Styles of Scientific Reasoning—a Cultural Rationale for Science Education?

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Abstract

In this paper, we contend that what to teach about scientific reasoning has been bedeviled by a lack of clarity about the construct. Drawing on the insights emerging from a cognitive history of science, we argue for a conception of scientific reasoning based on six ‘styles of scientific reasoning’. Each ‘style’ requires its own specific ontological and procedural entities, and invokes its own epistemic values and constructs. Consequently, learning science requires the development of not just content knowledge but, in addition, procedural knowledge, and epistemic knowledge. Previous attempts to develop a coherent account of scientific reasoning have neglected the significance of either procedural knowledge, epistemic knowledge, or both. In contrast, ‘styles of reasoning’ *do* recognize the need for all three elements of domain-specific knowledge, and the complexity and situated nature of scientific practice. Most importantly, ‘styles of reasoning’ offer science education a means of valorizing the intellectual and cultural contribution that the sciences have made to contemporary thought, an argument that is sorely missing from common rationales for science education. Second, the construct of ‘styles of reasoning’ offers a more coherent conceptual schema for the contruct of scientific reasoning – one of the major goals of any education in the sciences.

Keywords: Scientific reasoning, content knowledge, procedural knowledge, epistemic knowledge, goals of science education.

Introduction

The project of this paper is to offer a contribution towards improving our understanding of the construct of scientific reasoning used in science education. While the study of scientific reasoning is far from new, this review and these reflections are required for several reasons. First, ever since its inception, one justification for science education has been that it might instill the disciplinary habits of mind of the scientist (Chinn & Malhotra, 2003; DeBoer, 1997; Dewey, 1916; Layton, 1973; Turner, 1927). In contemporary society, such arguments have become even more pre-eminent (Economist, 2014; Gilbert, 2005; Hanushek & Woessmann, 2015; Hill, 2008; National Research Council, 2008, 2012a). Hill (2008), for instance, argues that the societies that sustain their competitive edge in the coming decades will be ‘post-scientific’ societies. In such a society, skills that are highly valued will be the ability to draw on a range of disciplinary knowledge, to think creatively, and to evaluate and critique new ideas. Employers will require individuals who, while having a core understanding of scientific and technical principles, have the ability to communicate and synthesize knowledge in an original manner (National Research Council, 2008, 2012a) using the higher order reasoning skills of evaluation, synthesis, and critique. If so, as Hill (2008) argues, it is important to “emphasize what we want” lest we get “what we emphasize” (p. 9). When it comes to the skill of reasoning scientifically, however, we argue that science education has suffered from a lack of clarity about “what we want”. The result is a substantial gap between the goals of science education and the classroom reality such that both the sciences, and its students, have been short-changed.

One consequence of the failure to define what is meant by scientific reasoning has been an over-emphasis on content knowledge (Layton, 1973; Reddy, 1979; Turner, 1927; Weiss, Pasley, Sean Smith, Banilower, & Heck, 2003) – a feature which is reflected in the external assessment of much school science (Au, 2007; Osborne and Ratcliffe, 2002*)*. Indeed, the rise of demands for accountability in education and state testing has led to an even more deeply entrenched emphasis on content (Hout & Elliott, 2011; Wilson & Bertenthal, 2005.). In the case of assessment in science, many items make lower-level cognitive demands of recall and comprehension (Osborne and Ratcliffe, 2002;(Pellegrino, Chudowsky, & Glaser, 2001; Shavelson, Baxter, & Pine, 1991; Wilson & Bertenthal, 2005) failing to test higher-order analytic and reasoning skills. This outcome, we argue, is a consequence of the lack of a coherent account of the goals of the sciences, the reasoning they use, and their achievements within the field of science education.[1] In the absence of such an account, the field has belittled and distorted the accomplishments of the sciences and their epistemic success to a singular algorithmic process – 'the scientific method' – an account that grossly misrepresents and undervalues scientific work and its cultural contribution.[2]

In this paper, we argue for a conception of scientific reasoning drawn from the neglected field of scholarship undertaken in the cognitive history of the sciences which shows that there is *no single form* of reasoning in the sciences, but rather, *six distinct styles of reasoning*. The notion of 'styles of reasoning' has emerged from a body of scholarship in the history of science that has identified the major forms of argument within science and their distinctive features (Crombie,

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[1] The plural 'sciences' is chosen deliberately throughout as each of the sciences invokes different styles of reasoning and different ontic entities. Indeed, we would argue that the field would benefit by talking not about the 'science' curriculum but the 'sciences' curriculum to emphasize the fact that science is characterized by its diversity of thought rather than any singular unity.

[2] This comment is not true of the Next Generation Science Standards (Achieve, 2012) which have broadened the notion of what it means to do science by introducing a set of 8 practices which are common across the sciences.

1994; Davidson, 2004; Hacking, 1992, 2012; Nersessian, 1995; Netz, 1999; Tweney, 2001). Each style of reasoning is distinguished by its own entities, procedures, and epistemic constructs. Consequently, scientific reasoning is dependent *not on one*, but rather, *three* forms of knowledge. These are:

- *Content* knowledge of the appropriate domain-specific concepts – that is the ontological entities that science uses to reason with;
- *Procedural* knowledge which is knowledge of the procedures and associated constructs that science uses to establish it claims to know; and
- *Epistemic* knowledge which is knowledge of the epistemic constructs and values and how these are used to justify science's claims to know.[3]

The common stance of cognitive historians is that the modes of reasoning within science are better determined by taking a descriptive, naturalistic examination of the outcomes of scientific reasoning, rather than by empirical investigations of how humans reason. Such modes of thinking are not an innate quality of what it means to be human, but rather, are entrenched in the language, belief systems, and world-views we hold. Consequently, they are assimilated by each of us from the interpersonal interaction that arises from simply *being in* that culture (Vygotsky, 1978). In short, all cognitive science can do is illuminate the way we reason but not how such reasoning has emerged or what it has achieved. Thus, like Fodor (1983), we share his skepticism about the ability of cognitive science to determine the workings of the central processor or intra-personal processes of the human mind. Rather, we believe that such attempts

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[3] To exemplify their distinct nature, an ontological entity e.g., a wave, gene or element is distinct from a procedural entity such as a variable, a measurement error, or procedure such replication which, in turn, is distinct from an epistemic entity such as a theory, a hypothesis or an inductive argument.

will simply discover the specific ways of thinking that are already culturally embedded. Thus our position follows a long line of American pragmatists such as Pierce, Dewey, and Rorty whose concern is not with revealing truth per se but with the cultural modes of thought that have evolved, what makes them distinctive, and moreover, what makes them successful.

Using the notion of 'styles of reasoning', we then explore what this particular conception offers – not least that there is more to scientific thinking than 'the scientific method'; and that scientific reasoning requires not just a knowledge of its domain-specific constructs but also a knowledge of a set of procedural and epistemic constructs. Perhaps, most importantly, as we shall argue, what 'styles of reasoning' offers is a *cultural argument* for the value of an education in the sciences – a long overdue riposte to the dominant, neo-liberal, economic imperative. We then show how this perspective illuminates the nature of the confusion that has existed, and still exists, around the construct of scientific reasoning. For instance, at different points in time, the conception of scientific reasoning has been dominated by the views of psychologists, who have seen it as requiring a set of domain-general heuristics; philosophers, who have sought to characterize reasoning in terms of a set of normative and epistemic features; and sociologists, who have sought to characterize it as a collective activity undertaken as a body of socio-cultural practices. In contrast to any one of these accounts, each of which identifies *certain specific features* of scientific reasoning, 'styles of reasoning' offers a coherent, domain-specific vision of both the entities required *and* the different forms of reasoning that the sciences have developed. We then finish by exploring the implications – in particular, how this framework offers a means of escaping from the tyranny of content.

Styles of Scientific Reasoning

The goal of scientific reasoning is to answer three specific questions about the material world (National Research Council, 2012b, Osborne, 2011). These are the questions of:

1. What exists? (the ontic question);
2. Why it happens?(the causal question); and
3. How do we know? (the epistemic question).[4]

How scientists commonly develop and construct answers to these questions is, we contend, best found in the neglected work of cognitive historians of science. Two major contributions to this field are Reviel Netz's study of the origin of Greek mathematics (Netz, 1999) and Alistair Crombie's three-volume study of *Styles of thinking in the European Tradition* (1994). Cognitive historians argue, first, that human reasoning is much better understood using a historical approach and by taking an external perspective that looks at the *products* of that reasoning; second, that there are no general, universal rules of reasoning. Instead, the cognitive tools used by science have emerged historically as a contingent, cultural product of specific contexts—an accident of history—and, given an alternate historical narrative, may well have existed in a different form, or not at all.

Using such an approach, Crombie's examination of scientific thought since the Greeks reveals *not one* but *six* distinct 'styles of reasoning' and that "the history of science in the

[4] There is also the question of 'what can we do with such knowledge?' but this is a technological question.

