A Place for the Nature of Biology in Biology Education

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Abstract

Although the nature of biology and the nature of the physical sciences share many common aspects, the focus of biology – life – creates unique philosophical, methodological, and ethical premises on which biology should be understood. Unfortunately, school science often ignores the unique questions, obstacles, and claims raised by the study of life. This paper synthesizes the existing literature on the nature of biology with the new dimensions of the *Framework for K-12 Science Education* to argue that the nature of biology can play an important role in the biology classroom. Obstacles to this approach are identified and possible research questions are raised for the science education community.

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Introduction

"There is only one science, physics: everything else is social work."
– James Watson, Nobel Laureate in Medicine (Rose, 1997, p. 8)

James Watson's words illustrate the tenuous position that biology has long held among the sciences (Grene & Depew, 2004; Mayr, 2004; McComas, 2003; Rudolph, 2002). While this physics-centric view might be expected from the likes of Galileo, Kepler, or Newton, it is surprising that a preeminent biologist provides this perspective. However, beginning with the Scientific Revolution, biology has often been subordinated to the physical sciences, largely due to the latter's initial success at explaining causal mechanisms of the natural world (Harding, 1991; Magner, 2002; Rosenberg, 1985; Sober, 2003). Centuries later, despite advancements in areas like germ, cell, and evolutionary theory, social and political factors – especially the need for advanced weaponry in the two World Wars – funneled disproportionate amounts of research funds to physics and chemistry research (Rudolph, 2002). Yet, despite being overshadowed by and often conflated with the physical sciences, biological achievements arise from an enterprise whose philosophical, methodological, and ethical positions differ, at times, from the other scientific disciplines (Ayala & Arp, 2009; Mayr, 2004; Rose, 1997; Schrödinger, 1944).

Extensive volumes have detailed diverse perspectives on the nature of biology (e.g. Agutter & Wheatley, 2008; Matthen & Stephens, 2007; Panchen, 1992; Ruse, 2007) and an expanding literature is focused on the role of the history, philosophy, and epistemology of biology in biology education (e.g. Reydon, 2011; Svoboda & Passmore, 2011). The recent publication of the *Framework for K-12 Science Education* (National Research Council, 2011) provides a new, unique opportunity to articulate how a discipline-specific nature of biology can be integrated into biology education to enhance what is currently taught about the general nature of science. I argue that this will improve biology education's ability to focus on core disciplinary ideas and scientific practices. But this task raises many questions including: How is studying life similar and different from studying the physical world?; What implications might these differences have for the teaching and learning of biology?; and How can the nature of biology – its history, philosophy, and epistemology – inform students about the practices of science in developmentally appropriate ways? This position paper draws on the existing nature of biology and science education literature to identify opportunities and obstacles for incorporating a more discipline-specific nature of biology into biology curriculum and instruction as a means to faithfully fulfill the charge issued by the *Framework for K-12 Science Education*.

To accomplish this goal, this paper first conceptualizes what is meant by the nature of biology – not a unitary, fully established construct, but rather a contested and evolving understanding of how the living world exists and is studied. Next, the paper discusses three of many possible aspects of the nature of biology – essentialism, determinism, and ethics – and possible opportunities and obstacles for their inclusion in the biology classroom. The paper concludes by raising further questions for researchers who, in collaboration with practitioners, can make significant contributions to our understanding of the place for the nature of biology in biology education.

Conceptualizing the Nature of Biology

Suggesting that the nature of biology deserves a more significant role in biology education first requires a conceptualization of this construct. Unfortunately, narrowly defining even the more general nature of science, let alone the nature of biology, has, at times, been contested among historians and philosophers of science (Gieryn, 1999; Smith & Scharmann, 1999), thus resulting in educational practices that reflect multiple perspectives. For example, science education researchers McComas and Olson (1998) posit that no less than four disciplines – philosophy, history, sociology, and psychology of science – comprise the nature of science (p. 41), while Lederman's (1992) literature review of students' and teachers' conceptions of the nature of science defines the construct as "the values and assumptions inherent to the development of scientific knowledge" (p. 331). These definitions show distinct, but not necessarily contradictory positions, but as Smith and Scharmann (1999) argue, the nature of science is quite unsettled as, "positivists argue with radical constructivists, who argue with empiricists, not to mention the realists, feminists, Marxists, multiculturalists, universalists…and so on, ad infinitum" (p. 494). Similarly, the nature of biology cannot be clearly defined and is best understood as a set of socially negotiated, diverse, and contested perspectives

(Harding, 1991) that are continuously constructed by those participating in the conversation (Smith & Scharmann, 1999).

