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Finding the place of argumentation in science education: Epistemics and Whole Science

Douglas Allchin[1] | **Gábor Á. Zemplén**[2]

[1]Minnesota Center for the Philosophy of Science, University of Minnesota, Minneapolis, Minnesota

[2]ELTE Institute of Business Economics, Eötvös Loránd University, Budapest, Hungary

Correspondence
Douglas Allchin, Minnesota Center for the Philosophy of Science, University of Minnesota, Minneapolis, MN 55455.
Email: allchindouglas@gmail.com

Abstract

Argumentation constitutes an important element in nature of science education. However, its virtues and scope can be overstated. Here, we survey in detail the place of argumentation in science education. Our benchmark is the range of epistemic processes relevant to citizens and consumers as they assess the reliability of scientific claims in personal and public decision making. We consider multiple epistemic stages in the development (or ontogeny) of such claims: (a) observation and material investigation; (b) the crafting of concepts through individual cognition; (c) the checks and balances of the scientific community; (d) the challenges of credibility and expertise in a cultural context; and (e) the interpretation of "science in the wild," where authentic scientific claims mingle with imitators and misinformation on the Internet and social media and in public discourse. We conclude that many conventional rationalist assumptions haunt current approaches to argumentation and limit its effectiveness, especially in the implicit goal of achieving intellectual independence for students as autonomous scientific agents. A more fruitful approach, from the perspective of functional scientific literacy, is a Whole Science perspective, which gives full expression to the spectrum of epistemic processes in science and science communication.

KEYWORDS
argumentation, epistemic practices, nature of science, scientific

1 | INTRODUCTION: WHENCE ARGUMENTATION?

Historically, recognizing the role of argumentation in science was an important step for nature of science (NOS) and science literacy education (Peterson & Jungck, 1988). It supported an emerging shift from teaching ready-made science to science-in-the-making (Latour, 1987; see also Flower, 1995). Decades ago, science education embodied a narrow positivist conception of science, largely defined by static conceptions of theory, evidence, strict logical reasoning, and a simplified view of testing and crucial experiments. In the 1960s, 1970s, and 1980s, studies in the history, philosophy, and sociology of science revealed a more complex (and more human) image of scientific practice. Science was animated with conceptual change, debates and controversies, competition for credit, the influences of ideology and culture, and the roles of language, rhetoric and persuasion. The theme of argumentation helped open the "black box" of scientific facts and reveal the "constructed" nature of knowledge (Driver, Newton, & Osborne, 2000, p. 309; Hodson, 2008). It also helped underscore the importance of social discourse among scientists and the role of mutual critique and justification (among students also). In the classroom, it fostered more emphasis on student-centered discussion and more opportunities for developing writing and communicating skills—elements that also echoed the growing commitments to constructivist pedagogy. A focus on argumentation helped transform science education.

The importance of argument in science is now widely acknowledged among educators (e.g., Adúriz-Bravo & Chion, 2017; Erduran & Jiménez-Aleixandre, 2008; Osborne, 2010). For example, the model curriculum in the United States, the Next Generation Science Standards (NGSS Lead States, 2013), identifies argumentation as one of its 8 "scientific practices" (with communication as yet another). Similarly, PISA standards include competencies in epistemic knowledge, in scientific explanations and inquiry, and in the ability to "interpret data and evidence scientifically." Namely, students should learn to "analyse and evaluate data, claims and arguments in a variety of representations and draw appropriate scientific conclusions" (OECD, 2017, pp. 15, 21–24). We also note that approaches to argumentation in science education emphasize analytical skills and reflective thinking, and thus resonate strongly with the tradition of teaching critical thinking (e.g., Hand, Shelley, Laugerman, Fostvedt, & Therrien, 2018). (This tradition extends broadly from John Dewey's pragmatism to Copi and Cohen's [1988] informal logic to the comprehensive treatment of Walton [2006].) Moreover, engaging in public discourse on socioscientific issues (SSIs) relies in part on media literacy—of growing importance—and which similarly tends to focus on the analysis of arguments, their sources and their justification (e.g., American Press Institute, 2019; Center for Media Literacy, 2018; Jarman & McClune, 2007; News Literacy Project, 2012). Argumentation has found a secure place in contemporary science education and allied fields.

At the same time, the role of argument can easily be overstated. In the view of some advocates, argumentation is "a core activity of science," hence "central" to science education (Driver, et al. 2000, pp. 287, 290, 296, 297, 301, 309; Erduran & Jiménez-Aleixandre, 2008, p. 4). It is variously characterized as "essential," the "core," the "essence," or a "hallmark" of science (Osborne, 2010). Accordingly, proponents afford argumentation a "pre-eminent role" in science education (Adúriz-Bravo, 2014, p. 1445). It is "paramount… in scaffolding and configuring science learning," and declared "a privileged strategy to teach science" (Adúriz-Bravo & Chion, 2017, pp. 157, 161). Indeed, arguments have been described as "the very vertex of the 'scientific pyramid'," and hence as the "most inclusive and elaborate scientific processes" (Adúriz-Bravo & Chion, 2017, p. 162). Some go so far as to characterize science as nothing more than argument itself. Thus, student views of the nature of science are to be regarded as fundamentally "discursive achievements" (Deng, Chen, Tsai, & Tsai, 2011, pp. 967, 977, 979). Educators should ensure that "students are not separating the concept of argument from how knowledge is constructed in science" (Hand, et al., 2018, p. 697). Science *is* argument (Kuhn, 1993, 2010). For many advocates, therefore, students need only engage with argumentation to learn about the workings of science and/or its epistemic practices (e.g., Adúriz-Bravo, 2014; Adúriz-Bravo & Chion, 2017; Deng et al., 2011; Driver, et al. 2000; Henderson, MacPherson, Osborne, & Wild, 2015; Osborne, Erduran, & Simon, teaching the nature of science (NOS). That is, mastery of argumentation alone cannot fully equip citizens and consumers with the essentials they need to assess the reliability of scientific claims in personal and public decision making. Accordingly, echoing and extending earlier analyses by Bricker and Bell (2008) and Manz (2015), we wish to clarify the place of argumentation in NOS education, as contextualized in the current institutional standards of functional scientific literacy.

We intend our analysis to be general and thematic, perhaps even impressionistic. Namely, we wish to avoid relying unduly on any strict conceptualizations of the core concepts, "nature of science" and "argumentation." (We find limited use in claims that hinge precariously on precise or narrow definitions.) Caution is warranted especially where (as in these two cases) different scholars adopt diverse positions and the concepts are still actively debated. Still, how should one characterize these two central concepts, to provide some grounding and orientation?