European tradition is the history of vision and argument" (Crombie, 1994, p3).[5] The success of science can then be attributed to the development of cognitive tools, resources and styles of reasoning that have been used to argue for a set of ideas – ideas that have initially seemed absurd, such as the idea that day and night are caused by a spinning Earth and not a moving Sun, or the idea that the Continents were once one, or the idea that all species on the Earth have evolved over millions of years. Specifically, Crombie argues that the styles of scientific reasoning are:

1. *Mathematical Deduction,* which is the use of mathematics to represent the world and for deductive argument. The Greeks were the first to initiate this form of reasoning with the work of Euclid, Pythagoras, and others. The representation of physical phenomena by numerical quantities or algebraic symbols is something that is key to all the sciences. All kinds of entities are depicted in a mathematical form, and mathematics is very much one of the major languages of the sciences used as a means of making deductive predictions both in the sciences and engineering.
2. *Experimental Evaluation,* which is the use of empirical investigation to establish patterns, differentiate one form of object from another, and to test the predictions of hypothetical models. Galileo is commonly seen as the key figure who initiated this style of reasoning testing his hypothesis that all masses would fall with equal acceleration by dropping two

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5 We must emphasize that what is presented here is an argument for the nature of science in the Western tradition that forms the basis of the school curriculum across most if not all of the globe. We recognize that there are good arguments that this fails to present the nature of thinking and reasoning about the material world offered by other cultures – see for instance Medin and Bang (2014).

cannonballs of different sizes from the tower of Pisa.[6] Since Galileo, experimental exploration has become a key method in nearly all the sciences. Empirical evidence is used to test whether scientific ideas can be falsified and to substantiate or critique arguments.[7] Only those ideas that survive such tests are the ones that we hold to be true.

3. *Hypothetical Modeling*, which is the construction of analogical and hypothetical models to represent the world. Science advances by developing explanatory models for what scientists observe.[8] Indeed, some would argue that *this is* the primary goal of science. Analogical models are used to represent things which are too large to imagine (the Solar System), or too small to see such as the cell or the Bohr model of the atom. Models, such as the kinetic theory of matter, are used to make predictions and are now commonly built with computers to simulate the possible behavior of the world, e.g., climate models. Models and representations are then central to providing the tools and heuristics necessary to reasoning how the world might behave.

4. *Categorization and Classification*, which is the ordering of variety by comparison and taxonomy. Establishing what exists is a fundamental aspect of science. Many scientists engage solely in the process of classification – for instance, distinguishing rocks, animals, particles, and chemicals from each other. Defining what exists, and the concepts that we use

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6 There is no evidence that Galileo actually performed this experiment but there is a record that he performed an experiment to show the same point empirically demonstrating that the period of a pendulum was independent of the mass of the bob.

7 Popper, K. (1963). Conjectures and Refutations: the growth of scientific knowledge. London: Routledge and Kegan Paul.

8 Schauble, Leona. (1996). The development of scientific reasoning in knowledge-rich contexts. Developmental Psychology, 32(1), 102-119.

to talk about them, has been key to building our understanding of the world – not just in biology, but in chemistry where the development of the periodic table was totally dependent on establishing the elemental nature of the material world, and in physics for distinguishing concepts such as heat and temperature, mass and weight, and energy and power. Both field work and experimental exploration are vital means of establishing what exists as, until we agree on the ontic entities that exist, there can be no common language to reason about such entities.

5. *Probabilistic Reasoning,* which is the statistical analysis of regularities in populations, the identification of patterns, and the calculus of their probability. The determination of patterns is an essential feature of the sciences and the basis, for instance, of the science of epidemiology. For example, the link between skin cancer and sunshine was established by a data that showed a linear decrease in incidence of skin cancer per thousand members of the population with increasing latitude (Findlay, 1928). Likewise the current concern about the Zika virus emerges from studies suggesting correlation rather than any understanding of a causal mechanism. Scientists, such as Gauss and Poisson, are the individuals who have made major contributions to establishing the epistemic criteria used to reason about the existence of patterns, and a range of methods for describing variation and the chances of its occurrence.
6. *Historical-Based Evolutionary Reasoning,* which is the construction of historical accounts of the derivation of the development of species, the Earth, the solar system, the universe, the elements and more. Attempts to explain the origins of the material world and its features are a major element of reasoning in the sciences. They rely on constructing theories about what might have happened in the past. Darwin's ideas emerged from his detailed observation of the variations of patterns that exist in nature and asking how such differences could have

come to be. In astrophysics, evolutionary accounts have been developed by constructing mathematical models that would account for what we observe. Such theories have succeeded because t they have been the *best possible inferences* for what exists, and notably not because there has been any application of 'the scientific method'.

As Hacking (2012) argues, "such styles of reasoning do not answer to some other, higher, or deeper, standard of truth and reason than their own" (p. 605). These forms of reasoning exist because they have been, and still are, successful in answering the ontological, causal, and epistemic questions that are the focus of the sciences. They are good not because they detect the truth; rather, they are good because they are successful. And, because of their success, "they have become part of our standards for what it is to find out the truth" (p. 605, (Hacking, 2012).

Importantly though, each of these forms of reasoning brings into being a distinct set of ontic, procedural, and epistemic entities that are required to perform their reasoning – examples of which are offered in Table 1. Procedural entities are used as cognitive tools which are essential to engaging in that style of reasoning, e.g., the notion of a variable which is central to experimental exploration, while epistemic knowledge is a knowledge, for instance, of the forms of argument used in science, or the nature of a scientific hypothesis.[9] Both of these forms of knowledge are necessary for justifying how we know what we know – that is, how we reason in the sciences. Thus, the evolutionary account of human development introduces the ontic

[9] Cognitive tool are important constructs that are used to reason with. For instance, for Greek mathematics it is the diagram that exploits human visual cognitive resources. Likewise, physicists use ray diagrams to reason about the behavior of lenses, or free body diagrams to reason about the effects of forces. Chemists use molecular models to reason about the behavior of molecules while biologists use the construct of a gene to reason about the effects of breeding and inheritance.

concepts of natural selection, adaptation, and genes. Experimental exploration, which emerges in the 16th Century, develops the procedural notion of a variable and the need for their identification and control. Greek Mathematics makes the case for the epistemic importance of deduction as a form of argument. Notably, each of these modes of thought is associated with a legendary hero – Euclid and Pythagoras with Greek Mathematics, Galileo with the introduction of experiment and hypothetical modeling, Linnaeus and Mendelev with categorization and classification, Poisson and John Snow with statistical and correlational thinking, and Darwin and Wegner with evolutionary thinking. That it is possible to identify a name with the achievements of one style of reasoning is an indicator of both its *distinctive* nature and its significance.

[Insert Table 1 about here]

In the first column of Table 1 are the ontic entities that science has invented to reason with. Thus the Copernican model of the solar system requires planets to move in 'orbits'; the Torricellian explanation of the barometer requires the existence of a 'vacuum'; Pasteur's model to explain the rotting of food requires the invention of 'microbes'; Maxwell's equations to explain the velocity of light introduces an 'ether'. That there *is* something to be explained is first dependent on the categorization and classification of the variety of the material world – the fourth of Crombie's styles of reasoning. Darwin's work, for example, was totally dependent on the notion of a species introduced by Linnaeus, and Lyell's historic 1815 map of the geology of Great Britain was dependent on the idea that there are distinct categories of rock that have different origins and different histories. The categorization of the world – that is, the ordering of variety by comparison and taxonomy – is essential to the advancement of the sciences. The ability to then see patterns is dependent on the analysis and classification of regularities. Snow's foundational epidemiological work on the causes of cholera typifies the fifth of Crombie's styles of reasoning – probabilistic and statistical thinking. Demonstrating the validity of any given explanatory model may depend on deductive mathematical reasoning (style 1), arguments from data obtained by experimental observation (style 2), or inferential reasoning as to the most likely possibility, as in the case of Darwin's argument for evolution, or Wegner's argument for continental drift (style 6).

The second column of Table 1 represents the procedural entities that support reasoning about these entities. Most familiar is the notion of dependent and independent variables and the control of variables strategy. However, the skilled experimenter also has a diverse knowledge of sources of error and techniques for their minimization and the statistical techniques for reducing the the possibility that any empirical finding occurring by chance. More recently such procedural knowledge has been elaborated as a set of 'concepts of evidence' (Gott, Duggan, & Roberts, 2008) and it is a feature of the PISA framework for assessing scientific literacy (OECD, 2012).