While a consensus definition of the nature of biology is absent from the literature, Gieryn's (1983, 1999) notion of "boundary work" for defining science from non-science provides a helpful framework for conceptualizing the nature of biology with respect to the nature of physics or the more general nature of science. Gieryn's extended analogy compares the nature of science to mapmaking. He stresses that many factors – a map's purpose or its readers – impact how the contour and landscape is represented, all in an effort to "help us find our way around" (Gieryn, 1999, p. 7). The boundaries of the map, such as those that might be demarcated between the nature of biology and the nature of the other sciences, can be solid on one map, but blurred and overlapping on another and regardless of their current state, always susceptible to change and contextualization. A map of the nature of biology created by a scientist may not fully account for the philosophical terrain while a philosopher's map may not recognize the practical obstacles that must be negotiated to further the boundaries of biological knowledge. Given this rugged terrain, it would be naïve, and likely unhelpful, to assume that middle or high school students need to be fluent in the history or philosophy of biology. Rather, in order to better understand the major explanatory accounts and practices of biology, students should recognize that in some ways, the nature of scientific disciplines differ from each other. Thus, the history, philosophy, sociology, and epistemology of a discipline can impact one's understanding of science and its applications.

It is beyond the scope of this paper to adequately discuss all of the epistemological, philosophical, or historical perspectives that comprise the nature of biology. Therefore, the following sections focus on three constructs – essentialism, determinism, and ethics – as cases for the role that the nature of biology might play in biology classrooms as they adopt the new science education framework. Each section provides a brief description of how, at times, each construct is uniquely positioned in the nature of biology, the implications this has for biology teaching and learning, and suggestions for how this idea might add value to classroom practices that already promote the general nature of science.

Essentialism, Taxonomy, and Model Organisms

Charles Darwin's *On the Origin of Species* provided biology with an overarching explanatory theory that radically changed the discipline (Rudolph, 2002; Ruse, 1999; Sober, 2003). This theoretical framework revolutionized biologists' understanding of taxonomical relationships and in doing so, raised new questions about essentialism within the biological sciences. Essentialist philosophy, as established by Plato, Aristotle, and the Pythagoreans (Rudolph & Stewart, 1998; Ruse, 1999), argues that natural phenomena are defined by classifiable "essences"; an entity possesses specific characteristics that are both necessary and sufficient for inclusion in a particular class (Agutter & Wheatley, 2008; Reydon, 2011; Ruse, 1999; Sober, 2003). Given these characteristics, one member of the class can represent any other member of that class. For example, the Pythagoreans showed that triangles fundamentally differ from other multi-sided figures – all triangles have three sides, no triangle can have more than one obtuse angle, and the sum of the interior angles equals 180°. Variation occurs in the types of triangles – obtuse, scalene, and isosceles – but all triangles possess fundamental properties that differentiate them from other polygons and negate the possibility of intermediate figures (Mayr, 2004).

In the science studied in schools, this philosophical position applies well to the physical sciences where the exploration of what Schrodinger (1944) calls "periodic crystals" – groups of matter, such as atoms, that have specific characteristics that hold true across time and space (Ruse, 1988) – is the norm. For instance, a chlorine atom with 17 protons not only represents all other chlorine atoms, but also distinguishes itself from elements like bromine or argon. Similarly, a magnet necessarily has two poles, north and south, in which opposite ends attract and like ends repel. Magnets come in various types – bar, disc, horseshoe, permanent, temporary – but all magnets possess fundamental properties that define their "essence."