Consider, first, the NOS. NOS education has a venerable heritage. An early expression was embedded in Conant's (1947) advocacy for science education after World War II, with its call for understanding "the tactics and strategy of science" as a part of civic literacy (see also Conant & Nash, 1957). The turn of the century was marked by a relative convergence of views, as embodied in the shared elements (or intersection) of major international curricular documents (McComas & Olson, 1998), and which was soon echoed by a multidisciplinary expert panel (Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003). That led to a widely adopted "consensus view" (e.g., Lederman, 2007), which has since dissolved into a broad-based dissensus (*Canadian Journal of Science, Mathematics and Technology Education*, Vol. 17 [2017], No. 1). Emerging approaches now tend to emphasize instead a pragmatic and more inclusive eclecticism (e.g., Allchin, 2013a; Erduran & Dagher, 2014). Nevertheless, our benchmarks here for conceptualizing NOS are the major policy documents that currently provide the explicit institutional rationale for NOS learning (e.g., NGSS Lead States, 2013; OECD, 2017; Rutherford & Ahlgren, 1991). They underscore the need to understand "scientific practices" or "how science works," contextualizing NOS as a factor in empowering public discourse surrounding science. That is, they reflect the aim of functional scientific literacy (well articulated by Hodson, 2008; Kolstø, 2001; Ryder, 2001: and Toumey, et al., 2010). In other words, NOS may be characterized by its educational outcome:

> *Students should develop a broad understanding of how science works to interpret the reliability of scientific claims in personal and public decision making (Allchin, 2013a, pp. 4, 154).*

This approach to NOS conveniently brings together two perspectives: it identifies the relevant boundary of NOS and also contextualizes NOS content in the institutional aims of science education. We think this view is shared by most proponents of argumentation, too. In summary, the conceptualization of NOS that guides our analysis is squarely focused on the *epistemics* of science, as they are relevant to citizens and consumers.

How, then, should one characterize "argumentation"? This task, too, proves potentially fraught with contention. Scholars of argumentation differ widely on theoretical approaches and definitions (see, e.g., Bricker & Bell, 2008; van Eemeren, et al., 2014; Tseronis & Forceville 2017; Wagemans, 2019). Nor does there seem to be a single concept of argumentation within science education (Bogar, 2019, pp. 2–5). At the same time, one does find surprising similarity in classroom approaches (see especially Driver, et al., 2000; Jiménez-Aleixandre & Erduran, 2007). For the analytical purposes here, we will construe argumentation as the explicit marshaling of evidence and exercising of sound reasoning to justify a particular claim (or set of claims). That is, the chief educational objective is to engage students in mindful, public, and defensible reasoning. In a social context, argumentation in science is also the discourse for resolving conflicting views, by reference to empirical evidence. (We contrast this meaning to a more general and widespread use of the term "argument" or "argumentation" to denote any social and dialogic process that supports constructivist pedagogy or mutual understanding.[1]) Students are typically introduced to, and encouraged to think in terms of, prescribed argument structures, such as Toulmin (1958) (see, for example, Osborne, et al., 2004 or Sampson and Clark, 2008) or a modified hypothetico-deductive model (e.g., Lawson, 2010). These structures (as normative models) are intended to guide students when they discuss how to interpret experimental results, say, or when they gradually assemble and try out prospective arguments to support their own explanatory models. The argument structures (or templates) are generally also intended to help in a sociocultural context, for interpreting and analyzing other persons' arguments (such as one might find in the Media or in public discourse). In using these various schemata in research, educators further indicate their concept of argumentation at the operational level. Ultimately, educators tend to conceptualize classroom argumentation as a proxy for scientific reasoning. Hence, one might say that the guiding norm is to gradually develop the skills for constructing a "final-form" scientific paper, as a fully mature product (Duschl & Osborne, 2002). The guideposts (often only implicit) also embody the connection (noted above) between the argumentation programme and established traditions that promote scientific reasoning, critical thinking, and news media literacy. All seek the implicit goal of helping students achieve intellectual independence. While this conceptualization of argumentation may not apply equally to all instances in science education, we feel that it does capture the overall spirit of the enterprise and is reflected in the typical activities described under that rhetoric.

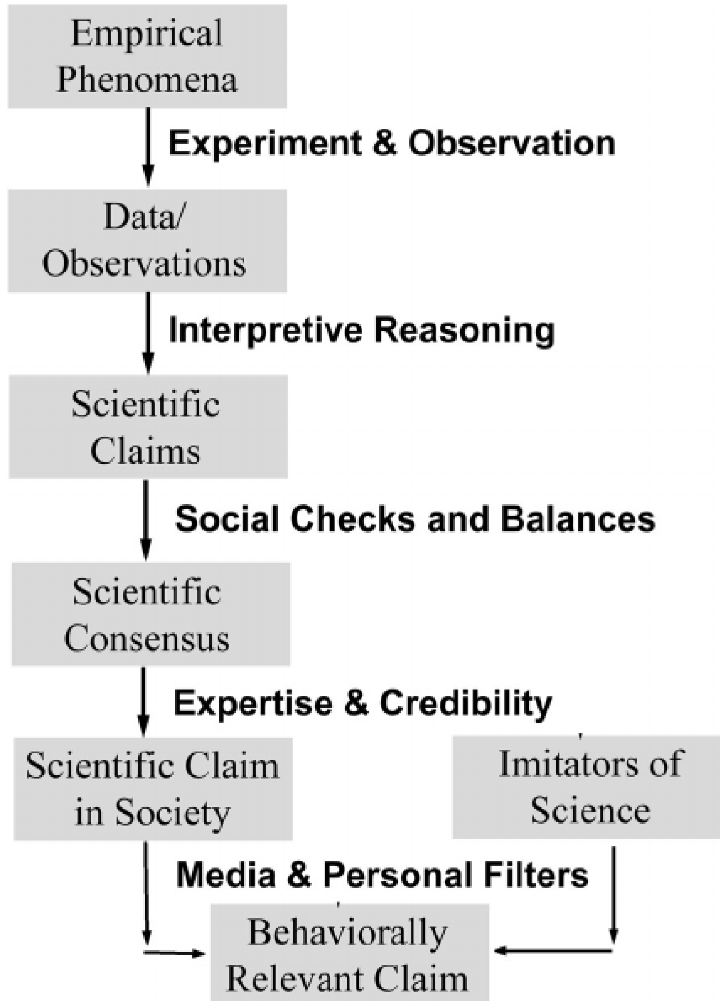
Several prominent features of this conceptualization may be noted here. It is deeply rooted in assumptions that scientific arguments are: (a) rational, (b) empirically based, (c) well structured (usually with deductive logic as the ideal), (d) mostly context-independent (unambiguous and universal), (e) stable (once validated), and (f) honest. Confidence in these features seems closely related to the goal of intellectual independence. As we will observe below, however, these assumptions falter at times in actual scientific practice, and fail in ways that significantly affect how citizens and consumers should interpret scientific claims. Noting such exceptions to the typical approaches to argumentation in science education is one of the chief purposes of this paper.