Arguments for any of the models are, in turn, dependent on epistemic criteria that are an intrinsic feature of any given style of reasoning. Thus probabilistic reasoning, of the form used to establish the existence of the Higgs Boson, uses, as a criterion of justified belief, the idea that the probability of the event observed at CERN being anything other than the Higgs Boson was so low as to be virtually impossible. Taxonomic reasoning rests on the application of criteria to demarcate one entity from another – for instance, the classification of species depends on the criterion that a species can be demarcated by how they reproduce. More recently, the field has adopted genetic criteria for its arguments. Experimental exploration is highly dependent on the notion of a variable and an epistemic belief that controlling all but the salient variable – an idea often communicated in elementary science as a ‘fair test’ – can enable science to identify causal relationships. Mathematical reasoning is reliant on the epistemic belief that it is acceptable to represent physical quantities in idealized symbolic forms (e.g., frictionless planes, point masses) that can be used to make a deductive argument.

Moreover, the framework of ‘styles of reasoning’ shows that a key epistemic element missing from the account of scientific reasoning offered by school science has been the role of explanatory models in science (Cartwright, 1983; Giere, Bickle, & Maudlin, 2006; Suppes, 1960). Yet, the construction of models (style 3) is “a signature of much research in the sciences” (Nercessian, 2008), a standard part of its practice. Experimentation, similarly, is not just a matter of knowing *how* to get reliable data – which is a procedural issue – but also *why* reliability is important – which is an epistemic issue. To conduct an experiment, undoubtedly, it is essential to have some understanding of what a variable is, and which variables might be controlled. Why it is necessary to control variables, however, is an epistemic construct. Further arguments for the importance of epistemic knowledge are the findings of research (Reiner & Gilbert, 2000) that suggest that it also plays a crucial role in the production of new knowledge. Thus engaging in scientific reasoning requires a body of epistemic knowledge which needs to be taught explicitly to students – the third element of a knowledge of the sciences whose significance is justified by the perspective of styles of reasoning.

What Crombie’s work also shows is that establishing the validity of any hypothesis may depend on a hypothetico-deductive argument from premises to conclusion, *but* it could also be an abductive argument that it is the best explanation, *or* an inductive argument about the patterns that exist in nature. Yet the simplistic model of scientific reasoning pervasive to most curricula would suggest that the sciences draw solely on hypothetico-deductive arguments captured by the notion of ‘the scientific method’ (Bauer, 1992; Windschitl, Thompson, & Braaten, 2008). This ‘myth’ does the sciences a disservice in two ways. First, the sciences are better characterized by their ontological, methodological, and epistemic diversity (Baird, Scerri, & McIntyre, 2006; Cartwright, 1983; Mayr, 2004) rather than their commonality – a point which has been made consistently by scholarship within the field of science education over the past two decades (Martins & Ryder, 2015; Rudolph, 2000; Van Dijk, 2014). Second, the idea that there is some singular algorithmic procedure responsible for the production of scientific knowledge undervalues the nature and diversity of creative thought that has revolutionized our understanding of the material world over the past 450 years sustaining the misconception that there is a single form of reasoning unifying the sciences.

Our view is that, over the past two decades, the field has been wrestling with how to incorporate epistemic knowledge within the science curriculum. The movement to teach more about the nature of science (Lederman, 1992, 2007; Matthews, 1994) can be seen as one such attempt. Coupled with empirical evidence suggesting that epistemic knowledge is perceived as a significant element of any science education (Osborne, Ratcliffe, Collins, Millar, & Duschl, 2003), epistemic knowedge has become a more prominent feature of contemporary curricula. Indeed, the previous version of the English national curriculum (Qualifications and Curriculum Authority, 2007) included a specific component entitled ‘How Science Works’, while the framework for K-12 science education outlines eight epistemic practices which should be an essential element of the curriculum (National Research Council, 2012b) – though notably this document does not define what are the specific elements of either procedural or epistemic knowledge. In contrast, the PISA assessment framework for 2015 (OECD, 2012) *does* incorporate epistemic knowledge defining it as: a) a knowledge of the constructs and defining features essential to the process of knowledge building in science; and b) the role of these constructs in justifying the knowledge produced by science.

Notably, what all these attempts lack, however, is a coherent rationale for the incorporation of such elements other than the argument that such knowledge is essential to be an informed and participatory citizen. What is missing is some broad picture that conveys not only something of the variety of the forms of reasoning of the sciences, but also, and above all, why its practice and development constitutes such an epistemic achievement. While, in and of themselves, the practices in the NGSS, offer some insight into the epistemic activities conducted by scientists, they offer neither a big picture of the distinctive forms of reasoning in the sciences nor their outcomes – outcomes which have changed the way we think as a culture. In what ways then, do 'styles of reasoning' offer an improvement?

Why styles of reasoning?

A focus on styles of reasoning offers three important advances for science education. First, it helps to undermine the hegemony of the scientific method (Bauer, 1992; Windschitl et al., 2008) for 'the scientific method' draws on only two of the six forms of reasoning used in science – that is style 3 (hypothetical modeling) and style 2 (experimental exploration). As a corollary, students are offered an impoverished account of scientific thinking. Second, as we have shown, it demonstrates unequivocally that scientific reasoning is dependent, not on one form of knowledge but *three* – all of which need to be taught explicitly. Finally, it offers a better rationale for educating all students in science rather than the habitual and dominant economic imperative or the argument based in education for citizenship – an argument to which we now attend in some detail.

To start, the economic argument is highly flawed because there is no universal shortage of individuals with STEM qualifications (Salzman, Kuehn, & Lowell, 2013; Xie & Killewald, 2012). Moreover, it is a highly unconvincing argument for the overwhelming majority of students who have no aspiration to pursue the study of science or a STEM career. Furthermore, no other curriculum subject has such a propaedeutic function as its primary goal. Why then should science be saddled with such a responsibility? However, in the absence of strong contending arguments, the economic imperative has filled a vacuum to become the dominant argument for the value of science education.[10] The argument that a knowledge of the sciences is necessary to be an effective citizen, in contrast, does have universal and utilitarian validity. However, at the personal level of decision making it must compete with arguments that other competencies are more valuable for citizenship, such as financial literacy, computer literacy or health education. In short, what is it about science that makes it more deserving than other forms of knowledge, such that it not only earns itself a place at the curriculum table, but one alongside mathematics *and* a first language? Rudolph and Horibe (2015) make a stronger argument that science education should develop a "second-order ability" to "locate and use expert knowledge as a means to public ends" (p. 12) for the purpose of what they call 'civic engagement' – both to evaluate the application of scientific knowledge and to consider what forms of knowledge it might be valuable to produce. This is fundamentally a pragmatic argument – that such knowledge is necessary to be a responsible, participating member of a democratic society. As such, it is 'a programmatic concept' (Norris, Phillips and Burns, 2014) defined by elements that

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[10] For example, the recently published Royal Society document *Vision for Science and Mathematics Education (The Royal Society, 2014)* singularly fails to make any argument for science education other than its economic value.

embody a valued direction or a desired goal – in this case that the outcome of science education should enable individuals to engage in civic considerations of both the application and the production of scientific knowledge. While many, including the authors of this paper, find such arguments convincing, they are contentious in two ways. First, others may not agree about the goals. For instance, the modest changes in the UK curriculum to incorporate an element on 'How Science Works' in 2000 met with considerable opposition (Perks, 2006). Second, even if there is agreement about the goals, there may be disagreement about the means by which they are to be achieved. Indeed, despite numerous attempts to argue for the importance of such programmatic goals e.g., (Aikenhead, 1994; Fuller, 1997; Millar & Osborne, 1998; Ziman, 1994), and strong empirical evidence that such goals require a body of knowledge and understanding that differs significantly from the content of most school science curricula (Ryder, 2001), no coherent consensus has emerged about the means to achieve such an end.

Missing in all this discussion of the rationales for science education is the *cultural argument* that the sciences offer some of the "best that is worth knowing" (Spencer, 1884). This is an argument that:

> "the distinguishing feature of modern Western societies is science and technology. Science and technology are the most significant determinants in our culture. In order to decode our culture and enrich our participation - this includes protest and rejection - an appreciation/understanding of science is desirable" (p. 339). Cossons (1993)

It is this form of argument that is used to justify all other curriculum subjects that are seen as distinct and valued forms of knowledge (Bereiter, 2002; Committee on the Objectives of a General Education in a Free Society, 1945; Hirst, 1965; Hirst & Peters, 1970) – and it is only this argument that is sufficiently sound and defensible to justify teaching science to *all* children. Why? Because, unlike the citizenship argument, the cultural argument has a much less contentious programmatic objective as, while the choice of what might be taught is a reflection of the values of the society, such choices do not embody a program of action. Rather, the theory of plate tectonics, the law of conservation of energy, or adaption of species to their environment simply aims to capture the best description of the material world we can offer. As expressed by the Havard Committee "our culture depends in part on an inherited view of man and society which it is the function, though not the only function, of education *to pass on*[11]…To study the past is immensely to enrich the meaning of the present and at the same time to clarify it by the simplification of the writings and the issues which have been winnowed from history." (p69, Committee on the Objectives of a General Education in a Free Society, 1945). Or, as stated by Hector, a leading character in Bennet's play *The History Boys (*Bennett, 2004), the function of education is to "Pass the parcel. That's sometimes all you can do. Take it, feel it, and pass it on. Not for me, not for you, but for someone, somewhere, one day. Pass it on, boys."