At first glance, biology's extensive taxonomical research might suggest that an essentialist perspective would also be a useful framework for understanding the life sciences (Rudolph & Stewart, 1998). Indeed, the ordering of millions of organisms into kingdoms, phyla, and species based on particular attributes or essences has helped us better understand relationships among living things. In popular textbooks, like Holt's *Biology*, essentialist themes can be found in the dozen or so chapters that classify the earth's different living organisms by introducing "typical" species (DeSalle & Heithaus, 2008), thus allowing students to get a sense of the traits that comprise the diversity of earth's microbes, plants, and animals. However, this essentialist perspective provides, as Gieryn (1999) might say, only one map of the discipline that does not detail all the contours and boundaries of what we now understand about life. For example, the classification scheme portrayed in textbooks fails to recognize the controversy among biologists about whether a three-domain hierarchy that utilizes genetic relationships is more accurate than the traditional five-kingdom hierarchy that is ordered on congruent structures (Hedges, 2002). Furthermore, the concept of "species" – so fundamental to our understanding of the living world and important in research and conservation decisions (Reydon, 2011) – has ignited debate over its ability to be defined (Grene & Depew, 2004; Mishler, 2009). Some biologists identify species by essential physical traits, some by their ability to interbreed, some by the increasingly popular use of molecular genetics, and some negate the existence of unique species altogether (Mishler, 2009; Sober, 2003). Unfortunately, high school textbook chapters do not represent classification schemes as socially negotiated theoretical constructions that are useful in some contexts, but flawed in others. Rather, the books portray taxonomical classifications as what "is", merely reinforcing what Schwab deemed science education's "rhetoric of conclusions". With a focus in the new *Framework* on fewer core disciplinary ideas, engaging students in a deeper understanding of how biological evolution impacts unity and diversity among organisms is an appropriate place for inserting aspects of the nature of biology in biology education.

The flaws of an essentialist perspective extend beyond biological classification. At the micro level, a comparison of cells to the chlorine atoms described above is helpful in making this point. All chlorine atoms are defined by a structure of 17 protons and each chlorine atom can be expected to function the same way in a given environment. In contrast, specialized cells can vary in both composition and function not only among different organisms, but also in the same environment (Rudolph & Stewart, 1998; Ruse, 1999). For instance, muscle cells from different organisms will produce varying levels of proteins – the drivers of cell function – based on differences in the genetic code. Even muscle cells from the same tissue can vary in the amount of mitochondria and thus, their respiratory function in the tissue varies. Similarly, healthy red blood cells may all bind oxygen, but the binding affinity and metabolic rate at which this process occurs differs slightly from cell to cell. Although cell types are more alike than different – hence they can be classified as skin or nerve cells – it is important for students to understand that variation, however slight, is a result of and can affect long-term evolutionary processes (Love, 2011). Even at the macroscopic level, the intellectual, behavioral, affective, and physical differences between identical twins – organisms that are genetically the same – exemplify how an essentialist framework can fall short in biology. Said best, perhaps, by Schrodinger (1944), in contrast to the "periodic crystals" explored by the physical sciences, biology explores life's "aperiodic crystals" that are both ordered and consistent, but vary among individuals and populations.

Beyond this handful of examples, how might a better understanding of the nature of biology, specifically essentialism, be incorporated into biology classrooms in ways that matter? As mentioned above, the new *Framework for K-12 Science Education* integrates scientific practices into the heart of the curriculum. In biology, a student's understanding of the nature of biology directly impacts how students understand a major biological practice – the use of model organisms. The use of models and model systems is inherent to all scientific disciplines and is identified in the new *Framework for K-12 Science Education* (National Research Council, 2011) as a crosscutting concept common across all fields. But if teachers only focus on the general notion that all scientific disciplines use models and model systems, then students may not fully understand how living model organisms affect biological practices and results.

Studying life presents several unique challenges to biologists that require the careful selection of model organisms. Temporal factors such as life span and reproductive period limit what organisms can be studied and make research on many evolutionary relationships especially difficult. Historically, many model organisms have been chosen mainly for economic reasons (Hedges, 2002). Given these and other limitations, the range of living organisms that have been used for extensive research represents only a small fraction of living organisms on earth. For example, among the approximately 300,000 plants that exist, only a "handful" of species and families are used as models (Hedges, 2002, p. 843). Furthermore, for technical and ethical reasons, a large portion of research on human health and diseases are carried out on model organisms like yeast, fruit flies, and mice. Understanding how evolutionary similarities allow researchers to make claims about human mechanisms from single-celled organisms or rodents is an important bridge between biological practice and knowledge construction.