Ultimately, we contend that argumentation (as envisioned above) and epistemic processes in science (constituting NOS) are not always aligned. There are significant gaps and deviations. In our view, the place of argumentation in NOS education needs to be strongly circumscribed and delineated. Accordingly, we place argumentation *as just one among many relevant NOS facets* of scientific literacy (e.g., as profiled in NGSS's scientific practices or in Whole Science; see Allchin, 2011, 2013a, 2017; NGSS Lead States, 2012).

We present our analysis in the context of a comprehensive view of epistemic processes in science (again, what we take to be the relevant scope of NOS in the context of standard versions of functional scientific literacy). We trace the sequential development and transformation (or "ontogeny") of scientific claims from their original observational sources in scientific labs and field sites to the claims encountered by citizen-consumers: namely, "from test tubes to YouTube," "from lab bench to judicial bench," "from field site to website," "from lab book to Facebook" (see Figure 1). This is similar to following a pathway along a Latourian network (Latour 1987; see also Kelly & Takao, 2002), or the synoptic approach of Whole Science (Allchin 2011, 2013a, 2017).

We describe each successive stage in the process and address the role of argumentation in each one. First, we consider the material (empirical) dimension of science (Section 2). Next, we look at how concepts are formed, and in particular how they are shaped by cognitive thinking patterns (with their departure from normative ideals) and the "biases" and errors that inevitably emerge (Section 3). Following, we consider social dimensions internal to the scientific community (among experts; Section 4). We then follow the development of scientific claims as they move outside "science," from experts to non-experts: how are epistemic processes and argumentation relevant there? (Section 5). The Whole Science approach allows us to follow scientific claims even further, through the media, where they are transformed, and in a context where they compete with claims from non-scientists. Epistemic assessments and argumentation (both rational and other) continue to be relevant (Section 6). We then conclude with a review of the many virtues and limits of focusing on argumentation in science education, allowing us to

FIGURE 1 The development of a scientific claim, exhibiting a series of epistemic stages, each with its own strategies and methods. When read from top to bottom, this constitutes the "ontogeny" of a fact, from empirical sources to socially relevant beliefs ("from test tubes to YouTube"). When read from bottom to top, it indicates the provenance of a purported claim, critical to a thorough epistemic analysis and assessment of its reliability



2 | THE EPISTEMICS OF OBSERVATION AND MATERIAL INVESTIGATION

Let us begin with what we hope is uncontroversial: namely, that science is empirical (e.g., McIntrye, 2019; Zimring, 2019). The construction of scientific claims is rooted in observations and measurements. In the lab, in the field, in the clinic, in the observatory. And in the mining of vast reservoirs of digitized data. Epistemic processes and questions begin even at this initial interface between investigator and physical phenomena. That is, what makes these basic raw data and their interpreted meanings—the observational "facts"—trustworthy, or reliable? Epistemic challenges include accuracy, precision, clear specification of conditions (relevant controls), appropriate methods, theory of the instrument, calibration, standardization, replication and sample size (and statistical uncertainty), experimental skill, the craft of stabilizing phenomena, detecting technical artifacts, placebos, blind and double blind studies, concurrence among alternative methods, choice of model organism, curation of large data bases, and more. In a sense, there is no such thing as a "simple" fact. Indeed, these concerns have developed into a whole sub-field in philosophy of science: the New Experimentalism (Franklin, 1986, 1991; Galison, 1987; Hacking, 1983; Kohler, 1994; Pickering, 1995; Rheinberger, 1997, 2010). As Ian Hacking once mused, "experimentation has a life of its own" (1983, p. 150).

Ironically, perhaps, much of this occurs without "argument." Reasoning, yes (of course?). And investigators may differ in perspective, leading them to negotiate claims, as well. But only rarely do these rise to the level of explicit and formally constructed "arguments" (of the types educators promote). Here, we survey briefly some of the

One fundamental problem is the bridge between the physical world and the conceptual world, expressed through language. Observations and measurements are, by themselves, idle. To be useful conceptually, they must be recorded in a form that can be managed cognitively. Measurements are entered as numeric symbols. Physical phenomena are converted into "text." Laboratory devices yield "inscriptions." They are all transformed into linguistic entities (Latour & Woolgar, 1979, pp. 51, 63–69, 88, 245–246; Latour, 1987, pp. 63–79). These are the "raw data." Unfortunately, perhaps, the data are not the phenomena (Bogen & Woodward, 1988). A persistent epistemic problem, therefore, has been: what links the (linguistic) map unambiguously to the (empirical) territory? The conundrum also once plagued the logical positivists, who wanted to transform observations into unambiguous logical expressions that ideally could be subjected to pure formal analysis. They struggled with protocol statements and the notion of operational definitions, but never reached an effective resolution. Philosopher Gaston Bachelard (1953) developed the notion of "phenomenotechnique" to characterize the hybrid nature of such "representations," imbued with assumptions and procedures (see also Latour & Woolgar, 1979, pp. 63–69). They are not just unproblematic observation statements. Similarly, sociologist Andy Pickering (1995) refers to the "mangle of practice"—the intimate relationship and interaction between the experimenter and the physical world. Despite commonly found appeals, the data do not "speak for themselves."