The question, of course, is what is that the sciences offer that is so valuable that is worth passing on? What does it mean to 'appreciate' science as a form of thought and a 'way of knowing'? The sciences themselves have singularly failed to develop such an argument seeing it as a task for the popularisers of science and often treating such work with disdain. And, while many of these have written notable accounts of the specific sciences e.g., Stephen Jay Gould, Asimov, Carl Sagan, Richard Dawkins, there is no overall, useable larger picture. Yet, if school science has to leave students with more than a miscellany of facts (Cohen, 1952) and a sense that the production of more knowledge simply requires the application of a standardized algorithmic method, there has to be an argument for its cultural significance which is more substantive than the argument made by Cossons cited above.

[11] Emphasis added.

This, we contend, is what 'style of reasoning' offers. For, as Bereiter argues, a liberal education (Bereiter, 2002) is an enculturation into a world of ideas, learning how to use and reason with those ideas enables the individual to participate in the discourse of modern society, and thus intiates " the young into a culture which transcends the particularities of their own social and ethnic backgrounds" (p. 12), or, as put by Hirst (1965), "to learn to see, to experience the world in a way otherwise unknown, and thereby come to have mind in a fuller sense" (p. 125). If so, we are forced to ask what are the features of scientific thought that makes it so valuable? What are the scientific ideas that have transformed our understanding of the world? Attempts to define the distinguishing elements of science in terms of a set of transcedent features (Lederman, 2007; Osborne et al., 2003) have failed to gain any traction within science education (Duschl & Grandy, 2013) – a fate which we would suggest is likely to befall the cross-cutting concepts of the *Framework for K-12 Science Education* (National Research Council, 2012b).[12]

Where then is the coherent vision of the cultural contribution that makes science an unquestionable element of the education of all children from K-12? To argue that the sciences are an essential foundation of a liberal education, the form of knowledge has to be specified in ways that are more than a collecton of information e.g, (Hirsch, 1987). Instead, there has to be a framework or narrative which enables students to grasp some understanding of the complex conceptual schemes that the sciences have achieved, and the different types of reasoning they afford (Hirst, 1965). It is this conception that students need to acquire and to make part of themselves, and moreover, which is needed to engage with, and evaluate, the science they

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[12] As we shall show, this is because they focus on only one element of science – its epistemic practices and do not offer a coherent conceptual vision of all the forms of knowledge required by the sciences.

encounter in their daily lives. For instance, many of the findings of the sciences are framed in terms of probabilities – from the likelihood that it will rain to an assessment of the risk of dying from surgery for a given operation. Thus probabilistic reasoning (style 5) needs to be a core feature of any science curriculum rather than a marginal or, more commonly, a missing feature.

However, both the sciences and scientists seem to suffer from collective amnesia when it comes to the magnitude of their achievements. Science, for instance, has transformed our understanding of who we are, what we are, and where we are. No longer is the planet on which we reside the center of the universe but a rather ordinary, dull object orbiting a sun, which is itself a star and part of a collection of 100,000 other stars which form just one of billions of galaxies. Moreover, other than the hydrogen and helium in our bodies, most of the elements from which we are constituted were synthesized in some star billions of years ago. Perhaps even more astounding is the idea that every cell in our bodies carries a chemically coded message about how to reproduce each of us. How then has such knowledge been achieved? By engaging in specific 'styles of reasoning' – a perspective which provides both the sciences *and* school science with what has long been missing – a vision of the sciences' achievements and the distinctive nature of its thought. In short *a cultural argument* for the value of school science.

Some Further Insights provided by "Styles of Reasoning"

In examining how the major ideas about scientific reasoning have developed, the impression we have often gained is that of the Indian fable of the blind men studying the elephant. Each new approach has pointed towards one or more of the features of scientific reasoning, but never have the components been drawn together to provide a complete and coherent picture. It is impossible in this paper to review or discuss all the attempts that have been made to address the construct of scientific reasoning and its implications for teaching science. Rather, to illustrate the partial nature of any one perspective, we have selected one strand of work that has attempted to address the challenge – the scholarship undertaken by psychologists. Drawing on the notion of 'styles of reasoning' we show the limitations of viewing a cognitive process through one particular lens. We then turn to examine the notion of scientific practices embodied in the recent *K-12 Framework for Science Education* (NRC, 2012). In doing so, our goal is to show how, seen from the perspective of styles of reasoning, the nature of the weaknesses of such approaches becomes more evident.

The Psychological Approach to Scientific Reasoning: A Partial Perpective

Many of the attempts to define scientific reasoning have presented it as a *knowledge-independent* skill, or, as expressed by Inhelder and Piaget (1958), a facility to be seen as "liberated from particular contexts" (p. 331). Another version of this is seen among psychologists who commonly take a 'nothing-special view' (Simon, 1966) arguing that general reasoning abilities can account for the main characteristics of scientific reasoning, and that these are more important as they are *transferable*. While most psychologists today admit that reasoning is knowledge-dependent (Willingham, 2008; Zimmerman, 2007), many have continued to study domain-general reasoning processes in *knowledge-lean* tasks.

For instance, a major contribution has been made by Klahr and Dunbar (1988) who have argued, from their detailed studies, that scientists work in dual spaces of hypothesis generation and experimental investigation. This conception was later extended to include a third space of evidence evaluation (Klahr & Carver, 1995). Klahr and Carver saw that these three spaces have both a domain-general and a domain-specific focus – a conception which is summarized in Table 2.

[Insert Table 2 about here]

Klahr's program of research has been dominated by a focus on students' abilities to engage in hypothesis generation, experimental design, and evidence evaluation in the context of experimental inquiry. Along with others, a particular focus has been the ability to control variables (Klahr & Li, 2005; Klahr, Zimmerman, & Jirout, 2011; Kuhn, 1991; Shayer, Wylam, Adey, & Kuchemann, 1979). Yet this particular form of reasoning is only *one* of the six styles of reasoning common in the sciences. In addition, in two extensive reviews of the nature of scientific reasoning (Zimmerman, 2000, 2007), Zimmerman notably excludes the study of hypothesis generation (A and D) from her reviews, suggesting that this cognitive operation is of less interest because of its domain-specific character when the reality is that it is core feature of science! Indeed, many would argue that it is *the defining activity* of science (Crombie, 1994; Lehrer & Schauble, 2006; Nercessian, 2008; Oakeshott, 1933). Instead, both Zimmerman and Klahr and Li (2005) emphasize the importance of domain-general approaches – although Zimmerman does acknowledge that "understanding the development of scientific thinking would be incomplete without studies in which participants take part in all phases of scientific discovery" (p. 192, Zimmerman, 2007). In so doing, she has avoided the issue of identifying what are the requisite knowledge bases for scientific reasoning.

The contrary argument for the importance of domain-specific knowledge, made by Perkins and Salomon (1989), is that "general heuristics that fail to make contact with a rich domain-specific knowledge base are weak," and that "a domain-specific knowledge base without general heuristics…is brittle" (p. 24). A similar argument was made by Koslowski (1996) in her critique of Kuhn's (1991) studies of individuals' ability to engage in scientific reasoning. Koslowski argued that Kuhn had presented abstract puzzles that operationally defined causation in terms of co-variation and had ignored the role of theoretical constructs. As she elegantly stated:

> …to study scientific reasoning by asking subjects to evaluate co-variation evidence while ignoring what they already know about theory or mechanism is analogous to studying verbal memory by studying memory for *meaningless* nonsense syllables in order to control for the effects of meaning....Similarly, studying scientific reasoning by ignoring what we know about theory or mechanism might tell us something about the subject's ability to follow experimental instructions *but not about scientific reasoning*[13]. (p. 39)

In contrast, the 'styles of reasoning' framework offers a means of identifying both the distinctive forms of reasoning *and* the knowledge required for their undertaking. In so doing it offers a vision of the *diversity* of cognitive processes that science has developed to achieve its goals. Empirical support for the importance of domain-specific knowledge is provided by Schunn and Anderson (1999) who show how, lacking domain-specific knowledge, their undergraduate subjects "did not use theories in designing their experiments" and "did not relate their results to their experiments" (p. 368) concluding that what the scientist has acquired "is not just a matter of general reasoning ability." Within domain-specific contexts, a considerable body of work has also been undertaken on the processes of evidence evaluation (Chinn & Brewer, 1993; Howe, Tolmie, Duchak-Tanner, & Rattray, 2000; Koslowski, 1996). Likewise, Passmore

[13] Emphasis added

and Stewart (2002) have argued that “scientific practice is discipline specific” (p. 187), as have Sandoval and Morrison who conclude from their analysis of student explanations of Galapagos data “that epistemic and conceptual understanding are tightly interrelated” (p. 48).

