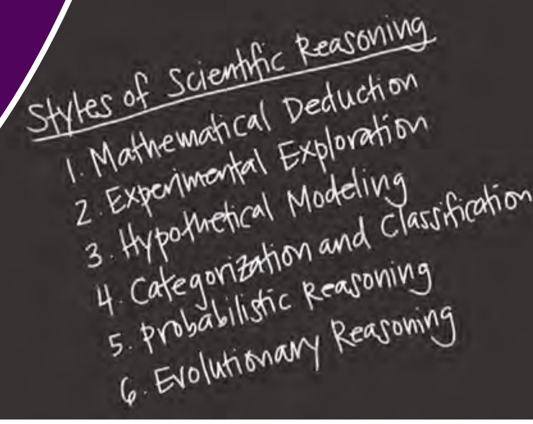
FEATURE ARTICLE

How Might the *Next Generation Science Standards* Support Styles of Scientific Reasoning in Biology?



STEPHANIE RAFANELLI
AND JONATHAN OSBORNE

Abstract

In this article, we put forward a new approach to the teaching of scientific reasoning in biology with the Next Generation Science Standards *(NGSS). We argue that a framework based on the idea of six styles of scientific reasoning provides the best guide for biology teachers to the nature of scientific reasoning in biology and how it might be taught. The current framework of the crosscutting concepts fails to provide a narrative for what makes biology distinctive and how biological scientists reason. By contrast, a framework of styles of scientific reasoning does offer a coherent argument for the biology curriculum in grades K–12, a justification for each performance expectation, and a vision of how each standard might support the development of scientific reasoning in biology. Examples and implications for curriculum designers and educators are discussed.*

Key Words: *scientific reasoning; curriculum models; coherence; standards.*

> Biology is without question the most diverse of the science, technology, engineering, and mathematics (STEM) disciplines. What began as an observational science has blossomed its own set of key concepts, experimental techniques, and approaches to the study of life.
>
> Brownell et al. (2014, p. 200)

○ Introduction

Biology is a distinct and unique science. While it shares with other sciences the fact that it is an "intellectual and practical activity encompassing the systematic study of the structure and behaviour of the physical and natural world through observation and experiment" (*Oxford English Dictionary*), there are significant differences. For instance, in the study of living things and their environments, categorization plays a more prominent part and categories change more rapidly than in the other sciences. Probability is encountered much earlier through the use of Punnett squares and probabilistic models of genotype expression. When designing experiments, the fact that living things are the focus of study raises ethical dilemmas that are unlikely to appear in the other sciences. Moreover, there are no universal "laws" of the kind that feature prominently in the physical sciences. Argument in the life sciences is often abductive (essentially, based on inference of the best possible explanation), the archetypal example being Darwin's arguments for evolution based on natural selection. Darwin used his observations of variations in the beaks of finches to argue that the best possible explanation was that the finches that had survived were better adapted to the nature of the food source on each island. By contrast, arguments in the physical sciences are fundamentally deductive or inductive. Deductive arguments start from agreed premises and deduce the outcomes (e.g., the effects of a given force on a mass). Inductive arguments (e.g., that all metal oxides are bases) are essentially generalizations that are consistently found to be true. Darwin, for instance, did not engage in using "the scientific method" to derive his theory of evolution, and neither did Goodall when revolutionizing the field of primatology. Indeed, we would argue that the myth of a singular scientific method is best challenged by the life sciences, for which it is simply one among many approaches. The contemporary understanding of the living world that has been achieved over the past 400 years is one of the greatest intellectual achievements of our culture. All teachers of biology have a basic responsibility to communicate how that understanding has been attained, the forms of reasoning it requires, and what makes it distinct from the achievements of the other sciences. However, in order to fulfill this

> *"Neither the disciplinary core ideas nor the crosscutting concepts in the NGSS address the particular types of arguments used in the life sciences and how they differ from those in the other sciences."*

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responsibility, teachers of biology must have access to a narrative that illuminates and demonstrates these facts and demonstrates how biologists think and reason. Where might such a narrative be found?