Further, many dimensions of work in the lab do not reduce to conceptual thinking or arguments. They are based instead on performance and skill (Collins & Evans, 2002; Crease, 1993; Pinch, Collins, & Carbone, 1996). For example, physicists examining a new phenomenon may simply aim to stabilize it and "tease it into relief" by manipulating experimental conditions, guided only by their intuition (Galison, 1987). In other forms of exploratory science, there is no hypothesis being tested (as prescribed in the canonical classroom "scientific method"). Rather, investigators may blindly vary parameters hoping to find informative differences; they may pursue oddities or "errors" for clues to unknown causes; or they may simply try to refine their technique to be more efficient or to yield clearer, more definitive results (Elliot, 2007). For example, Joseph Priestley made many of his important discoveries about gases and the restoration of air by plants through endless "tinkering" in his lab (Johnson, 2008). Or consider the claim that a neutrino traveled faster than the speed of light: headline news in 2011. Who would have identified cable connections in the equipment as part of the "argument"? But when the anomaly was diagnosed, that's what it was: a loose cable that transmitted an erroneous time signal (Cartlidge, 2012). Similarly, the revolutionary discovery of polywater in the 1960s was undone by isolating a single causal variable: dirty glassware (Franks, 1981). Hence, the popularity of an aphorism by biochemist Efraim Racker, "Don't waste clean thinking on dirty enzymes." Experimental skill and practice matter epistemically, although rarely mentioned in arguments. Still, they can be taught. A fine example is provided by educators who help teachers acquire reflective "know-how" in interacting with laboratory apparatus through famous historical cases (Heering, Klassen, & Metz, 2013; Heering & Wittje, 2011; Reiß, 1995).

A focus on argumentation also risks misportraying experimental practice and even experimental reasoning. What scientists *do* in a lab and what they *report* in their published arguments frequently do not match (Medawar, 1964). The argument is not a faithful narrative. Thus, the order of reasoning may be conspicuously inverted (Knorr-Cetina, 1981, pp. 94–135; Latour & Woolgar, 1979, pp. 177–183). Events may be severely truncated, discarding false leads, blind alleys, and errors. The real process of discovery is easily disguised by the reorganized justification. Thus, some science educators have been misled into thinking that the rhetorical posture of hypothetico-deductive reasoning in the scientific paper accurately describes the nature of scientific discovery (Allchin, 2004a, 2006, 2013a). From an educational NOS perspective, the difference between argument and real unfolding lab work matters. Students need to first understand the scientific practices. Only then can they appreciate how the reasoning is transformed into an argument quite different in structure from the process that produced it. To understand "how science works" (the explicit NOS goal), one cannot use argument as a substitute.

Educators who regard argumentation as "central" or "paramount" also typically emphasize the conceptual dimension of science—its theories, models and explanations.[2] They tend to discount the material and technical dimensions, including the role of instruments. Notably, Nobel prizes have frequently been awarded for research technologies, not theories: green fluorescent protein (2008), PCR (1993), MRI (2003), transistors (1956), lasers (1964), the scanning tunneling microscope (1986) and cryo-electron microscope (2017); recombinant DNA (1980), and monoclonal antibodies (1984), to name a few. Instruments may seem no more than transparent tools—"instrumental" in collecting the more critical evidence. However, they involve epistemics, too. How do we know our observations with them are valid? "Do we see through a microscope?" Hacking once famously asked (1983, pp. 186–209). What is "the epistemology of a spectrometer"? (Rothbart & Slayden, 1994). Consider, for example, a quite famous piece of equipment: Millikan's oil-drop experiment for determining the charge-to-mass ratio of the electron. Millikan did not publish every experimental trial. Was he dishonestly cherry-picking his results? Or, as argued by Allan Franklin, did he recognize that the apparatus was not functioning according to its design on those occasions, and justifiably exclude the "bad data" (Franklin, 1986, pp. 140–162; Panusch & Heering, 2011)? Observation can be a complex process. Note that no less than 398 people collaborated to "observe" the top quark in 1995. Even simple measurements can have hidden complexities. For example, to measure the percentage of carbon dioxide in the atmosphere, Dave Keeling quantified the air's absorption of infrared radiation. That was as an indirect indicator, so he needed first to calibrate the device against the more time-consuming volumetric methods. Keeling also had to establish an exacting protocol to ensure precision and consistency from one measurement to the next. That included creating a set of reference samples to ensure uniformity of devices across multiple sampling locations, from Mauna Loa to Antarctica to La Jolla, California. These experimental procedures matter to the claims linking carbon dioxide to global warming. This is NOS relevant to scientific literacy. Fortunately, students can learn about the principles of measurement—in this case, through a guided historical inquiry (Allchin, 2017, pp. 14–18; Leaf, 2011). From an argumentation perspective, however, they seem invisible. With an eye only to concepts and models, one may miss how the material processes of instruments are integral to the trustworthiness of scientific claims.

That is, "evidence" cannot be taken for granted. It, too, involves epistemic processes. Thus, an argument that appeals to "data" (as in Toulmin's model) does not address the reasoning and material processes that went into producing that data and securing its reliability. As noted by Duncan, Chinn, and Barzilai (2017), the practices used to create and evaluate forms of evidence belong in educational goals as much as the arguments that use them. The justification for scientific claims exhibit multiple layers or levels, built from chains of successive epistemic processes (Kelly & Takao, 2002; Latour, 1987). From test tubes to YouTube.

Argumentation does occur in the laboratory. But, as documented in numerous ethnographic studies, the *in situ* "argumentation" of lab talk is often fleeting. And it rarely exhibits a formal structure (Knorr-Cetina, 1983, 1999; Latour & Woolgar, 1979; Lynch, 1985; Traweek, 1988, pp. 126–156). Such informal discourse rarely appeals solely to the data or the evidence. Researchers may allude to the cost of adding another control, the time required to do another set of replicates, the perceived competence of a lab technician, the stature of anticipated critics, and so on. Decisions are also shaped by politics—who is the primary investigator, who is a veteran in the lab, who a trainee. These factors are not irrelevant epistemically. They do not, however, conform to the typical rationalist models typically advocated by science educators. The process is also full of false starts and dead ends. It does not follow the argument that later appears in publications. Indeed, these quick "negotiations" make applying a formal argumentation framework to experimental work problematic. Even a concerted effort will likely fail to capture the important material dimensions. Namely, a focus on argumentation tends to take evidence at face value and overlook how the evidence is produced, and whether it is epistemically trustworthy. In our view, students need to understand this epistemic dimension as part of complete NOS lessons. Namely, argumentation fails to map fully the epistemics of observation and material investigation.