Undoubtedly, in the past six decades there has been a development in our understanding of what types of knowledge are required for reasoning in any domain – for instance in their revised version of Bloom’s taxonomy, Anderson and Krathwohl (2001) use not one but four categories to describe their knowledge dimension: factual knowledge, conceptual knowledge, procedural knowledge, and metacognitive knowledge. Likewise, Li and Shavelson (2001) have used a similar framework splitting knowledge into declarative knowledge (knowing what), procedural knowledge (knowing how), schematic knowledge (knowing why), and strategic knowledge (knowing when, where, and how knowledge applies) – a perspective that was influential in developing the NAEP 2009 framework for assessment in science. However, to date, none of these frameworks have offered a vision of how all of these three features of domain-specific knowledge (content, procedural, and epistemic) are central to the performance and teaching of scientific reasoning. In contrast, ‘styles’ do.

Finally, we would contend that defining scientific reasoning as a domain-general cognitive skill is unsustainable. First, it misrepresents the nature of scientific reasoning. While individuals in everyday situations may use reasoning akin to that of scientists, such forms of reasoning cannot be used to define *what is distinct* about scientific reasoning. Second, arguments for the value of teaching domain-general reasoning within science are unsustainable as general reasoning does *not have to* be taught in science. Other school subjects may be better at teaching it. For example, moral reasoning could be taught in the humanities, deduction in mathematics, and problem-solving skills in technology.

An examination of the body of research conducted by psychologists, however, would suggest that they study either “hypothesizing”, “experimentation” or “evidence evaluation” separately and that their attempt to present a complete and coherent construct for scientific reasoning have avoided the issue of identifying the nature of the required domain-specfic knowledge. Hence the debate over its nature remains unresolved (Tricot and Sweller, 2014, Fischer et al, 2014). While many of these features identitied have been ‘right’ in their own limited way, an overall picture of the diversity of reasoning and its knowledge-dependent nature, such as that offered by ‘styles of reasoning’, has been missing.

Teaching Science as a Set of Practices

What insights then can ‘styles of reasoning’ offer about the conception of the sciences advanced in the *Framework for K-12 Science Education* (NRC, 2012)? The model advanced within this document is that the sciences should be taught as a set of eight practices that are considered to be a distinctive feature of the sciences. The turn to practice has emerged from the social studies of the sciences, which has sought to portray the sciences as an activity undertaken by a community of practitioners who engage in a range of specific practices such as the asking of questions, developing models, analyzing and interpreting data, and engaging in argument from evidence, enable the justification of knowledge. As all of these practices require the use of scientific reasoning per se, such an approach clearly demands a greater emphasis on reasoning within the teaching and learning of science. In addition the argument in the *Framework for K-12 Science Education* that the central project of science is the construction of theories and models, rather than empirical investigation, communicates an important and long neglected message that the crowning glory of the sciences are theories (Harré, 1984) and that science is, first and foremost, a set of ideas about the material world (Oakeshott, 1933).

The central model outlined in the Framework – see Fig 1 below – draws on a synthesis of empirical results emerging from the work of the psychologists Klahr and Dunbar (1988) and the philosopher Giere (1984; 2006). This model defines the activities of science in terms of three spheres of activity – one devoted to conducting investigations, one to developing explanations, and one to evaluating these ideas by comparing them with the empirical evidence.

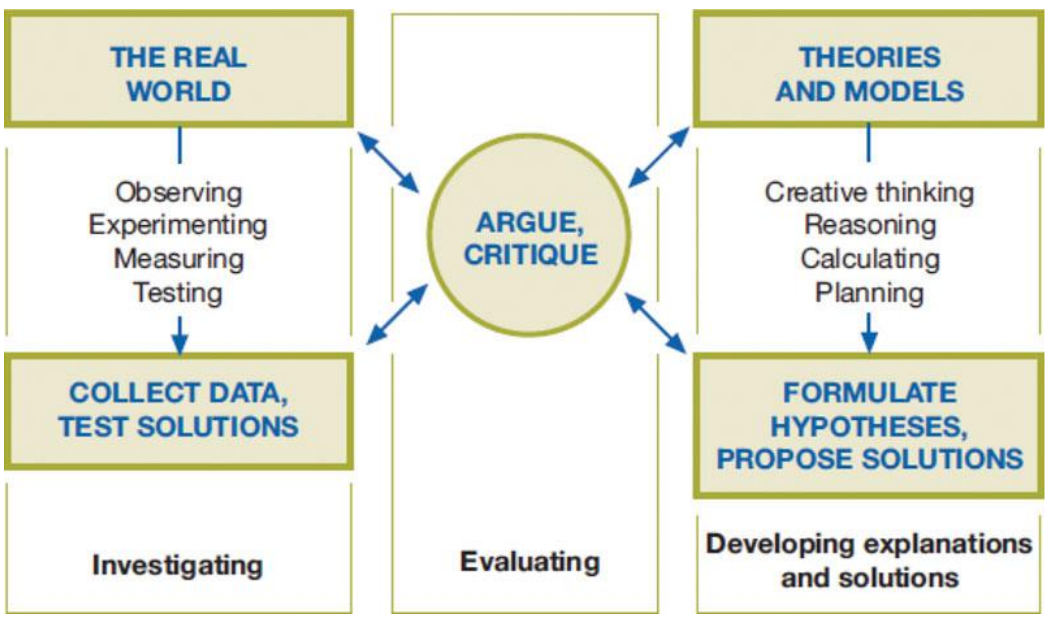

Figure 1. Model of science presented in the framework for science education (NRC, 2012, p. 45).

There is much to commend in this model. For instance, evidence would suggest that these spheres of activity are not self-evident as studies of young children reveal that students often see the sciences differently (Driver, Leach, Millar, & Scott, 1996; Klahr & Carver, 1995; Millar, Lubben, Gott, & Duggan, 1995; Schauble, Klopfer, & Raghavan, 1991). Schauble et al. (1991), for instance, have identified that much investigatory work is conceptualized by students in terms of an ‘engineering frame’, in which the children do not set out to test ideas, but instead, to test a design (i.e., change variables to achieve 'best' or optimal conditions). Again, another study (Kind, Kind, Hofstein and Wilson, 2011) has demonstrated that students recognize the activity required for hypothesizing and experimentation more readily than that required for the evaluation of evidence. Furthermore, the Framework does acknowledge the centrality of critique (Henderson, Osborne, MacPherson, & Wild, 2015) – something which no other K-12 science curriculum of which we are aware manages to do.

However, drawing on the concept of 'styles of reasoning' we see three weaknesses in the model of science offered by the Framework. First, its emphasis on engaging students in scientific practice places all of the stress on the activity itself and not its goals and purposes. For instance, one major reason for asking students to 'analyze and interpret data' is to develop an understanding that all data has a degree of uncertainty associated with its measurement, that there are standard ways of reducing the uncertainty, and that there may be competing interpretations of any given data set. Essentially that engaging in any practice has specific procedural and epistemic knowledge as its learning outcomes – outcomes which the framework notably *fails to specify*. Second, the emphasis on practice itself does not recognize that there is a set of distinct 'styles of reasoning' in science. Yes, scientists do engage in argument from evidence but the forms of argument may be deductive, inductive, or abductive, and, moreover, the ontological and procedural entities and epistemic criteria used are dependent on the specific domain of interest, and the relevant style of reasoning as shown by Table 1.

A recognition that there are six distinct styles of reasoning in science would have enabled the Framework to make a more explicit statement about the *diversity* of reasoning in the sciences, its cognitive tools, and *all* of the forms of knowledge that are intrinsic to reasoning in the disparate sciences rather than just content knowledge. Seen in this light, it is strange that the

Framework makes an extensive statement about the disciplinary core ideas that should be the goal of learning science K-12 – that is the content knowledge – but only minimal statements about the other forms of knowledge which are so core to the practice of science. Moreover, the sciences are not a human activity bound together by a universal set of practices or a set of cross-cutting themes, but rather, are a distinctive and diverse mode of thought defined by a set of 'styles of reasoning'.

Third, we ask whether sustained engagement in scientific inquiry and the practices of the sciences can develop the overview of the sciences that the framework of 'styles of reasoning' suggest we should be seeking to attain – something that Duschl and Grandy (2013) believe it can attain? Our view is that, while illuminating, practices focus on the actions that scientists take within the moment or *short term*. What is needed is a 'bigger picture' of what this collection of activities achieves in the *long term* and its goals – that is what are the significant outcomes of engaging in scientific practices . Currently, only 'styles of reasoning' offers such an overview of the nature and diversity of scientific rationality (Kusch, 2010).