Equally important, students should recognize the limitations of model systems and the assumptions that biologists must make in order to use them. For example, when one hears a report in the media about a successful cancer drug tested on mice, understanding how close and how far this model system is to the human body may determine how this information is evaluated. Furthermore, a deeper understanding of biological model organisms helps one understand that for practical reasons, scientists may assume an essentialist framework by ignoring or technically limiting inherent variation among individual model organisms (Reydon, 2011). For example, plasmids, circular pieces of extra-chromosomal DNA, containing a gene of interest can be injected into bacteria that can then be cloned for research purposes. Analogous procedures using “p-elements” in fruit flies and breeding in mice can also produce organisms with specific genotypes and phenotypes. These procedures are important for biologists in order to run controlled experiments with large enough sample sizes that can produce significant results (Love, 2011). However, students should be aware that this practice knowingly limits variation that is present – variation that is the raw material on which evolutionary pressures can change the structure and functions of life. By purposefully excluding variables or controlling the phenotype-environment interactions, scientists explore one frontier while they risk missing something of evolutionary importance (Love, 2011).

Specifically, teachers might address this aspect of the nature of biology with an objective in which students, “Develop an understanding of the scientific value and limitations of using living model organisms in biological research, especially as they pertain to an understanding of human health, medicine, and physiology.” Translated into practice, teachers could address this standard by presenting students with case studies of historical or contemporary experiments that use model organisms such as fruit flies, frogs, or mice. Along with exploring the conceptual principles at hand, students could discuss developmentally appropriate perspectives of essentialism and living organisms. For example, students learning about the cell cycle and cancer might investigate current attempts at cancer cures that use model organisms. While exploring current case studies of cancer research on mice, students could be presented with the questions: “Will all mice and all cells react in the same way to the treatment?”, “If not, how will this impact the interpretation and validity of results?”, or, “How generalizable are these results to other living organisms such as humans?” Addressing these questions can give students an opportunity to analyze living model systems that are unique to biology and think about ways in which popular media reports about health issues should be interpreted.

Essentialism is a complex, often contested philosophical concept that has practical implications. In some cases, an essentialist assumption allows biologists to further expand our understanding of the living world. In other cases it limits their understanding of long-term evolutionary implications. Conveying this complexity and tension may have less applicability for teachers of the physical sciences as atoms, molecules, and colliding bodies can generally represent all entities of the same class in the same conditions. In contrast, life science teachers who present these ideas to students in a developmentally appropriate way, present students with a more accurate representation of the structure of the discipline and its practices, place these positions within an evolutionary context, and allow students to view critically how essentialist positions both help and limit what we understand, among other concepts, about our own health and physiology.

Determinism and Genetics

The importance of deterministic physical laws – descriptive patterns of regularity seen in nature – in the advancement of science, even for biology, cannot be overstated. The 18th century satirical poet, Alexander Pope, captured the reverence for Newton's famed laws by writing, "Nature and Nature's Laws lay hid in Night. God said 'Let Newton be!' and all was Light." In school science, Newton's laws of motion provide a reliable, mechanistic and deterministic view of the physical world. In reality, physical science research, especially modern physics' investigations of quantum mechanics, recognizes the important role of probability and random chance in the physical world (Howson, Urbach, & Gower, 1993). But in K-12 settings, time spent on physical science generally assumes a Newtonian deterministic framework (Barad, 1999). When applied to biology, however, this same deterministic position may cause students to inappropriately adopt mental models of the living world in which nature necessarily behaves in particular ways.

While a comprehensive discussion of determinism in biology is beyond the scope of this paper and beyond what is necessary for high school biology students to understand, the following examples illuminate how the nature of biology and determinism impact one's understanding of the living world. To begin, a comparison of Newton's first law of motion and Mendel's law of independent assortment is helpful. A knowledgeable high school physics student might state Newton's 1st law as saying "A resting object on which no net force acts will remain at rest and a moving object on which no net force acts will continue moving at a constant velocity". This student could use basic motion detectors or photogates to confirm this law within the limits of technological precision. In most classroom settings, aberrant results would not disprove the law nor limit its predictive power, but rather would be attributed to the presence of unaccounted forces, like friction or technological error. To the student, Newton's law is exact and any deviance from what the law predicts is due to his error or the constraints of the technology; how an object behaves is determined by the physical laws (McComas, 1998).