3 | THE EPISTEMICS OF INDIVIDUAL COGNITION: CONCEPTS-IN-THE-MAKING

many and varied. For example, repeated associations may lead to tentative generalizations. Correlations provide clues to possible causation. Differences allow one to isolate causal factors. Similar cases invite exploration through analogy (using a partly filled or suggestive template). Of course, researchers apply the many well-known forms of reasoning: deductive, inductive, abductive, probabilistic, and error-statistical (at least). They may also use more sophisticated combinatorial strategies: such as the method of multiple working hypotheses (Laudan, 1980); natural-selection type search (Campbell, 1960; Kantorovich, 1993; Plotkin, 1993); hypothetico-deductive inference or Mill's method of difference (controlled studies; see Allchin, 2020). Through these, the mind develops simple "laws," taxonomies, schemata, formal exemplars (or paradigms), models, families of models, causal mechanisms, explanatory structures, and more comprehensive theories—all concepts of varying scope and levels of generality or abstraction. Epistemically, all these constructions must be regarded as provisional, eventually to be cross-checked against further experience and targeted observations. Some may be revised. Sometimes, multiple interpretations of the same data arise and prompt further analysis, comparison, and differentiation of the alternatives (if not sparking an outright controversy!). Even if conclusions fit with existing evidence, the concepts or theories may be actively subjected to rigorous error probes or "severe tests" (Mayo, 1996). Over time, philosophers, psychologists, historians, and others have documented an extensive repertoire of scientific reasoning methods (to use a general, if somewhat vague label) for developing conceptual interpretations.

Now, envision making that reasoning more visible and explicit through argument. Here you find succinctly expressed the educational vision (Duschl, 2000). Educators have long been interested in fostering scientific reasoning skills. For them, a formalized argumentation structure seems a welcome framework to help students reason with more self-awareness and, ultimately, with greater discipline. In this sense, the recent advocacy for argumentation is not all that revolutionary, but feeds and reorients a revered tradition. Indeed, the nurturing of scientific reasoning through student-centered inquiry and reflection is just where an educational focus on argumentation generally proves most fruitful (e.g., Ford, 2012).

At the same time, in real practice cognitive processes do not always exhibit the epistemic ideals. Mistakes enter. Fallacies abound. Biases intrude. Human cognition regularly fails to meet the exacting normative standards of "rationality" articulated by philosophers (and generally embraced by educators; Gilovich, 1991; Gilovich, Giffin, & Kahneman, 2002; Kahneman, 2011; Sutherland, 1992). Indeed, the "lapses" or "biases" seem deeply embedded in our psychological make-up—quite likely a product of our evolutionary history (Barrett, 2015). We may be suboptimal beings. Many philosophers and psychologists have thus adopted a more modest *naturalized epistemology* that acknowledges the limits and actual capacities of human cognition (Bechtel & Richardson, 1993; Callebaut, 1993; Wimsatt, 2007). The goals are more descriptive. How does science work, and work effectively, even without adhering to purely "rational" rules? The tendency of educational promoters of argumentation to remain faithful to the conventional rational models thus poses problems for a healthy, realistic understanding of NOS.

Perhaps the most widespread cognitive tendency of note is confirmation bias (Ariely, 2008, pp. 155–172; Gilovich, 1991, pp. 30–37; Kahneman, 2011, pp. 79–88; Kida, 2006, pp. 155–165; Mercier & Sperber, 2017, pp. 212–218; Nickerson, 1998, pp. 175–220; Sutherland, 1992, pp. 135–142). Namely, once particular concepts are formed and adopted, they guide later mental processing. Filters develop. One is more likely to notice similar instances and regard them as confirming examples. At the same time, one easily overlooks counterexamples. They are more likely to be viewed skeptically, or discounted entirely. Thus, first impressions—even if not fully justified—become entrenched. Subsequent research may be deficient because a test was designed to merely confirm, not to potentially disconfirm, a hypothesis (a major loophole in hypothetico-deductive reasoning). Arguments may present evidence, but the data may be (unwittingly) "cherry-picked" to accord with the original conclusion. A genuine effort at justification may become no more than an exercise in rationalization. The argument may seem well formed and logically complete, but it is not based on a fair view of all the relevant evidence. (That was the concern about Robert conceptual biases of the writer. That is, one needs information beyond what the argument itself provides, making the argument somewhat redundant, in a sense. Confirmation bias as a cognitive blind spot is a critical dimension of NOS, essential for contextualizing arguments fully. Ironically, however, it lies outside the internalist concerns of most argumentation schemata.

The effect of confirmation bias is amplified by another cognitive disposition. Basically, our minds are "lazy." We jump to conclusions. We form "hasty generalizations." We seem to minimize mental effort: why work harder than you have to? (It may thus be, ironically, an evolutionary adaptation: "the early bird gets the worm"?) Psychologist Daniel Kahneman calls it WYSIATI: "what you see is all there is" (2011, pp. 85–88).[3] Our minds seem to prefer coherence and speed, rather than completeness of argument. Dispositionally, we are satisficers, not optimizers (Nisbett & Ross, 1980; Simon, 1956, 1969; Wimsatt, 2007). Consider, for example, the case of the viceroy butterfly as an illustration of Batesian mimicry—an error which persisted for over a century (Allchin, 2015a, pp. 24–25). The original argument was first presented in 1869. The notion that a palatable species may evolve through natural selection to resemble an unpalatable species was still fresh and inspiring. Benjamin Walsh and Charles Riley noticed the resemblance of the viceroy to the monarch and after some modest field observations announced it as the first case to be discovered in North America. Later, the identification of the milkweed plant as the source of the monarch's toxins seemed to confirm the interpretation. But no one had tested the viceroy. WYSIATI (or, equally, "what you look for is all you will ever likely find"). When the obvious tests were done in the early 1990s, the viceroy proved distasteful, as well. The butterflies have evolved to resemble one another for a different reason: by sharing a "warning-signal" that helps them both. They exhibit Mullerian, not Batesian, mimicry. Despite the prevailing rhetoric (in education and elsewhere), science is not always "self-correcting" (Allchin, 2015a). Because of the WYSIATI syndrome, blind spots can develop and remain amazingly difficult to detect. Arguments sadly tend to foster a misplaced confidence that one's justification is full and complete. They hide their own deficits. Again, one needs an understanding of the cognitive dimensions of NOS (*outside* argumentation) to interpret them.

Another cognitive tendency relevant to scientific literacy is our ability to project our personal or cultural ideologies onto nature, where they appear to arise purposefully from the given world, rather than from our own psyche. The naturalizing error, as it is called, is found historically, as well as in contemporary science (Allchin, 2017, pp. 117–152; Allchin & Werth, 2017). For example, evolutionary biologist E.O. Wilson hypothesized that humans have a "natural," or innate, affinity to life—what he called biophilia—that inherently justifies conservation efforts. Wilson makes no secret of his own fascination with ants, and he promotes the preservation of wilderness, so biophilia aligns neatly with his own values. But even when he wrote an entire book on the topic, there was no strong empirical evidence to suggest that it was universal, or genetic, or adaptive in any way. Studies since have failed to confirm what was once presented as a "scientifically" validated value (Allchin, 2018). Naturalizing has been found in ideas about tool use as central to human evolution, in views of natural selection as fundamentally competitive, in the concept of race (and its presumed relationship with skin color), in the Paleo diet, and in norms of pair bonding, nuclear families and "abnormal" sexual behaviors. When such conclusions find their way into science, they seem to have strong justification for social policy, but they are ultimately manifestations of a cognitive tendency to see "purpose" in nature.