Finally, we must point to the fact that there is little evidence that professional scientists develop a deep understanding of the nature science by engaging in its practice. Imre Lakatos, once memorably commented that "most scientists tend to understand little more *about* science than fish do about hydrodynamics" (Lakatos & Musgrave, 1974)(p. 148). This would suggest that practice itself does not develop the overview of the sciences or the epistemic and procedural knowledge that should be the outcome of any education in the sciences.

In contrast to the partial or, more often, absent conception of the nature of scientific reasoning, what styles of reasoning does offer is a more coherent and comprehensive vision of its nature and the knowledge bases required – in short, a comprehensive overview of the contribution of European science to the intellectual capital and cognitive resources of contemporary society. Only when armed with this kind of vision and understanding, we contend, can the teacher act as an effective guide to the scientific landscape and its cultural achievement.

Implications for Science Education

What then are the implications for science education? First, we see it as essential that a primary goal of science education should be to introduce students to all of the six styles of reasoning, some of the ontic, procedural, and epistemic entities they use, and the scientific practices they deploy. More importantly, 'styles of reasoning' offers a framework for the choice of curriculum topics – as any coherent curriculum should insure that students experience each of the major types of reasoning that characterize the sciences. Essentially that scientists need to establish what entities exist by engaging in categorization and classification (style 4) to answer the primary ontological question of what exists. Then – to answer causal questions about the nature of the world – they construct hypothetical models of the world (style 3). To test their models and to establish what exists they engage in experimental exploration (style 2). Some of their models are best represented mathematically, as is much of the data they collect from experimentation (style 1). Some of their observations of the world lead to the identification of patterns and, by applying probabilistic thinking, they can predict with a degree of certainty/uncertainty what might happen (style 5). And finally, to explain how the world came to be as it is, they have to make abductive arguments about what might have happened in the past based on observations and/or simulations (style 6). Each of these styles of reasoning illuminates how the sciences answers its epistemic question of how we know. Any education in the sciences that omits one or more of these styles, then, would only offer a partial account of the cultural achievements of the sciences. And, given that these styles of reasoning represent the major contribution of science to contemporary culture, they offer a framework and rationale for the choice *and excision* of content.

Moreover, the singular emphasis on what we know without some insights into the methods that have led to the justification for the belief in these entities and concepts – that is procedural knowledge – or the constructs that are used to justify their existence and the way in which they are used (epistemic knowledge) – is akin to offering students a description of a great cathedral without any understanding of how it came to be built, or the creative achievement it represents. And, without any understanding of the procedural or epistemic elements of scientific reasoning, students will emerge from their formal education lacking a key aspect of the knowledge required to evaluate scientific arguments (Ryder, 2001).

Thus, the first implication is that there needs to be a rebalancing of the curriculum. Mathematical and computational thinking cannot be excised. Likewise the development of analogical models and theories that are central to science has to be given the pre-eminence that a cognitive history of the sciences suggests it occupies. Moreover, the omission of any treatment of evolutionary accounts of the origins of species, stars, the universe, and more would be a failure to introduce young people to one of the major paradigms of scientific thought – in the case of evolution itself a paradigm of which Dobhansky famously noted that “nothing in biology mades sense except in the light of evolution” (Dobhansky, 1973), and a paradigm that has become influential in the psychological and social sciences (Barkow, Cosmides, & Tooby, 1992; Rose & Rose, 2010).

The role of taxonomy and classification in the development of science provides an organizing framework where disparate piece of the science curriculum – classification of life forms in biology, the categorization of rocks in the earth sciences (the foundations of geology), the identification and separation of elements (essential to the development of the periodic table), and the differentiation of heat and temperature can all be seen as a mode of thought which is essential for progress in science. The identification of patterns – the work of the epidemiologist – is also fundamental to establishing potential causal relationships. In school science these can be studied through historical examples, or alternatively they can be modeled using exercises that explore relationships between eye color and hair color, reaction time and gender, or height and foot size. Likewise, the emergence of probabilistic thinking in the 17^{th} Century (Hacking, 1984) has become a style of reasoning which is fundamental to science (Fine, Goldacre, & Haines, 2014). As a style of reasoning it can be exemplified through the collection of data sets that produce Gaussian distributions such as the variation in the heights of a set of students of the same age, the use of Punnett Squares to predict the outcomes of monohybrid and dihybrid crosses, and, at higher levels, statistical and quantum mechanics.

A major focus of science is producing an answer to the causal question of why the world behaves as it does requiring 'the hypothetical construction of analogical models' and a mode of thinking that is pervasive to science. Students, for instance, are introduced to the physical models of the human body, they construct physical models of cells, they are asked to use the particle model of matter to explain phenomena such as condensation and evaporation, the phenomena of diffraction and refraction are explained using a wave model of light, the atom is represented by the Bohr model as a kind of mini solar system, and molecular models of chemical structures are used to explain ionic and covalent bonding, the properties of materials, and the nature of chemical reactions. Yet, despite the significance of modeling to the scientific enterprise as a style of reasoning, it is rarely discussed explicitly within science education (Justi & Gilbert, 2002; Schwarz & White, 2005).

The second implication is that an emphasis on styles of reasoning offers school science a rationale for transcending the dominance of content knowledge in the curriculum, for as long as content knowledge is seen as the sole organizing framework for the determination of the curriculum, school science will continue to struggle with an overloaded curriculum. Moreover, the ever-expanding body of scientific knowledge exerts more and more pressure to squeeze ever more concepts into a finite and limited time such that the curriculum runs the risk of becoming a mile wide and only microns deep.[14] In contrast, a curriculum which saw its primary goal as a means of introducing students to the six major styles of reasoning in science could simply limit itself to a set of key examples which have established the success of scientific thought. Arguments for any specific aspect of scientific knowledge would have to be made not in terms of its importance to physics, biology, or the earth sciences, but instead on why it was key to illuminating and exploring one of the major modes of scientific reasoning.

Third, students need to see not only how such modes of thought have been successful but also to experience and practice their use to: a) understand their value and utility for the production of reliable knowledge; b) to develop some basic competency in their use; and c) to appreciate their intellectual and cultural significance. In a society that seeks to develop students' ability to reason critically, any understanding of styles and modes of reasoning is not acquired *en passant*. Rather it is acquired through *systematic* opportunities to engage in some of the key

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[14] The superficial scratching of the scientific landscape is captured by the common use of the argument that there is a need to 'cover' the curriculum. A 'cover' is something which rest on the surface and does not permit the investigation of the underlying structure.

epistemic practices of the sciences, to use the entities on which such reasoning draws, *and* to engage in meta-level reflection on the process. Practice, of itself, has demonstrated "little effectiveness in developing any real understanding of how science works within and across fields and how that knowledge might relate to civic goals" (p1073)(Linn, Palmer, Baranger, Gerard, & Stone, 2015; Rudolph, 2014). Hence, the primary function of asking students to engage in the activity of scientific reasoning should be to build a deeper understanding of how such knowledge came to be and the intellectual achievement it represents. This in turn requires a well-defined conception of the learning outcomes that engaging in practice might seek to achieve – that is the procedural knowledge essential for practice, the epistemic criteria by which new knowledge might be judged, and the forms of reasoning used in science – all of which are conjoint with much of the knowledge needed for civic engagement (Ryder, 2000) and all of which emerge from a perspective that draws on 'styles of reasoning'.

Fourth, in the development of our current scientific understanding of the material world, critique has played an essential role, for instance, in identifying why – Ptolemy's geocentric universe, Lamarkianism, the ether, cold fusion, phlogiston, spontaneous generation, and many other ideas were ultimately flawed. As Allchin (2012) has cogently argued, "students also need to learn *how* science can go wrong" (p. 905, emphasis in original) and that establishing error is scientific work that can also help to deepen student understanding. Critique and argument are, therefore, central to learning science and there can be no attempt to teach students how to reason in science without providing them opportunities to review and evaluate alternative interpretations of data sets, experimental designs, explanatory models, or causal explanations – features which are notable by their absence from many, if not most, science curricula (Henderson et al., 2015).

Ultimately, the reader might ask why this emphasis on teaching scientific reasoning and its conceptualization matters? Our response is twofold. First, leaving students with the overwhelming impression that science is a body of unequivocal and uncontested knowledge that offers no space for intellectual engagement or human creativity does both the sciences and its students a disservice. It does the sciences a disservice by presenting them as a ‘final form’ (Duschl, 1990) product without any insights into the processes that led to their attainment; and it does students a disservice by offering them an educational experience dominated by the lower order cognitive challenges of recall, comprehension, and application. In contrast, recent research suggests that students who are challenged in their classes are more likely to feel confident, successful, and happy during their science classes as well as in other academic classes (Schneider et al., 2015). By exploring how reasoning in science is central to its practice it will be possible to offer a means of illuminating the intellectual creativity required to do science, and to cultivate the critical disposition and distaste for easy answers that is the hallmark of the scientific thinker.