Here, we argue that what distinguishes the sciences from other disciplines is their use of six *styles of reasoning*, which require the development of a set of entities, procedures, and epistemic ideas that are distinct and whose use varies *between the sciences*. Building on this, we then argue that the current vision embodied in the *Next Generation Science Standards* (NGSS) fails to capture what makes the sciences and the intellectual achievements they represent distinct.

○ The Vision of the NGSS

Each generation of school science standards has sought to articulate a useable and justified structure for the biology curriculum. Most recently, the NGSS argue that, if implemented properly, they will lead to "coherent, rigorous instruction that will result in students being able to acquire and apply scientific knowledge to unique situations and to think and reason scientifically" (NGSS Lead States, 2013, p. xvi). The vision of the NGSS is that this will be achieved by a curriculum that blends a set of disciplinary core ideas, eight scientific practices, and seven crosscutting concepts. The focus on scientific practices and their detailed elaboration represents a welcome change, offering a better representation of what life scientists and other scientists actually do. However, the NGSS provide no guidance, beyond the broad statement quoted above, about the types of biological reasoning that students are expected to develop. Rather, these standards propose that "the performance expectations for high school life sciences blend core ideas with science and engineering practices and crosscutting concepts to support students in developing useable knowledge that can be applied across the science disciplines" (NGSS Lead States, 2013, p. 103). This is based on the view advanced in *A Framework for K–12 Science Education* (National Research Council, 2012) that the life sciences share a set of seven crosscutting concepts with all other sciences. In short, this view proposes that there is nothing in the types of questions asked by the life sciences, or in the entities, methods, and arguments that are their focus, that distinguish them from the other sciences.

We wish to differ with this view. Over the past 30 years, the work of a number of individuals – notably Ernst Mayr (1982, 2004) and Michael Ruse (2007), among others – has led to the realization that, while the life sciences may share certain features with the physical sciences, there are important differences. Thus far, those differences have been insufficiently acknowledged. Kloser (2012) points out two such differences: the rapidly changing criteria used in taxonomy and the probabilistic but random nature of genotype expression. The physical sciences have to define the entities found in the material world, but that is a less prominent feature of those sciences, and changes are infrequent. For example, a classification system based on 82 stable elements dominates the teaching of chemistry, and it is a relatively unchanging system. In general, classifications within the physical sciences are more stable and enduring than those in biology, and the mechanistic laws derived in the physical sciences are commonly dominated by inductive generalizations, which are inapplicable in only a very few, anomalous situations (e.g., the failure of Newton's laws to explain the precession of the perihelion of Mercury). And while the physical sciences do make use of probabilistic descriptions of the behavior of the material world (e.g., quantum mechanics), these can be represented mathematically and their outcomes predicted with a degree of precision that the life sciences find difficult to match.

Furthermore, while the major theories that a student will meet in the physical sciences are the product of deductive or inductive arguments, the major theory that underpins all of biology – evolution – is, as noted above, an abductive conclusion, or the best possible explanation of the extant facts. Neither the disciplinary core ideas nor the crosscutting concepts in the NGSS – ostensibly the connecting narrative that unifies the sciences – address the particular types of arguments used in the life sciences and how they differ from those in the other sciences. As a result, biology teachers are left to negotiate the bewildering array of performance expectations (the most of any discipline) without a keen sense of the ways in which biology is distinct from, and similar to, other sciences. In short, they lack a map of the modes of reasoning essential to biology. What is needed then is a good answer to the question of how reasoning is conducted in the sciences in general and, in particular, *how biologists reason*. On this issue, the crosscutting concepts of the NGSS are silent.

