was far from secure. According to historian Stanley Guralnick, early in the 19th century science faculty held tenuous status: "The science professor, to apply the term loosely, was at best a peripheral entity in the collegiate organization. [. . .] His salary was uniformly lower than that of other professors, and his security such that he easily fitted the classic mold of the 'last hired and the first fired'" [12, p. 142]. The acceptance of science as a regular course of study in American higher education did not occur until the late 19th century, terminating a long struggle against philosophy and religion as the bedrock of the classical university training [13, p. 246].

Several factors contributed to this acceptance. Enrollments in higher education rose tremendously—from 67, 350 students in 1870 to 355, 215 students in 1910 [14, p. 31]—and these students were far more diverse and more practically minded than earlier generations of largely elite males who were being educated for a narrow range of professions. Study of science and engineering also responded to the spread of American industrialization and its concomitant challenges [15, p. 280]. Finally, science study in the field and laboratory could draw on new ideas about teaching and learning, ones that placed high value on student experience, just as Agassiz did. Drawing was a natural process of this technique, and many writers of the late 19th century and curricular materials from that era, particularly in biology and its associated fields, reinforce this message. For example, in 1894 the influential Harvard Committee of Ten made several recommendations for high schools to be more in accord with college-level science study. Among them for the study of botany was the following:

> Careful examinations of specimens is secured best by careful sketching. Too much importance cannot be given to drawing, as it is not only an excellent device for securing close observation, but it is also a rapid method of making valuable notes. A very few verbal descriptions may accompany the sketches to make their meanings clear. These sketches and notes should be made in a permanent note-book, for future use [16, p. 152].

For the college-level study of zoology, William Locy of Lake Forest University recommended in 1889 an approach that could have been directly distilled from Agassiz's notebooks:

> The value of drawing, in giving directness to observations, is recognized by all teachers, and additional points of structure and relationship of parts will be noticed by the students as soon as they begin to sketch. These laboratory sketches should be viewed, not as artistic efforts, but as a means of expressing observations and conclusions in lines, and of value in proportion to the accuracy with which they represent characteristics actually observed and intelligently interpreted [17, pp. 675-676].

Drawing to learn science, then, was a key technique in larger attempts to have students learn inductively, as opposed to memorizing textbook explanations and faithfully regurgitating those points in recitations and exams. The late 19th century, by these accounts, seemed a golden era for the study of science, a student- and science-friendly atmosphere that held great promise as America geared up to face the challenges of a new century. John Campbell surveyed the scene of biological teaching in U.S. colleges in 1891 and declared the following:

> Perhaps the most striking point by which the educational methods of the present are distinguished from those formerly in vogue is the great prominence which is given to inductive methods, and as a consequence, the little attention that is now paid to mere facts, as contrasted with the great stress laid on the processes by which those facts are acquired [9, p. 7].

In terms of curricular examples of drawing-to-learn, laboratory instruction from this period was not quite the pure inductive learning as practiced by Agassiz. Assignments were usually tightly prescribed directions with a few more open-ended tasks. For instance, at the University of Kansas in 1914, Professor of Physiology Ida H. Hyde, included the following instructions in one of her physiology class lab assignments:

> Experiment 50. Microscopic Examination of Blood.
> (a) Place a drop of your own blood on a clean slide, cover quickly, and examine under the high power of microscope,
> 1. Draw several red corpuscles as seen flat or suface [sic] view and edgewise (both singly and rouleaux)
> 2. Find and draw a white corpuscle. Compare the number of red and white corpuscles. Compare their size, shape and structure; name all parts. (Note:- Sterilize your skin and the lance or needs, in 95% alcohol before obtaining the blood)
>
> (b) Examine the frog's blood under the microscope and draw as directed above. Draw to the same scale. Write a note of comparison between frog and human blood as to size, shape, and structure. Which are nucleated? [18, pp. 25-26].

At the KU Extension School in the same year, a final examination in a physiology correspondence course contained such open-ended assignments as follows: "Assignment XII. Laboratory Work: Get a sheep's or pig's heart from the market. Draw" [19]. The same exam also asked students to perform the following specific tasks:

> Final Exam questions Over Physiology I: Laboratory Work
> 1. How would you prove that saliva changed starch to sugar?
> 2. Illustrate the path and name the parts of a reflex action. When an object touches the eyes.
> 3. Illustrate a section of the heart, name all the chief parts, showing the vessels that enter and leave the heart.
> 4. Illustrate and name the parts of the whole digestive system.
> 5. Illustrate an epithelial cell, the different parts of the eye, red and white corpuscles, naming all the parts [19].