Our argument has been that the failure to place scientific reasoning at the center of the science curriculum can be attributed to the lack of clarity of its role and function in learning science. In short, the absence of a big picture of what it might be. To borrow from Thomas Kuhn’s notion of *paradigms* within a discipline, our limited portrayal of some of the confusion about the teaching of scientific reasoning would suggest that as a field we have been working in what Kuhn calls the period of *pre-science*, the period in which there is a clearly a phenomenon of interest, worthy of study, but no coherence or agreement about its theoretical framing within the community. Present knowledge is now such that the time has come, we think, for the establishment of a period that is more akin to *normal science* where the science education community can coalesce around a more unified vision of the disparate nature of scientific reasoning, its role and function within any science education, and the knowledge bases required. To the question 'which vision?', the contention of this paper is that a focus on 'styles of reasoning' offers a good answer – in short a way out of the sea of confusion that we have observed looking backwards. For those who do not agree with our answer, the challenge is to develop a better and alternate answer. For only then, can we offer students a less-distorted account of the scientific enterprise and the cultural achievement it represents.

Conflict of Interest Statement

Neither of the authors of this manuscript are aware of any conflict of interest between the work presented here and their other interests and working commitments.

References

Achieve. (2012). Next Generation Science Standards. Retrieved from http://www.nextgenerationscience.org/

Aikenhead, G. (1994). What is STS Science Teaching? In J. Solomon & G. Aikenhead (Eds.), *STS Education: International Perspectives on Reform* (pp. 47-59). New York: Teachers College Press.

Anderson, L. W., & Krathwohl, D. R. (2001). *A Taxonomy for Learning, teaching and Assessing: A revision of Bloom's Taxonomy of Educational Objectives*. London: Longman.

Baird, D., Scerri, E., & McIntyre, L. (Eds.). (2006). *Philosophy of Chemistry : Synthesis of a New Discipline*. Dordrecht: Springer.

Barkow, J. H., Cosmides, L. E., & Tooby, J. E. (1992). *The adapted mind: Evolutionary psychology and the generation of culture*: Oxford University Press.

Bauer, H. H. (1992). *Scientific Literacy and the Myth of the Scientific Method*. Chicago: University of Illinois Press.

Bennett, A. (2004). *The History Boys*. London: Faber and Faber.

Bereiter, C. (2002). Liberal Education in a Knowledge Society. In B. Smith (Ed.), *Liberal Education in a Knowledge Society* (pp. 11-34). Chicago: Open Court.

Cartwright, N. (1983). *How the laws of physics lie*. Oxford: Clarendon Press.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition. A theoretical framework and implications for science instruction. *Review of Educational Research, 63*, 1-49.

Chinn, C. A., & Malhotra, A. B. (2003). Epistemologically Authentic Inquiry in Schools. A theoretical framework for evaluating Inquiry task. *Science Education, 86*, 175-218.

Cohen, I. B. (1952). The education of the public in science. *Impact of Science on Society, 3*, 67-101.

Committee on the Objectives of a General Education in a Free Society. (1945). *General Education in a Free Society: Report of the Havard Committee*. Retrieved from Cambridge:

Cossons, N. (1993). Let us Take Science into our Culture. *Interdisciplinary Science Reviews, 18*(4), 337-342.

Crombie, A. C. (1994). *Styles of scientific thinking in the European tradition: The history of argument and explanation especially in the mathematical and biomedical sciences and arts* (Vol. 1): Duckworth London.

Davidson, A. I. (2004). *The emergence of sexuality: Historical epistemology and the formation of concepts*. . Cambridge, MA: Harvard University Press.

DeBoer, G. E. (1997). Historical Perspectives on Scientific Literacy. In W. Gräber & C. Bolte (Eds.), *Scientific Literacy* (pp. 69-86). Kiel: Institut für die Pädogogik Naturwissenschaften an der Universität Kiel.

Dewey, J. (1916). *Democracy and Education*. New York: The MacMillan Company.

Dobhansky, T. (1973). Nothing in Biology Makes Sense Except in the Light of Evolution. *The American Biology Teacher, 35*, 125-129.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young People's Images of Science*. Buckingham: Open University Press.

Duschl, R. (1990). *Restructuring Science Education*. New York: Teachers College Press.

Duschl, R., & Grandy, R. (2013). Two Views About Explicitly Teaching Nature of Science. *Science and Education, 22*, 2109-2139.

Economist, T. (2014). Coming to an Office Near You. *The Economist*. http://www.economist.com/news/leaders/21594298-effect-todays-technology-tomorrows-jobs-will-be-immenseand-no-country-ready

Findlay, G. M. (1928). Ultraviolet light and skin cancer. *Lancet, 2*, 1070-1073.

Fine, P. E. M., Goldacre, B., & Haines, A. (2014). Epidemiology - A Science for the People. *The Lancet,, 381*, 1249-1252.
Fodor, J. (1983). *Modularity of Mind*. Cambridge, MA: MIT Press.
Fuller, S. (1997). *Science*. Buckingham: Open University Press.
Giere, R. (1984). *Understanding Scientific Reasoning* (2cnd ed.). New York: Holt, Rinehart and Winston.
Giere, R., Bickle, J., & Maudlin, R. F. (2006). *Understanding Scientific Reasoning* (5th ed.). Belmont, CA: Thomson Wadsworth.
Gilbert, J. (2005). *Catching the Knowledge Wave? The Knowledge Society and the Future of Education*. Wellington, New Zealand: NZCER Press.
Lent to Tony Sherborne 22/10/06
Gott, R., Duggan, S., & Roberts, R. (2008). *Concepts of evidence*. Retrieved from School of Education: http://www.dur.ac.uk/rosalyn.roberts/Evidence/cofev.htm
Hacking, I. (1984). *The Emergence of Probability: A Philosophical Study of Early Ideas About Probability, Introduction and Statistical Inference*: Cambridge University Press.
Hacking, I. (1992). 'Style' for Historians and Philosophers. *Studies in the History and Philosophy of Science, 23*(1), 1-20.
Hacking, I. (2012). 'Language, Truth and Reason' 30 years later. *Studies in History and Philosophy of Science, 43*, 599-609.
Hanushek, E. A., & Woessmann, L. (2015). *The knowledge capital of nations: Education and the economics of growth*: MIT Press.
Harré, R. (1984). *The Philosophies of Science: An Introductory Survey* (2nd ed.). Oxford: Oxford University Press.
Henderson, B., Osborne, J., MacPherson, A., & Wild, A. (2015). Beyond Construction: Five arguments for the role of critique in teaching science. *International Journal of Science Education, 37*(10), 1668-1697.
Hill, C. (2008). The Post-Scientific Society. *Issues in Science and Technology on Line, 24*(1), 78-84.
Hirsch, E. D. (1987). *Cultural Literacy: What Every American needs to know*. Boston: Houghton Mifflin.
Hirst, P. H. (1965). Liberal education and the nature of knowledge. *Philosophical analysis and education, 2*, 113-140.
Hirst, P. H., & Peters, R. S. (1970). *The logic of education*. London: Routledge.
Hout, M., & Elliott, S. W. (Eds.). (2011). *Incentives and Test-Based Accountability in Education*. Washington, DC: National Academies Press.
Howe, C., Tolmie, A., Duchak-Tanner, V., & Rattray, C. (2000). Hypothesis testing in science: group consensus and the acquistion of conceptual and procedural knowledge. *Learning and Instruction, 10*(361-391).
Inhelder, B., & Piaget, J. (1958). *The Growth of Logical Thinking from Childhood to Adoloscence*. London: Routledge and Kegan Paul.
Justi, R. S., & Gilbert, J. K. (2002). Modelling, teachers' views on the nature of modelling, and implications for the education of modellers. *International Journal of Science Education, 24*(4), 369-387.
Klahr, D., & Carver, S. M. (1995). Scientific thinking about scientific thinking. *Monographs of the Society for Research in Child Development, 60*(4), 137-151.
Klahr, D., & Dunbar, K. (1988). Dual space search during scientific reasoning. *Cognitive science: A multidisciplinary journal, 12*(1), 1-48.
Klahr, D., & Li, J. (2005). Cognitive Research in Elementary Science Instruction: From the Laboratory to the Classroom and Back. *Journal of Science Education and Technology, 14*(2), 217-238.
Klahr, D., Zimmerman, C., & Jirout, J. (2011). Educational Interventions to Advance Children's Scientific Thinking. *Science, 333*, 971-975.
Koslowski, B. (1996). *Theory and Evidence: The Development of Scientific Reasoning*. Cambridge, MA: MIT Press.
Kuhn, D. (1991). *The Skills of Argument*. Cambridge: Cambridge University Press.

Lakatos, I., & Musgrave, A. E. (1974). Falsification and the Methodology of Scientific Research Programmes. In I. Lakatos & A. E. Musgrave (Eds.), *Criticism and the Growth of Knowledge*. Cambridge: Cambridge University Press.