In the rational argumentation approaches, cognitive factors such as culture, gender, race, or class are supposed to be filtered out and not influence science. But historical and sociological studies over many decades now have clearly indicated that they frequently do. Science is not wholly insulated from culture. Scientists are humans and their personal values shape their cognitive filters, perceptions, and ideas, just as previous scientific experiences do. Ideally, perhaps, arguments function to distill the reasoning, so that only evidence becomes relevant. But as in the cases above, it becomes a question of "which evidence?," and for "whose idea?" Once again, normative and descriptive approaches generate an uncomfortable tension (Allchin, 2013b, pp. 107–120). Ultimately, a steadfastly internalist perspective of argumentation is ill equipped to help students appreciate why science can be biased by culture, or how to cope with it.

Given the biases of human cognition, one may want to reinvigorate efforts to objectify all scientific reasoning. Namely, try to reduce or eliminate the role of individual cognition or perspectives. Again, for educators, a focus on argument may seem like the prime tool. However, diverse individual perspectives also have a positive epistemic role. That is, sometimes "bias" can be fruitful to science. New contexts open fresh interpretations. Discoveries are often rooted in new ways of seeing. Thus, Darwin was able to make several spectacular discoveries based on a distinctive way of thinking that led, on other occasions, to spectacular error (Allchin, 2017, pp. 79–86). For example, Darwin's gradualist thinking (a legacy of Lyell) helped him interpret how coral reefs form—his first major scientific contribution. Yet it also led him to propose that the rocky shelves lining the valley of Glen Roy were the historical shorelines of a receding ocean. That proved conspicuously wrong. (They were left by receding glaciers.) Darwin's family upbringing among the British elite supported a view of a cultural ranking among humans. Darwin thus conceptualized the tribal Fuegians as intermediate between orangutans and more civilized beings. That enabled him to see human evolution was vividly possible, even for mental capacities and a moral sense. At the same time, that hierarchal view nurtured biological conceptions of race, which others later used to support racist ideology. Both insights and blind spots emerged from the same perspective. Epistemically, squelching individual ways of thinking may not be desirable. What problems arise from individual cognition seem to be effectively addressed at the social level (see Section 4).

In summary, the assumption of many educators that reasoning and argumentation neatly align is misplaced. Many cognitive processes—including confirmation bias, WYSIATI, the naturalizing error, and cultural bias—occur without conscious awareness, yet significantly shape scientific thinking and concepts—and arguments. An educational approach to scientific literacy needs to recognize and profile these processes—and how to address them epistemically. A focus on argumentation is insufficient. One may need to go beyond the abstract, apparently objectified argument to consider how the mind works in practice and how the social dimension of scientific discourse is an integral part of NOS, as addressed in the next section.

4 | THE EPISTEMICS OF THE SCIENTIFIC COMMUNITY: CHECKS AND BALANCES

Having explored new phenomena and collected data (Section 2), and interpreted them to craft new concepts (Section 3), researchers turn to their colleagues and fellow experts. The epistemic work shifts from problem-posing and problem-solving to persuading peers (Peterson & Jungck, 1988). The goal is to establish concurrence and develop an actionable consensus (Oreskes, 2014, 2019; see Figure 1). However, other scientists may disagree. They may interpret the same evidence from their own perspective, or cognitive standpoint. With different background knowledge, they may be aware of unacknowledged data. With other forms of expertise, they may discern unrecognized sources of error. Ideological or cultural biases (as described in Section 3) may be exposed. Controversies may flare. The discordance may lead to replicating experiments or to seeking further evidence that can resolve the ambiguities and uncertainties. The process of reconciling different views almost always involves a certain degree of "negotiating"—in both senses of the word: first, negotiating what conclusions are justified (and how) and, second, negotiating a pathway to more evidence and more secure knowledge about the world. We trust that the countervailing prejudices will cancel each other. Ultimately, the scientific community functions crucially at the social level through an implicit system of checks and balances (Harding, 1991; Longino, 1990; Solomon, 2001). The collective thereby vets claims and generates more robust and reliable scientific knowledge. While individuals are

(McIntrye, 2019; Oreskes, 2019; Zimring, 2019; see also in this journal Allchin, 2012d). Science is indeed tentative. But, at the same time, also importantly social. What are the *social* structures and *social* practices that guide the epistemic processes (and that contextualize argumentation) at this stage?

The process begins through communication. Investigators customarily organize a scientific paper or "report" of their results for others to review. Again, argumentation (the marshaling of evidence to support a claim) seems at the very core of this activity. But from an NOS perspective, it is essential to also understand the context and epistemic purpose of this activity. Namely, a formal argument (at the level of publication or public presentation) is a *reconstruction* to secure endorsement and to credential the claim publically (Schickore, 2008; Suppe, 1998). The argument is a selective summary of evidence whose primary aim is to justify a particular set of conclusions. An argument in this specific form is decidedly *not* "science itself" (see educators' claims documented in Section 1 above). The mismatch between product and process was famously noted by Nobelist Peter Medawar in his provocatively titled 1964 essay, "Is the Scientific Paper Fraudulent?" Numerous studies since have echoed and underscored the disparity between what scientists do and what they ultimately argue in their published papers (Knorr-Cetina, 1981; Latour & Woolgar, 1979, pp. 94–135; Lynch, 1985; Mulkay, 1985; Traweek, 1988, pp. 117–123; Myers, 1990; see also Section 2). Namely, a context of communal justification differs markedly from a context of distributed discovery in science. Generative reasoning (in search mode) differs from retrospective argument and collective validation.

Accordingly, students should learn how real scientists compose, present, and interpret formal arguments (and why). An informative benchmark is Fred Suppe's (1998) careful analysis of "the structure of a scientific paper." His fine-scale dissection of a large sample of papers shows just how scientists try to persuade their readers of a particular interpretation of the data. It is an interplay of hypotheses, corollaries, data, stated interpretations, and associated doubts (or "queries") and their corresponding "rejoinders." Notably, authors systematically consider prospective alternative interpretations (other than their own) and present their responses (echoing the epistemic theme of reducing errors). Suppe found, significantly, that the pattern of argument does not fully align with many popular philosophical models of scientific reasoning. Neither the hypothetico-deductive (HD) method, nor inference to the best explanation (IBE), nor Bayesian induction can account for all the characteristic features of scientific papers. And yet one finds educators frequently trying to "shoehorn" science into one or another of these argument styles (e.g., see Lawson, 2010, in this journal, distorting historical cases to fit an HD model; see earlier relevant critiques by Allchin, 2013a, 2004a, 2006). We observe in classroom settings, in particular, a tendency to reinforce naive empiricism and to encourage students to pattern their arguments narrowly in the style of the canonical—but now widely discredited—"Scientific Method," built on the HD model. Educators may thus need to admit a larger spectrum of argument types, and even abandon the notion of standardized argument templates or schemes, to accommodate the particularity and context-dependence of all arguments.