At Yale University in the 1920s, Sheffield Scientific School students could expect to find similar kinds of drawing activities, a mix of instructions pointing to specifics to be observed and general admonitions to draw. For example, in 1923 Harry W. Cofrancesco (class of '26), completed the following assignment in his "Anatomy, laboratory sketchbook":

> SPERMATOGENESIS
>
> 1. Examine, with the low and the high power, a permanent microscopic preparation of Mouse testis. Note that it consists of a great number of tubules (**seminiferous tubules**) in the walls of which the male germinal cells (sperm) develop. The tubules are greatly convoluted, and, consequently, in the preparation, they are sectioned at various angles. At one side of the testis is a section through the coiled **epididymis**, which constitutes a portion of the conducting tube which carries the mature sperm from the testis to the exterior. Draw the entire testis in outline and fill in a portion with careful detail.
> 2. Select a seminiferous tubule which has been sectioned approximately transversely and study with the high power. Note the arrangement, size, and structure of the **spermatogonia, spematocytes, spermatids,** and mature **sperm**. Draw the entire tubule in outline and fill in a portion, showing, with careful detail, the germinal cells in various stages of maturation.
> 3. Examine the epididymis under high power. Note that the tubules are filled with mature sperm. Draw a tubule to show the structure as observed [20].

As these examples show, the kind of pure inductive learning as practiced by Agassiz was not quite fulfilled. Still, students were rendering observations by drawing and being led fairly strong-handedly to conclusions based on those drawings. In other science laboratory classes such as chemistry and physics, students were often asked to draw experimental apparatus or illustrate experimental results. Drawing was a key long-standing pedagogical technique, not necessarily needing justification for its use or clear criteria as to its assessment.

Despite these activities, the great mass of facts to be mastered and the structure of schooling into discrete blocks of time and discrete units of learning were soon to challenge student-centered approaches as science classrooms entered the 20th century. Repeated criticisms of science education took up many of the same points identified by Agassiz. For instance, by 1910, John Dewey would note that "science has been taught too much as an accumulation of ready-made material with which students are to be made familiar, not enough as a method of thinking, an attitude of mind" [21, p. 122]. However, by the time of the Efficiency Movement swept over all levels of education in the 1920s [22, p. 200], enacting a vision shared by Dewey and Agassiz was simply too costly, both in terms of time and money. By the 1930s, one writer made the problem clear: "Teaching costs per student credit hour in the college sciences are, in many cases, higher than the average cost of all other subjects combined, including the outlay for apparatus and equipment, thus making science instruction very expensive” [23, p. 19].

While student-centered practices might have been inefficient, a far more significant problem was a conflict in the theoretical justification for the teaching of science, one that continues to this day. How one learns science—in other words, an educational philosophy of learning—is rarely expressed in most protestations for or against current methods. The result is often an abstract appeal to what has worked for the individual writer—as was true for Agassiz—or an attempt to make learning more real life without acknowledging the contextual realities of schooling. The result is a recycling of reform efforts, rarely realizing significant change. While this charge might be leveled against many subjects, conflict in the teaching of science is particularly beholden to two competing philosophies: the belief in education as a form of “mental discipline” versus the belief in learning and knowledge as socially constructed in particular contexts. It is that conflict to which I turn next.

MENTAL DISCIPLINE VS. CONSTRUCTIVISM AND THE TEACHING OF SCIENCE

An original justification for the study of science in the late 19th century was its role, in the words of historian George DeBoer, “as a body of useful knowledge, as a way of thinking, and as a tool for disciplining the mind” [24, p. 62]. The last goal was in accord with the view that higher education was to be in the service of “mental discipline” or training of the “mental faculties” [25, p. 22]. This philosophy of learning offered the mind as a muscle of sorts with several “faculties,” each of which needed development in the interest of students achieving a “balanced, reasoning mind” [26, p. 59]. In historian Laurence Veysey’s words, “Taken together, the faculties constituted the divine recipe for a successful human being. If one or more of the elements were stunted, the results would be grotesque” [25, p. 23]. It is easy to see how a pedagogy of daily recitations in classical subjects would enact such a view of learning, but when science began to make its way into the higher education curriculum, its study was offered as a superior subject matter for developing mental discipline. In a series of influential late 19th century lectures, T. H. Huxley weighed in, noting that

> The great peculiarity of scientific training, that in virtue of which it cannot be replaced by any other discipline whatsoever, is this bringing of the mind directly into contact with fact, and practicing the intellect in the completest form of induction; that is to say, in drawing conclusions from particular facts made known by immediate observation of Nature [27, p. 126].