Students learning about and applying Mendel's law of independent assortment – foundational for genetics – would have to approach an investigation quite differently. If students crossed fruit flies, the results would vary from group to group. While biology students could attribute some deviation from the expected phenotypic ratio to technological error or mishandling of the flies, the nature of the biological law is ultimately the reason for this difference. Biological laws are far more contingent and probabilistic than the deterministic physical laws represented in textbooks. Mendel's laws provide a pattern of nature, but a pattern that lacks the predictability of Newton's first law for individual cases. Brandon (1997) argues that given these differences between the disciplines, biological laws are less law-like in the physical science sense and more accurately described as "contingent regularities" (p. S444).

Discoveries in developmental biology also support instances in which biology is better viewed not as a set of deterministic laws, but contingent regularities. Experiments in this field have shown that early stage embryonic cells can be explanted and when given the proper signals, develop into various cell types. For example, fruit flies exhibit specific eye patterning in which undifferentiated cells can develop into cells of either a primary or secondary fate; the results of this process being random as any cell in a group has an equally likely chance to induce nearby cells' fates. These cells have genetic predispositions that can fill multiple roles, but random chance and the environment produce a cell signal that tips the scales in favor of one cell developing a primary cell fate while the neighboring cells develop a secondary fate. Similarly in humans, totipotent embryonic stem cells have the capacity to differentiate into any of the nearly 250 types of human cells. This occurs because cells follow not only the laws of physics, but also respond to their environment, their genetic program, and random chance (Mayr, 2004; Rose, 1997).

The above examples suggest that biological laws can be understood and applied in ways different from the more deterministic physical laws (McComas, Clough, & Almazroa, 1998). As with other aspects of the nature of biology, it is important to note that biologists and philosophers of biology represent a spectrum of views about determinism in the discipline. Dawkins (1976), for example, offers a more deterministic vision of biology in which life can be explained as an attempt by the gene to ensure its preservation – an argument elaborated in his book, *The Selfish Gene*. In contrast, Rose (1997) conceptualizes genes not as deterministic mechanisms, but rather as toolkits that interact with the environment that let "organisms determine their own future" (p. 137). Similarly, in a thought experiment, Gould (1989) "winds back the tape of history" and in starting over, believes that no evidence suggests that life would turn out the same way.

The range of views expressed above from Brandon to Dawkins and Rose to Gould indicate that like other aspects of the nature of biology, the terrain is rocky and unsettled, all the more reason, perhaps, to explicitly address determinism in the biology curriculum. In the living world, life is beholden not only to the laws of physics, but also evolutionary pressures and probability that confront how students understand the living systems they encounter. Merely following a deterministic map of biological processes prevents students from exploring other important thoroughfares in the living world, namely, the role of random chance, an organism's genetic program, and an organism's interaction with its environment that can affect its future in unpredictable ways – each of these factors critical to understanding the core disciplinary ideas of inheritance and variation of traits and the ecosystem interactions.

Ethics

The new *Framework* does not specifically include the study of ethics in its crosscutting ideas or scientific practices, but the document clearly articulates that science should be framed as a human, social endeavor that has "moral and cultural underpinnings that vary across cultures" (National Research Council, 2011, p. 10–5) All scientific disciplines address ethics, but the "maps" of ethical terrain vary by discipline. Integrating the nature of biology with ethics in the biology classroom has the potential to provide students an even more nuanced and deeper understanding of the discipline. The following example shows one significant way in which the nature of biology may be applied to biology education that is unique from other scientific disciplines.

Consider the science behind the creation of the atomic bomb in World War II. This project required extensive physical science research that incorporated nuclear physics principles derived by scientists like Rutherford, Cockroft, and Walton – research that was not originally intended for the creation of a destructive weapon. In this case, a great deal of the knowledge fundamental to the creation of the atomic bomb was constructed not with this application in mind, but rather as the furthering of knowledge of nuclear science. By itself, exploring the nucleus raised few ethical questions, but the secondary consequences of this research – its application to the atomic bomb – raised enormous ethical questions about its use for the destruction of life and infrastructure.

Now consider the biological example of embryonic stem cell research. This sub-discipline studies the function and application of totipotent stem cells that, given the right stimulus, can form different cell types. Embryonic stem cells are undifferentiated cells that exist four to five days after fertilization when the embryo ranges from 50 – 150 cells. Since each stem cell can potentially form any of the nearly 250 different cells in the human body, current research looks to manipulate embryonic stem cells in hopes of developing methods to reverse the effects of such maladies as spinal cord injuries or Parkinson's disease. To achieve these goals, some stem-cell research requires the creation, use, and destruction of human embryos.