Layton, D. (1973). *Science for the People: The Origins of the School Science Curriculum in England.* London: Allen and Unwin.

Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. *Journal of Research in Science Teaching, 29,* 331-359.

Lederman, N. G. (2007). Nature of Science: Past, Present and Future. In S. Abell & N. G. Lederman (Eds.), *Handbook of Research on Science Education* (pp. 831-879). Mawah, NJ: Lawrence Erlbaum.

Lehrer, R., & Schauble, L. (2006). Cultivating model-based reasoning in science education. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 371-387). Cambridge: Cambridge University Press.

Li, M., & Shavelson, R. J. (2001). *Examining the links between science achievement and assessment*. Paper presented at the Annual Meeting of the American Educational Research Association, Seattle, WA.

Linn, M. C., Palmer, E., Baranger, A., Gerard, L., & Stone, E. (2015). Undergraduate research experiences: Impacts and opportunities. *Science, 347*(6222), 627.

Martins, A. F. P., & Ryder, J. (2015). *Nature of Science in science education: a proposal based on 'themes'.* Paper presented at the GIREP-MPTL INTERNATIONAL CONFERENCE ON TEACHING/LEARNING PHYSICS.

Matthews, M. R. (1994). *Science Teaching: The Role of History and Philosophy of Science*. New York: Routledge.

Mayr, E. (2004). *What Makes Biology Unique?: Considerations on the Autonomy of a Scientific Discipline*. Cambridge: Cambridge University Press.

Medin, D. L., & Bang, M. (2014). *Who's asking?: Native science, western science, and science education*: MIT Press.

Millar, R., Lubben, F., Gott, R., & Duggan, S. (1995). Investigating in the school science laboratory: conceptual and procedural knowledge and their influence on performance. *Research Papers in Education, 9*(2), 207-248.

Millar, R., & Osborne, J. F. (Eds.). (1998). *Beyond 2000: Science Education for the Future*. London: King's College London.

National Research Council. (2008). *Research on Future Skill Demands.* Washington D.C.: National Academies Press.

National Research Council. (2012a). *Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century. Committee on Defining Deeper Learning and 21st Century Skills*. Retrieved from Washington, DC:

National Research Council. (2012b). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas.* Retrieved from Washington, DC.:

Nercessian, N. (2008). Model-Based Reasoning in Scientific Practice. In R. A. Duschl & R. E. Grandy (Eds.), *Teaching scientific inquiry: Recommendations for research and implementation* (pp. 57-79). Rotterdam, Netherlands: Sense.

Nersessian, N. J. (1995). Constructing Knowledge in the History of Science. In H. o. S. Society (Ed.), *Osiris, 2nd Series, Vol. 10,* (pp. 194-211): The University of Chicago Press on behalf of The History of Science Society.

Netz, R. (1999). *The shaping of deduction in Greek mathematics: A study in cognitive history*: Cambridge University Press Cambridge.

Oakeshott, M. (1933). *Experience and its Modes*. Cambridge: Cambridge University Press.

OECD. (2012). The PISA 2015 Assessment Framework: Key competencies in reading, mathematics and science. http://www.oecd.org/pisa/pisaproducts/pisa2015draftframeworks.htm

Osborne, J. F., Ratcliffe, M., Collins, S., Millar, R., & Duschl, R. (2003). What 'ideas-about-science' should be taught in school science? A Delphi Study of the 'Expert' Community. *Journal of Research in Science Teaching, 40*(7), 692-720.

Passmore, C., & Stewart, J. (2002). A modeling approach to teaching evolutionary biology in high schools*. *Journal of Research in Science Teaching, 39*(3), 185-204.

Pellegrino, J. W., Chudowsky, N., & Glaser, R. (2001). *Knowing what students know: The science and design of educational assessment*: Natl Academy Pr.

Perkins, D. N., & Salomon, G. (1989). Are Cognitive Skills Context-Bound? *Educational Researcher, 18*(1), 16-25.

Qualifications and Curriculum Authority. (2007). *Programme of Study: Science KS4*. London: Qualifications and Curriculum Authority.

Reddy, M. (1979). The conduit metaphor. In A. Ortony (Ed.), *Metaphor and Thought* (pp. 284-324). New York: Cambridge University Press.

Reiner, M., & Gilbert, J. K. (2000). Epistemological resources for thought experimentation in science learning. *International Journal of Science Education, 22*(5), 489-506.

Rose, H., & Rose, S. (2010). *Alas poor Darwin: Arguments against evolutionary psychology*: Random House.

Rudolph, J. L. (2000). Reconsidering the'nature of science'as a curriculum component. *Journal of Curriculum Studies, 32*(3), 403-419.

Rudolph, J. L. (2014). Dewey’s “Science as Method” a Century Later Reviving Science Education for Civic Ends. *American Educational Research Journal, 51*, 1056-1083.

Rudolph, J. L., & Horibe, S. (2015). What do we mean by science education for civic engagement? *Journal of Research in Science Teaching*, n/a-n/a. doi:10.1002/tea.21303

Ryder, J. (2001). Identifying science understanding for functional scientific literacy. *Studies in Science Education, 36*, 1-44.

Salzman, H., Kuehn, D., & Lowell, B. L. (2013). *Guestworkers in the High Skill U.S. Labor Market: An analysis of supply, employment, and wage trends*. Retrieved from Washington DC:

Schauble, L., Klopfer, L. E., & Raghavan, K. (1991). Students' transition from an engineering model to a science model of experimentation. *Journal of Research in Science Teaching, 28*(9), 859-882.

Schneider, B., Krajcik, J., Lavonen, J., Salmela-Aro, K., Broda, M., Spicer, J., . . . Viljaranta, J. (2015). Investigating optimal learning moments in U.S. and finnish science classes. *Journal of Research in Science Teaching*, n/a-n/a. doi:10.1002/tea.21306

Schunn, C. D., & Anderson, J. R. (1999). The generality/specificity of expertise in scientific reasoning. *Cognitive Science, 23*(3), 337-370.

Schwarz, C. V., & White, B. Y. (2005). Metamodeling knowledge: Developing students’ understanding of scientific modeling. *Cognition and Instruction,, 23*(2), 165-206.

Shavelson, R. J., Baxter, G. P., & Pine, J. (1991). Performance Assessment in Science. *Applied Measurement in Education, 4*(4), 347 - 362.

Shayer, M., Wylam, H., Adey, P., & Kuchemann, D. (1979). CSMS Science Reasoning Tasks. *NFER, Nelson, Windsor*.

Simon, H. A. (1966). Scientific discovery and psychology of problem solving. In R. Colony (Ed.), *Mind and Cosmos* (pp. 22-40). Pittsburgh: University of Pittsburgh Press.

Spencer, H. (1884). *What knowledge is of most worth*. New York: JB Alden.

Suppes, P. (1960). A comparison of the meaning and uses of models in mathematics and the empirical sciences. *Synthese, 12*(2), 287-301.

The Royal Society. (2014). *Vision for Science and Mathematics Education*. Retrieved from London:

Turner, D. M. (1927). *History of science teaching in England*. London: Chapman and Hall.

Tweney, R. D. (2001). In K. Crowley, C. D. Schunn, & T. Okada (Eds.), *Designing for Science: Implications from Everyday, Classroom and Professional Settings* (pp. 141-173). Mahwah, NJ: Lawrence Erlbaum.

Van Dijk, E. M. (2014). Understanding the Heterogeneous Nature of Science: A Comprehensive Notion of PCK for Scientific Literacy. *Science Education, 98*(3), 397-411. doi:10.1002/sce.21110

Vygotsky, L. S. (1978). *Mind in Society*. Cambridge, MA: Harvard University Press.

Weiss, I. R., Pasley, J. D., Sean Smith, P., Banilower, E. R., & Heck, D. J. (2003). *A Study of K–12 Mathematics and Science Education in the United States*. Retrieved from Chapel Hill, NC.:

Willingham, D. T. (2008). Critical Thinking: Why Is It So Hard to Teach? *Arts Education Policy Review, 109*(4), 21-32. doi:10.3200/AEPR.109.4.21-32

Wilson, M., & Bertenthal, M. (2005). *Systems for State Assessment*. Retrieved from Washington, DC:

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the Scientific Method: Model-based inquiry as a new paradigm of preferences for school science investigations. *Science Education, 92*(5), 941-967.

Xie, Y., & Killewald, A. A. (2012). *Is American science in decline?* Cambridge, MA: Harvard University Press.

Ziman, J. (1994). The Rationale of STS Education is in the Approach. In J. Solomon & G. Aikenhead (Eds.), *STS Education: International Perspectives on Reform* (pp. 21-31). New York: Teachers College Press.

Zimmerman, C. (2000). The development of scientific reasoning skills. *Developmental Review, 20*(1), 99-149.

Zimmerman, C. (2007). The development of scientific thinking skills in elementary and middle school. *Developmental Review, 27*(2), 172-223.