The impression from many educational approaches to argument is that once scientists have written their papers (or given a presentation or poster at a conference), the epistemic work of science is done. Namely, the *argument* is complete. Of course, this is hardly the case. *Other* scientists may weigh in. They may reach different conclusions from the same data. They may appeal to other relevant evidence. They may be aware of counterinstances. They may have different conceptual perspectives and find alternative paths of reasoning. By engaging with the scientific community, the process becomes *social*. *Argument* gives way to *argumentation*. Many educators do, indeed, regard argumentation as inherently social (e.g., recently in this journal: Berland & Reiser, 2011; Chen, Benus, & Hernandez, 2019; González-Howard, 2019; Grimes, McDonald, & van Kampen, 2019; McNeill, González-Howard, Katsh-Singer, & Loper, 2018; among others). However, some educators focus on the comparative peer exchange and non-persuasive elements that contribute to "sense-making" (a standard feature of constructivist learning). Others contend that students should engage in formal (structured) argumentation (paralleling the justifications of scientists). Some see students as jointly creating an argument;

discursive frameworks. All too often, it seems, *arguments* are structured in the classroom (using various models and schema), but not *the social practices of argumentation*. What are the formal structures of *discourse* or the formal principles of *fruitful*, *rational interaction*? For scientists, these epistemic processes include such features as the customary criteria for peer review in publication and for responding to reviewers; the norms for reciprocal respect or addressing criticism responsibly (e.g., Michaels, O'Connor, & Resnick, 2008); and institutional norms for rational scientific communities, as articulated by social epistemologists (e.g., Longino, 1990, and others). Ironically, the strategies for epistemically productive social discourse ("negotiation" skills) generally remain unaddressed by educators, even when they acknowledge a social dimension to argumentation.

As noted above, a key role for having a community of scientists is detecting errors. Other researchers may find methodological flaws. They may expose theoretical or prejudicial biases. They may have significant counter-arguments. Critical exchange enables an important system of checks and balances. Some educators accordingly highlight the significance of critique, of actively *listening* to others' arguments, and of revising arguments through interplay (Henderson, et al., 2015; Iordanou, 2013; Leitão, 2000). Students may eventually internalize such encounters with "oppositional voices," thereby developing dispositions for self-critique and for assembling arguments that anticipate and address prospective objections (Ford, 2012; see also Suppe, 1998). However, these practices seem infrequent and undervalued in classrooms. There seems to be little engagement with addressing objections, even when this element is included in argument schemes (such as Toulmin's). In school interviews, Gray and Kang (2012) found that the "lack of qualifiers and rebuttals in the scientific arguments constructed by the teacher portrayed the epistemic process of science as if a piece of data led straightforward[ly] to the claim" (pp. 46, 60). Educators often omit a role for counterarguments—for example, by truncating Toulmin's original scheme in the simplified argument format they provide for students. They implicitly discount the importance of dialogue and critique. Nor are students typically provided with discursive (social) tools for resolving disagreement (e.g., Fisher, Ury, & Patton, 2011). Argumentation in the classroom thus fails to reflect the important epistemic contribution of the interplay between divergent perspectives.

How, indeed, do scientists resolve their disagreements or conflicting interpretations? Well, what they do *not* do is convene at a table and simply volley arguments back and forth, like a game of tennis, until one player fails to return the ball. Moving debate forward typically involves new data, new information. Counterarguments need counterevidence. That may mean replicating an experiment with new controls, to demonstrate the role of a hidden contaminant or confounding variable. It may mean showing how correlation does not indicate causation, when other variables are considered. It may mean exploring new cases to ascertain the generalizability of a result, or to discriminate the domains of two alternative interpretations. It may mean trying to demonstrate the seemingly improbable "predictions" of a conceptual model. That is, new rhetoric alone has limited effect. Justified *positions* do not constitute justified *conclusions*. In most cases, scientists generate new evidence. They go back to the material and observational processes of the laboratory or field site and probe further (Section 2). One needs a creative experimental design, rather than just a creative turn of argument. Classrooms that highlight argumentation as composed only of "arguments" will miss how the social dimension guides discovery and new findings essential to resolving controversies. Here, the metaphor of negotiation as finding the pathway to consistency in the data is more informative than of negotiation as a process of concessions or compromises among established alternative positions.

Educators must also contend with the potent vernacular metaphors of argument and persuasion. Namely, what is the nature of the interaction or social exchange? The language of and emphasis on "persuasion" (Berland & Reiser, 2011; Jiménez-Aleixandre & Erduran, 2007) can be misleading. In popular culture, persuasion is a zero-sum game. Win or lose. It does not imply using dialogue to reconcile apparently conflicting claims. The language of argument—"defending" a position with "strong" evidence or "winning" with "powerful" reasoning—carries comperather than to seek empirical *justification* through mutual critique. Partly reasoned *positions* often substitute for more fully justified *conclusions*. Thus, even after encountering effective negative evidence, rebuttals, or counterarguments—and even among those with some basic appreciation of NOS—students rarely revise their views (Berland & Reiser, 2011, p. 212; Evagorou, Jiménez-Aleixandre, & Osborne, 2012; Faize et al., 2018, p. 478; Khishfe, 2012, pp. 87–90; Ryu & Sandoval, 2012, p. 492). Confirmation bias and rationalization (Section 3) are thereby subtly reinforced, rather than probed, engaged, and resolved. An inappropriate emphasis on argumentation or persuasion may, ironically, undermine the intended lessons about social epistemic processes.