The social consequences of stem cell technology and its application are clear – with effective use, human lives will be changed, hopefully for the better. However, many groups regard stem cells as the constitutive elements of a living human being and question whether the use of such 'life' is justifiable for the good of others. In contrast to the physics example in which the *application* of scientific knowledge raised ethical questions, stem cell, and other biological research often raises questions about the actual *investigation* – the researcher's initial right to intervene with a living organism (National Research Council, 2011, pp. 10–5). Few people question the morality of applying scientific knowledge to relieve the suffering of humans debilitated by disease, but extensive and often heated arguments at the local and national level have occurred between those who consider life to begin at conception and those who consider life or the humanity of individuals to be defined at a much later time of development (Burley, 2011).

Stem cell research is not the only instance that raises the question of a researcher's right to intervene. Many biologists use animals as proxies for human testing. Millions of animals – frogs, mice, monkeys – are raised solely to be injected with lethal and in some cases painful pathogens. As a result, humans benefit from new drugs and treatments, but do so at the expense of non-human life (Festing & Wilkinson, 2007). Similar questions about the ethical nature of this enterprise arise each year in biology classrooms when students are required to participate in the classic biology dissection lab. Intended as a pedagogical tool to illustrate the complexity of life and provide students with a hands-on anatomy and physiology experience, many teens find the practice of killing animals for the purpose of demonstration morally vexing (Balcombe, 1997; Sapontzis, 1995; De Villiers & Monk, 2005). In one study, when asked whether they felt it was wrong to breed animals for dissection, 73% of nearly 500 high school students answered affirmatively (Millett & Lock, 1992).

Both biology educators and students have questioned the right or necessity of destroying life to reach academic goals (De Villiers & Monk, 2005). Each classroom must decide whether to use dissections or less-invasive means such as electronic simulations. Ultimately, the biology teacher is responsible for the final decision, but involving students in the ethical discussion behind this decision is an educative opportunity that not only shouldn't be missed, but also highlights the different types of ethical issues that can arise from different practices. In the classroom this might play out as part of the scientific practice "planning and carrying out investigations." Biology students might be asked to discuss the ethical boundaries that are approached when dissecting and working with living or once living organisms. While science ethics and discussions of ethical issues are important for the development of all future citizens regardless of the discipline, engaging in discipline-specific comparisons such as ethical issues that arise sometimes at the point of investigation and other times at the point of application will provide students with a better understanding of the variables that affect the structure of different scientific disciplines.

The Nature of Biology in Biology Education: Opportunities and Obstacles

This paper has focused on three short cases – essentialism, determinism, and ethics – in which the nature of biology has a place in biology education. Due to practical reasons, many aspects of the nature of biology like reductionism and teleology have been left off the table (for introductory information on these topics see, for example, Ariew (2007) and Hull (1974), respectively). However limited, the above discussion suggests that understanding the natural phenomena of life and the practices of the life sciences is made more accurate by having students engage explicitly biology's complex, contested, socially constructed, and sometimes unique nature. The same could likely be said for other science disciplines taught in schools including chemistry, physics, and earth science, but biology provides an important example since its concepts and practices have often been reduced to the physical sciences (Ruse, 1988; Takacs & Ruse, 2011; Van Regenmortel & Hull, 2002). With the coming release of the *Next Generation Science Standards*, the time is ripe to reflect on the opportunities for the nature of biology in biology education – like those discussed above – and think about the obstacles that remain in the way of its integration.

In order for biology teachers to change their practice, curricular resources must be available that more accurately represent the nature of biology. Textbooks are only one curricular tool for science teaching, but in biology classrooms, "the teacher and a single textbook are more important than any curricular materials or curriculum design in determining the focus of biology education in the secondary schools in the United States" (Hurd, Bybee, Kahle, & Yager, 1980, p. 395). One estimate in the 1980's suggested that 90% of science teachers use a textbook 90% of the time (Hurd, Bybee, Kahle, & Yager, 1980, p. 395) and while this may represent an extreme position, recent studies show that biology teachers – especially novices – rely on textbooks for over 50% of what is taught and over 70% of how it is taught (Weiss, Pasley, Smith, Banilower, & Heck, 2003).