In a sense, study of science could bridge a gap between early notions of education as a constant mental drill in key facts and contemporary ideas of education as a way of teaching students to become independent thinkers. The problem, however, is that this bridge is unstable at best. In a system of discrete disciplines, subjects, and classes—combined with the early 20th century attempts to make schooling (and American industry) more efficient—the goal of acquiring content knowledge would often supersede the goal of becoming a powerful thinker. Evaluating the former was, and continues to be, far easier than evaluating the results of the latter. For science, added pressure came from the explosion of scientific knowledge starting in the late 19th century and continuing today. Thus, mastering scientific facts has always been easy for education to strive toward, but such a goal has been a constant source of frustration for science educators interested in students learning as scientists might.

In contrast to mental discipline as an organizing principle of scientific education, constructivism posits a view of learning that Agassiz himself would have recognized. Central to constructivist belief in science education is the need for one to learn from the natural world, not merely from texts or lectures in a variation of the "banking model" of education, as coined by Paolo Freire [28, p. 58], in which facts are deposited in passive student heads. As described by Wolff-Michael Roth, "Constructivists recognize that, rather than being transferred from one individual to another, knowledge has to be constructed by each individual through his or her active engagement with the physical and/or social environment" [29, p. 146].

Science study, with its vast assemblage of principles and details to be learned, can easily succumb to the sort of knowledge transfer that constructivists decry. Instead, according to Tobin and Tippins, constructivism in science learning holds true the following: "Science does not exist as a body of knowledge separate from knowers. On the contrary, science is viewed as a set of socially negotiated understandings of the events and phenomena that comprise the experienced universe" [30, p. 4]. In this view, however, content is not necessarily sacrificed for the sake of process. Instead, according to Tobin and Tippins,

> Making sense of science is a dialectical process involving both content and process. The two can never be meaningfully separated. The process skills can be thought of as thinking processes, such as using the senses to experience; representing knowledge through language, diagrams, mathematics, and other symbolic modes; clarification; elaboration; comparison; justification; generation of alternatives; and selection of viable solutions to problems [30, p. 9].

As a philosophical principle, constructivism has its roots in the ideas of 19th century educational reformers such as Johann Heinrich Pestalozzi and Johann Frederich Hebart. Both Pestalozzi and Hebart believed in the study of natural objects (as opposed to merely texts) and in the necessity to structure classrooms so that children could pursue what was of interest through a process of discovery [24, pp. 21-30]. The Progressive Movement of the early 20th century is another foundation for these beliefs [22]. Whether called "laboratory-based learning," or "project-based learning," or "inquiry methods," or constructivism, reform efforts have attempted to make the learner's needs central. Unfortunately, while learners' needs seem to remain relatively static, advances in scientific knowledge are dynamic forces. Contemporary practice of science education and the use of drawing as a tool for learning continue to reflect a process/product dichotomy, with product chiefly winning out.