○ A Better Framework: Styles of Scientific Reasoning

To better understand what makes the life sciences distinctive, we draw on the idea that there are six different *styles of reasoning* in science. This concept has emerged from the study of the history of science, and in particular from the work of one man: Alistair Crombie. Drawing on his lifetime study of more than 2000 years of European science, Crombie (1994) showed how the natural sciences have developed the following six styles of reasoning:

(1) *Mathematical deduction:* the use of mathematics in deductive argumentation and to represent the world

(2) *Experimental exploration:* the use of empirical investigation to establish patterns, differentiate one form of object from another, and test the predictions of hypothetical models

(3) *Hypothetical modeling:* the construction of analogical and hypothetical models to represent and explain the world using causal reasoning (in the case of biology, models allow reasoning through the use of structure, function, and mechanisms)

(4) *Categorization and classification:* the ordering of variety by comparison and taxonomy, establishing what exists

(5) *Probabilistic reasoning:* the statistical analysis of regularities in populations, the identification of patterns, and the calculus of their probability (e.g., epidemiology and population genetics)

(6) *Historical-based evolutionary reasoning:* the construction of historical accounts of the derivation of the development of species, the Earth, the solar system, the universe, the elements, and more

Crombie's work shows how the success of the sciences can be explained by the development of these six styles of reasoning that have been used to argue for a set of ideas – including ideas that have initially seemed absurd, such as the idea that all species on Earth have evolved over millions of years. In short, "the history of science in the European tradition is the history of vision and argument" (Crombie, 1994, p. 3) – a vision that has often required the invention of entities that could not be observed directly (e.g., atoms, genes, electrons) and arguments based in and validated by empirical evidence (e.g., x-ray photographs, observed differences between and within species, anatomical dissection).

What the six styles offer is a succinct, coherent narrative that not only exemplifies the nature and diversity of scientific thought but also highlights the types of reasoning employed to develop each idea. For instance, when studying ecosystems, a teacher can point to the affordances of system models (style 3) while emphasizing a probabilistic analysis (style 5) of populations. When studying evolution, the teacher can show how Darwin developed an evolutionary account that drew on the best inferences that could be made (abductive reasoning; style 6) from his observational data in the Galápagos – inferences that have survived critical onslaughts for over 150 years. And while studying embryology, the teacher can point to the fact that the act of categorization and classification using inductive reasoning (style 4) remains a dynamic and often contested area of biology.

In short, the concept of styles of scientific reasoning offers a framework for clarifying how scientists think and how the sciences differ in their use of these forms of reasoning, the entities they reason about, and the methods they adopt to investigate the world. If the underlying framework that drives biological thought were to be exemplified in this manner, the biology curriculum would offer not only a view of what we know but also some grasp of the intellectual achievement our biological knowledge represents. Styles of reasoning provide a cultural justification for the place of biology on the curriculum, complementing the instrumental view of its significance for everyday living.

○ What Do Practicing Biological Scientists Think?

But do biologists really reason this way? Would practicing biologists recognize their work in this account? To test our ideas, we met with three prominent practicing life scientists at Stanford University. Rodolfo Dirzo, Bing Professor in Environmental Science, focuses on tropical ecosystems and the ecological impacts of species decline. Deborah Gordon, Biology Professor, examines ant colonies to understand collective behavior in different environments. Craig Heller, Lorry I. Lokey/Business Wire Professor of Biology, studies the integration of physiological systems, with a particular interest in cellular and subcellular mechanisms of circadian rhythms, sleep, and body temperature. Before revealing the six styles of scientific reasoning, we asked each professor a series of questions about their research. For example, we asked each to walk us through a recent research process, highlighting the thought and procedures that went into each step.

As each scientist explained a current project, it was easy to identify elements that corresponded closely with each style of reasoning. Dirzo, for instance, described the experimental nature (style 2) of creating an electrified enclosure to compare a controlled ecosystem with a comparable natural one. Gordon noted the importance of hypothetical modeling (style 3) when studying the rate of decay of ant pheromones and ant "exploring" behavior. Heller pointed out the importance of mathematical deduction (style 1) and probabilistic reasoning (style 5), which, he explained, are "absolutely used in every single experiment." All three scientists pointed to the importance of evolutionary thinking (style 6) as a theoretical framework underpinning their work. As Dirzo explained, "the fundamental theoretical concept here is how factors of the environment are important selective pressures for the adaptation and evolution of organisms." Gordon highlighted five of the six styles when she described her current work:

> To learn how colonies form and repair trail networks in the trees, I spend a lot of time looking at the ants in the trees and labeling the junctions that they use and mapping them [style 4], and then going back and looking to see how they change from day to day. Then do experiments [style 2] where I cut a piece of the vegetation and look at how they repair it. To understand how it fits with the vegetation, we make measurements in the vegetation [style 1] of the network of paths that they could use but don't.
>
> I'm working with a computer scientist who is a grad student at UC San Diego to try to specify, with simulations and a model [style 3], what is the algorithm that they're using. For that we do simulations on a computer and we try to match up some of the features of the model to some things that we've measured with ants [style 5], which doesn't prove that the ants are doing what the model does, but if they're consistent then we have a description of how they might be doing it that we can then go on to test.

While each biological scientist approached her or his own work from a unique perspective, all incorporated the styles of scientific reasoning at various points in their research.

At the conclusion of each interview, we shared the styles of scientific reasoning with each professor, asking them whether they thought that the styles resonate with their own work. In short, the answer was "yes." As they looked over each style and read the description, each scientist noted how and where they had applied that style of reasoning to a project. Thus, not only did we see the styles of reasoning in their descriptions of their work, but they too saw this framework as a reflection of their own reasoning. While we recognize that this is a limited, convenience sample that is not comprehensive, we contend that these data show that styles of reasoning are not just a theoretical construct but provide a language for talking about the kinds of reasoning that practicing scientists undertake. And until we are able to accurately categorize and classify a phenomenon – in this case, scientific reasoning and its attributes – we cannot talk about it and discuss its achievements.

○ Applying Styles to the NGSS

We argue that each of the 69 life science performance expectations for K–12 education can be seen as contributing to the understanding of one or more of the six styles of scientific reasoning – a feature

Table 1. Sample performance expectations and the *styles of reasoning* they exemplify.

Grade(s)	Performance Expectation	Styles of Reasoning Exemplified
2	2-LS4-1. Make observations of plants and animals to compare the diversity of life in different habitats.	• Asking students to make observations requires them to practice a fundamental experimental skill for a biologist – that of observing living forms – which is *style 2*. • To be able to compare diverse traits, distinctive attributes must have been identified; the classification and categorization of organisms and habitats under investigation are a product of *style 4*. • A discussion focusing on the diversity of life introduces an opportunity for adaptations and evolutionary thinking – *style 6*.
6–8	MS-LS4-4. Construct an explanation based on evidence that describes how genetic variations of traits in a population increase some individuals' probability of surviving and reproducing in a specific environment.	• A discussion of genetic variation provides an introduction to polynomial representation of genetic traits as variables, which is *style 1*. • Constructing models of meiosis and mitosis – *style 3* – affords an opportunity for students to visually represent and perhaps better understand sexual and asexual reproduction. • Any evaluation of adaptations must include categorizations of physical or behavioral traits, which is *style 4*. • The performance expectation clearly identifies the central role of probability in population survival, requiring an exploration of *style 5*, or probabilistic reasoning. • An evidence-based explanation of genetic variation and population survival provides an opportunity to engage in evolutionary thinking, which is *style 6*.
9–12	HS-LS2-6. Evaluate the claims, evidence, and reasoning that the complex interactions in ecosystems maintain relatively consistent numbers and types of organisms in stable conditions, but changing conditions may result in a new ecosystem.	• Prior to evaluating any claims or evidence, students will have had to engage in defining and identifying traits of the organisms and the ecosystem, which is *style 4*. • In order to evaluate evidence of interactions in ecosystems, students will rely on numerical data, which is mathematical representation, or *style 1*. • To evaluate both current and new conditions, students will develop and evaluate hypothetical models – *style 3*. • Modeling ecosystems and predicting population growth or decline will necessarily involve probabilistic thinking, which is *style 5*. • Finally, by evaluating complex ecosystems, examining changes that may have occurred, and predicting shifts that may develop, students will engage in historical-based evolutionary reasoning – *style 6*.

that is absent from the current articulation within the NGSS. To be clear, we are not suggesting a change to the existing performance expectations. Rather, we propose that the styles of reasoning illuminate, justify, and clarify each expectation in a new way. To illustrate our case, Table 1 shows example performance expectations for elementary, middle, and high school to show how each provides an opportunity to highlight and exemplify styles of scientific reasoning.