Unfortunately for students, these highly influential resources have been consistently criticized for more than half a century for their poor instructional resources (American Association for the Advancement of Science, 2005), overwhelming vocabulary (American Association for the Advancement of Science, 2005), and difficult lexico-grammatical structure (Hurd, 1983). One of the strongest criticisms, however, is aimed at how traditional textbooks represent the concepts as "inevitable rocklike formations that have existed for all time" (Arons, 1988, p. 15). Rather than reflecting biology content and processes as a product of inquiry rooted in living phenomena, a textbook's expository prose and authoritative claims result in what Duschl (1990) termed, "final form science".

Recent editions of widely-used textbooks do not totally ignore the nature of biology, but often sequester its inclusion to a few pages at the front of the book (Duschl, 1990). For example, in the popular Holt *Biology* (DeSalle & Heithaus, 2008) textbook, topics like "The Nature of Science", "Scientific Methods" and "Tools and Techniques" are briefly discussed in the first nineteen pages, but are not integrated with the remaining nine hundred pages of content. As Schwab (1962) suggests, this organization can be counterproductive as "a pious preachment of generalized caution and doubt in an introductory chapter will have no effect whatsoever. It is the massive influence of the hundreds of pages of running text, with their burden on content…which will do this work if it is done at all" (p. 60). Yet, despite extensive criticisms, traditional textbooks have changed very little while their adoption rate remains high (Lumpe & Beck, 1996; Wood, 2002).

Textbooks are unlikely to transform their content or organization and these texts will continue to provide students with a "lens for viewing and interacting with the world" (Chambliss & Calfee, 1998, p. 2). Therefore, the opportunity exists for students to engage other texts that can provide multiple lenses for how they come to understand not only content, but also the nature of studying living things. To accomplish this task, students need to encounter multiple texts side-by-side, focused on the same biological concepts so that they can construct a more multi-dimensional understanding of biology and its practices. Similar to the use of discrepant events to help science students confront alternate conceptions (Clement & Steinberg, 2002; Hammerich, 1998), students could also engage "discrepant texts" – texts that provide a different lens through which the nature of biology is presented when compared with traditional textbooks. These texts could include philosophical, methodological, or ethical perspectives related to the biology that students are learning. Issues of determinism and genetics provide one opportunity for this pedagogical approach. While exploring the foundational questions of inheritance and heredity, students could read excerpts from Dawkin's *The Selfish Gene*, Mayr's *What*

Makes Biology Unique, and the traditional textbook – that could spark student discussion of how determinism may or may not apply to living organisms. In other circumstances, like that chronicled in Weinstein's (2010) *Bodies Out of Control*, students could read textbook accounts as well as journal articles, newspapers, and magazines to explore how disease, unique to living organisms, not only affects living organisms, but also social interactions and public decision-making.

Properly scaffolded with reading guides and graphic organizers, this multi-textual experience could provide students with an opportunity to look at different aspects of the nature of biology and also help students recognize the strengths and limitations of information conveyed in traditional textbooks. Clearly, designing these modules would require time and resources, but some "discrepant texts" are already available to teachers like those produced by Hagen, Allchin, and Singer's *Doing Biology* (1996), historical case studies of major biological discoveries. Since it is unlikely that traditional textbooks will better integrate a more accurate account of the nature of biology with biological concepts, it is even more important to provide students with a variety of texts that can supplement the explicit explanations in traditional textbooks with different lenses on the nature of biology.

As Hurd mentioned above, the textbook as well as the teacher are the most important influences in determining the biology curriculum. Teachers represent a major variable in determining how well the nature of biology can be integrated into biology education. Literature reviews on the more general nature of science in science classrooms indicate that for several decades many teachers have held misconceptions about the nature of science, misrepresent the nature of science to students, or avoid addressing the nature of science altogether and focus instead on imparting scientific facts (Bell, Lederman, & Abd-El-Khalick, 1997; Lederman, 1992; McComas, 2003; McComas et al., 1998). As Lederman (1992) documents, calls for improving teachers' presentation of scientific practices date back to the early 1900's and multiple studies over the past century have corroborated deficiencies in students' and teachers' conceptions of the nature of science.