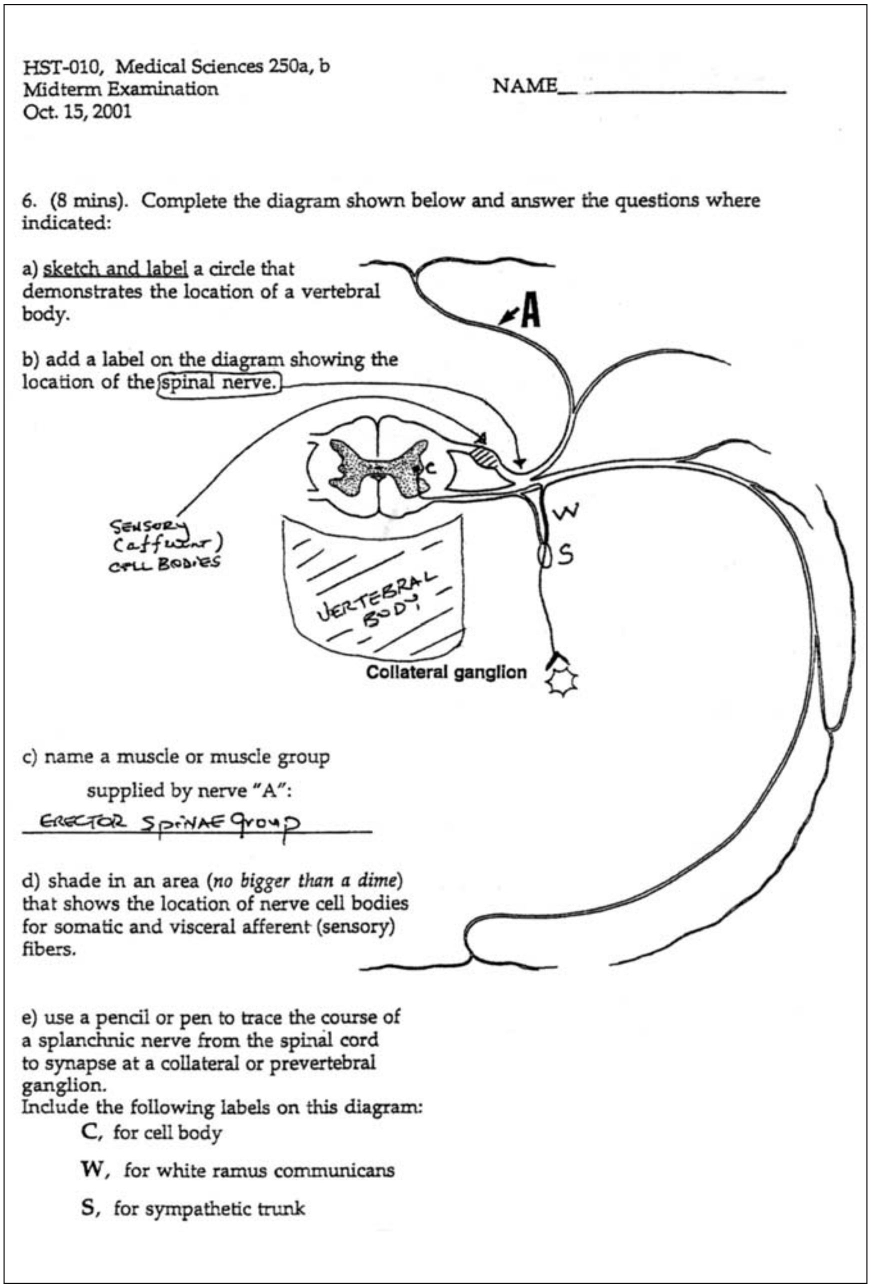
CONTEMPORARY DRAWING TO LEARN SCIENCE

For drawing to learn science—as well as communicating scientific learning via writing or speech—elements of mental discipline and constructivism can be seen in contemporary instructional materials, often simultaneously. Whether the justification is to better prepare students for the contemporary visually oriented world of science or as an effective learning technique, most uses of drawing do not necessarily make explicit the assumptions about teaching and learning that underlie these approaches. As is true in many educational practices, the logic is largely based on anecdotal evidence, whether it worked for the author of the materials or because it is simply the way instruction has always been done. Dominant, too, is drawing as a way of communicating what students might know, particularly in exam situations, rather than as a generative way of learning content. In this struggle, mental discipline seems to prevail.

In anatomy and physiology classes—both graduate and undergraduate—the long-standing appeal of drawing continues to hold sway. For example, for a recent midterm examination from Harvard Medical School students generally needed to fill in identifications in pictures or drawings supplied. However, one question asked students do some drawing as well as labeling/identification. As shown in Figure 1, this kind of assignment is remarkably similar to those assigned at the University of Kansas in 1914, reinforcing the use of drawing as primarily a means for students to demonstrate their content knowledge.