Using the styles framework, one of the goals of the the NGSS can be seen as an attempt to illuminate the intellectual achievement of six modes of reasoning. What the styles framework provides is a justification for each performance expectation, grounded in academic scholarship (Kind & Osborne, 2017) – which, in turn, offers coherence to the entire NGSS. The same, unfortunately, cannot be said of the crosscutting concepts, which our work has shown to have no basis in scholarship and to be distributed unevenly across grades K–12 (Osborne et al., 2018).

We would also point out that the emphasis on styles of reasoning offers a means of escaping from the tyranny of content. If the primary goal of teaching science were to be communicating the nature of the intellectual and cultural achievement of the sciences, then, as in the teaching of literature, there would be no need to cover everything! Given the vastness of biological knowledge, it is nonsensical to attempt to stuff more into the fixed time provided in the K–12 sciences curriculum. Styles of reasoning offer a framework that can provide an escape from too much content. For, if the primary goal is to illustrate how biologists think and reason, content could be chosen to illustrate how each of these distinct styles of reasoning has transformed the world in which we live. In this way, styles also offer the field of biological education something it has long sought – a means of selecting a limited set of content to illustrate what an enormous achievement biological knowledge is.

○ Summary & Conclusion

Approaching the NGSS through styles of reasoning will help build a better narrative about what science is and why it is in the curriculum. Transcending the weak argument that the study of science will help one get a job – an argument that is readily refuted by the data, in that only 5% of jobs require scientific training – the framework of styles of reasoning instead argues that science is simply one of the great cultural achievements of our society, and therefore something that everybody needs to know. Clearly, there are other arguments for the study of biology. On a personal level, an understanding of life science is fundamental to decisions about health and well-being. However, similar arguments could be made about financial literacy. What makes biology more important? What the life sciences community needs is an argument that justifies its place on the curriculum by identifying the significance of its contribution to the society and the contemporary cultural conversation.

Using this framework, each life science performance expectation can be presented as exemplifying one or more of six styles of reasoning. For example, the requirement to "analyze displays of pictorial data to compare patterns of similarities in the embryological development across multiple species to identify relationships not evident in the fully formed anatomy" (MS-LS4-3) provides students an opportunity to engage in evolutionary reasoning (style 6), experimental exploration requiring the analysis of data (style 2), and classification (style 4).

Moreover, the frequent recurrence of the styles will enable teachers of science to build connections between the styles of reasoning across years from elementary to middle to high school. For example, a fourth-grade teacher might see opportunities to link the ideas of evolutionary reasoning (style 6) found in the performance expectations for that grade in exploring structures that help plants and animals survive and reproduce (4-LS1-1); and a high school teacher might link style 6 to the expectation for students to identify the primary drivers of evolution (HS-LS4-2). Doing this would not require any addition to the existing curriculum. Rather, what styles of reasoning afford is a framework that provides coherence where there is currently little or none. The crosscutting concepts, for instance, have no basis in scholarship.

As teachers of biology, we have a very important story to tell. The notion that there are six distinct styles of reasoning in the sciences offers a narrative around which we can frame a conversation that not only tells a more coherent, more accurate, and hopefully more convincing story of the achievements of the life sciences, but also tells a story about how they were attained and why they matter.

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STEPHANIE RAFANELLI is a Research Associate at Stanford University, Stanford, CA 94305; e-mail: stephanie.rafanelli@gmail.com.
JONATHAN OSBORNE is Kamalachari Professor of Science Education, Emeritus, at Stanford University; e-mail: osbornej@stanford.edu.