This problem, therefore, is well known and expecting teachers to incorporate more discipline-specific perspectives of biology when a general nature of science is often misconceived, poses even greater obstacles. But underlying this obstacle is a potential opportunity for the science education research and teacher preparation communities. In most cases, teachers lack the time, training, and resources necessary to shift practice from conveying a general nature of science to, when appropriate, also conveying a discipline-specific nature of biology. Science education researchers can play a significant role in both defining how the nature of the discipline can be better reflected in classrooms that in turn can lead to training and resources that support these changes.

To begin, researchers need to build on the extensive, existing work devoted to understanding teachers' and students' conceptions of the nature of science (National Research Council, 2011) and develop a more focused picture of how these groups conceptualize the more specific nature of biology. Given the emergent and changing nature of biological research, philosophy, and practices, identifying the range of existing perspectives is essential for building on teacher, student, and even publishers' prior knowledge toward a more complicated understanding of how life is understood, life science is practiced, and how both of these domains are best communicated to students.

Prior to establishing curricula and professional development that helps teachers effectively incorporate the nature of biology into their classes, initial research aimed at identifying teachers' existing perspectives on biology might explore the following questions:

1. How do biology teachers perceive the different fields within biology and their relationship to other sciences, specifically the physical sciences?
2. What do biology teachers believe they are communicating to students about the nature of science and more specifically, the nature of biology?
3. What are biology teachers *actually* communicating in terms of the nature of science and the nature of biology in their biology classrooms?
4. Do particular teacher characteristics (e.g. lab experience, post-graduate degrees, undergraduate major, coursework in philosophy of science) correlate with more or less sophisticated philosophical, methodological, and ethical models of the nature of biology in biology classrooms?

Answering these questions will require diverse methods and instruments including classroom observations, surveys, quantitative analyses and access to representative samples of biology teachers from different backgrounds and in different stages of their teaching careers.

If efforts to integrate diverse perspectives of the nature of biology take hold, research on the impact of such changes will be extremely important for identifying how students' understanding of biological concepts and the structure of the discipline are shaped by this approach. In particular, research questions might focus on various aspects of what the *National Science Education Standards* (National Research Council, 1996) defined as hallmarks of scientifically literate citizens. Some initial questions might include:

1. How do students' existing beliefs about the nature of biology change after participating in a biology course that integrates different lenses focused on the unique nature of the discipline?
2. Does learning about diverse perspectives of the nature of biology affect students' conceptual understanding of the discipline?
3. Does the incorporation of diverse perspectives of the nature of biology into the biology curriculum affect student interest or engagement in the subject?
4. Does learning the philosophical, methodological, and ethical principles of biology affect students' abilities to make personal decisions, read popular media critically, or participate more thoughtfully in society?

These questions only begin to explore an area for which a great literature exists – the philosophy, epistemology, and ethics of biology – but for which much less is known about how discipline-specific perceptions of the nature of a discipline shape what occurs in the classroom and the classrooms' outcomes. Empirical studies and innovative ideas for educating teachers in the broad perspectives of the nature of biology are just two important ways in which science education research can contribute to the many calls for change in science teaching and learning in the United States. Progress toward the incorporation of the nature of biology and documenting this progress will provide a valuable addition to the literature and, may ultimately provide valuable information to shape teaching practice and student learning.

Concluding Thoughts

Perhaps arguing for a more discipline-specific approach to the nature of science raises more questions than it provides answers as the existing education literature focuses on broad perspectives of the nature of all sciences. Although historically biology has been subordinated at times to the physical sciences, the discipline has a prominent role in 21st century society. As the study of living organisms, the discipline has many unique methods, philosophical perspectives, and assumptions. How these differences and practices are conveyed to students in biology classrooms is lacking in the literature and whether this integration will impact student achievement and interest in biology is also unknown. This position paper begins to articulate why understanding these differences are important and that opportunities exist, especially in light of the upcoming standards release, for teachers, teacher educators, and science education researchers to integrate the nature of biology into biology education.

As a leading science of the 21st century, new discoveries and new frontiers in biology will raise new ethical questions and cause new public debates. The inertia of our educational system will not allow drastic changes in subject matter content or pedagogical approaches overnight, but curricular materials, and teacher-led instruction should provide students with a picture of biology that better reflects the diversity and contested perspectives of the discipline by explicitly teaching the ways in which biology differs not only from the physical sciences, but also how different branches of biology differ from each other and why these differences matter. If done effectively, future scientists and future citizens may be better able to make well-informed decisions about the living world and scientific findings in general.

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