A variation on this approach is a series of popular scientific "coloring books." In one, Robert D. Griffin offers students a way of mastering biology by coloring in detailed drawings of bodily systems. In his preface to *The Biology Coloring Book,* Griffin describes a quite mentally disciplined approach as coloring is primarily in the service of memorization and focus:

> The coloring activity is not some sort of happy playtime but an integral part of what has proved to be a highly effective learning method. [. . .] Not only does this physical activity make it much more difficult for your mind



HST-010, Medical Sciences 250a, b
Midterm Examination
Oct. 15, 2001

NAME__

6. (8 mins). Complete the diagram shown below and answer the questions where indicated:

a) sketch and label a circle that demonstrates the location of a vertebral body.

b) add a label on the diagram showing the location of the spinal nerve.

c) name a muscle or muscle group

supplied by nerve "A":

ERECTOR SPINAE GROUP

d) shade in an area (*no bigger than a dime*) that shows the location of nerve cell bodies for somatic and visceral afferent (sensory) fibers.

e) use a pencil or pen to trace the course of a splanchnic nerve from the spinal cord to synapse at a collateral or prevertebral ganglion.
Include the following labels on this diagram:

C, for cell body

W, for white ramus communicans

S, for sympathetic trunk

Figure 1. Midterm Examination from Harvard Medical School, HST-101, used with permission of the author [31].

> to wander to some other topic, but it also requires the activity of the parts of your brain that are involved in movement and in perception of color and shape. [. . .] As you probably know, the more areas of your brain you involve simultaneously in trying to learn something, the more easily you will understand and remember the material [32, n.p.].

In addition to the justification based on mastery of content, some authors argue for drawing to learn as essential to the development of science students' "visual-spatial thinking," according to James Mathewson. This strategy centers on replicating the processes of scientists: "Science and technology develop through the exchange of information and much of this is presented as diagrams, illustrations, maps, plots, schematics, etc." [33, p. 37]. Perhaps the best known proponent of these approaches is Edward Tufte, a Yale statistician and sculptor who offers readers ways of "visualizing data" in order to more effectively communicate and argue for scientific content [34].

Other contemporary approaches to having students draw to learn science focus on ideas of multiple modes of learning. For example, a pilot solid state chemistry class at MIT used "picturing to learn," which asked students to "create drawings from the concepts they learn from lectures and texts" [35, p. 1]. According to co-creator Felice Frankel, this technique can be effective because "visual thinking is one of the keys to a holistic understanding of any concept" [35, p. 1]. In an interview on the subject, Frankel added, "It is how I learn" [as cited in 35, p. 1].

THE FUTURE OF DRAWING TO LEARN SCIENCE

Fully enacting constructivist philosophy in the science classroom—particularly in higher education—has faced many challenges. For every call for students to learn to think scientifically and to create the next generation of world-class scientists, there comes another survey (and its associated standardized test) demonstrating how little students know about the *basics.* The tentacles of mental discipline are, indeed, many, much less the realities of overcrowded classrooms, the low priority of teaching for many science faculty faced with publish-or-perish pressures, and the dominance of standardized textbooks. There is also simply the idealized nature of a drawing-to-learn process as practiced by Agassiz and his followers. George DeBoer sums up his history of reform in science education with the following:

> It is questionable, then, that we will make better observers (and thus better scientists) out of students by having them carefully examine some object and telling us everything they observe. Likewise it is important for us to realize that not every observation leads inevitably to a sensible inference,

> especially if the student does not have an adequate conceptual background in that area [24, p. 232].

What cycles of educational reform in all fields demonstrate is that pedagogical techniques—whether fully grounded in sound theory or simply person's experience—will rarely meet the reality and challenges of implementation. For educators who ask their students to draw to learn science, success will depend on recognizing and countering these challenges. A starting place is simply one of goals and theory and recognizing the potential conflicts between ideas of mental discipline and constructivism. Another is certainly the spirit of Agassiz's vision of student learning. Shortly before his death, he offered the following advice to his natural history students on the island of Penikese, many of whom would go on to illustrative careers as scientists and science educators: "You can take your classes out, and give them the same lessons, and lead them up to the same subjects you are yourselves studying here. And this mode of teaching children is so natural, so suggestive, so true" [as cited in 7, p. 348]. Drawing to learn science certainly has that appeal, but its future success as an instructional technique will require more than replication. Instead, essential to success are a justification thoroughly grounded in sound theory and a recognition of the potential barriers—both historically and currently.

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