How are conflicting arguments ultimately resolved in science? Most educational frameworks of argumentation embody an either-or, winner-take-all approach (see Allchin, 1994, for similar perspectives in the philosophy of science). They provide crisp lines for deciding among ("competing") alternatives. But the reasoning is rarely that simple or dichotomous. Just as simplistic philosophical models of confirmation versus decisive falsification proved inappropriate (Lakatos, 1978; Losee, 2005; Zimring, 2019), simple dichotomous models of argumentation also fail to reflect real practice. In science, at least, winners are rarely declared. One theory grows in support, while another wanes and is finally, almost imperceptibly, abandoned. Even so, the more typical outcome is a synthesis, in which "opposing" positions are each partially correct, or in which the "competing" claims are differentiated, each applying to discrete contexts or boundary conditions (Donovan, Laudan, & Laudan, 1988; Engelhardt & Caplan, 1987). That kind of solution requires creative interpretation of the evidence and social exchange, not combative, either-or arguments. The educational danger is that students may perceive argumentation as an ultimate goal, rather than as a proximal instrument to develop knowledge (a misconstrual that McNeill et al. [2018] calls pseudoargumentation).

Developing a well-justified consensus in science is a thoroughly social activity. But what ensures that the system of checks and balances is effective *epistemically*? What prevents it from reducing to mere politics? In dialectic approaches to argumentation (if used), there are protocols for civil (and perhaps rational) discourse. But these dialogic norms may not be sufficient for science, which has its own additional "rules." These, too, are important NOS lessons outside the arguments themselves. Sociologist Robert Merton (1973) articulated some basic norms—what he called the conditions for the growth of certified knowledge: universalism, communality, disinterestedness, and organized skepticism. More recently, these have been echoed within philosophy of science and integrated with concerns about social epistemology (Longino, 1990). For example, dissent must be addressed. Also, persons of different backgrounds and perspectives must be afforded access to the community discourse. Diversity of scientists matters (Harding, 1991). In cases of disputes, the relevant complementary perspectives (or biases, or cognitive vectors) must be balanced (Solomon, 2001). The point is that these social features of discourse are not included in the arguments proper (they are not the data, the warrants, the rebuttals, etc.). They are part of the conditions under which arguments are presented and processed socially. Such social- or institution-level principles matter, for example, in assessing whether science has achieved a robust and stable consensus (Oreskes, 2019; Solomon, 2001). They are a part of NOS, beyond the argument or apparent reasoning itself.

Another apparent "rule" (or assumption) of argumentation in science is that one should approach all arguments with a skeptical attitude and judge them exclusively on their logical and evidential merits. Thus, philosophers of science and scientists often proclaim that empirical evidence is the only legitimate arbiter of any *scientific* argument or disagreement (e.g., McIntrye, 2019; Zimring, 2019). Ironically, perhaps, scientists do not always adhere to this principle. Ideally, perhaps, scientists scrutinize each argument, each assumption, each laboratory method, and each inference. They reproduce an experiment to confirm its results. However, in practice, this is rarely done. Scientists pursue replication only when the results seem highly unlikely—or are so exciting that they seem worth repeating as a first step to building on them further. Resources, including time, are limited. Nor can one pour over every relevant paper in detail. Scientists must economize. They must have a mechanism to exercise *trust*, in ironic contrast to skepticism. But by what measure? Scientists usually rely on an indirect heuristic. That is, they rate each other's

Latour & Woolgar, 1979). While this heuristic (like all heuristics) can fail on occasions, it seems trustworthy enough to be effective. It can matter to the practice of science. In the 1960s two labs, one led by Roger Guillemin and the other by Andrew Schally, were racing to discover the structure of a hormone, thyrotropin-releasing factor (TRF). Schally decided to trust Guillemin's results, but Guillemin insisted on repeating and confirming every result announced by Schally's lab. In short, Schally's trust allowed him to made the discovery first (Latour & Woolgar, 1979, pp. 131–136). In practice, assessments of credibility matter as much as, if not more than, the careful and detailed assessments of arguments. Hence, scientists work within an elaborate economy of "credit," closely allied to epistemic assessments (Bourdieu, 1975; Hull, 1988; Latour & Woolgar, 1979). That is another reason why a focus on argumentation seems incomplete in portraying the NOS, or how science works.

5 | THE EPISTEMICS OF SCIENCE-IN-SOCIETY: EXPERTISE AND CREDIBILITY

Once the scientific community has established a stable, well-informed consensus (Section 4), it may seem that the epistemic work of science is finally done. All that remains is for the conclusions of scientific experts to be disseminated and inform public policy and personal decision making (Figure 1). Yet here, the public communication of science is essential. And such communication introduces its own epistemic challenges (Höttecke & Allchin, 2020).

All scientific claims in society are *mediated*. That leaves citizens and consumers to ascertain for themselves which claims, which arguments, which evidence, and perhaps even which scientists to trust. The problem may seem similar to the task of scientists assessing each others' reports (just discussed above). However, there is a significant difference. Citizens are not experts. They are not equipped to participate in the scientific discourse in the same way as scientists. Without the relevant expertise, they are unable to discern which methods may be suspect, which controls may be missing, what other relevant data has not been addressed, what statistical model may be misapplied, what alternative explanations may have been omitted, and so on. The potential sources of error are many. This is the conundrum of *epistemic dependence* (Hardwig, 1985, 1991). Namely, in our culture, we depend on the division of intellectual labor, with its specialized knowledge and distributed expertise. (That applies as much to doctors, lawyers, plumbers, car mechanics, electricians, and accountants, as to scientists.) Assessment of trustworthiness, rather than of the quality of the argument, becomes foremost (Goldman, 1999, 2001). Ironically, perhaps, one needs evidence of the claimant's credibility, not evidence for the claims themselves. This constitutes a tectonic epistemic shift: from *what* to trust, to *who* to trust (Collins, 1985). *Who* is credible? *Who* is an expert? *Who* is a competent and honest spokesperson for the consensus? One may implicitly trust science (Sections 2–4), but *who* speaks for science? These questions characterize the weighty epistemic challenge of science communication and of assessing any knowledge that is mediated from experts to non-experts. And, of course, it is essential for a full understanding of NOS relevant to functional scientific literacy.

The typical educational approach to the problem of ensuring that consumers are scientifically well informed (now institutionalized for the most part in policy documents and curriculum standards) is to try to empower students to be autonomous scientific agents. The goal is to teach them to exercise the distinctive (and presumably privileged) style of scientific reasoning. This view seems especially pronounced among the advocates of argumentation in science education, who mostly envision the skills they promote as addressing this very problem head on (e.g., Adúriz-Bravo, 2014, p. 1445; Berland & Reiser, 2011, p. 192; Erduran & Jiménez-Aleixandre, 2008, pp. xii–xv). That is, they tend to equate a scientific claim in public discourse as no different than a claim within an expert scientific community. The classroom work, modeling research argument, is thus often framed explicitly as preparation for assessing claims in the public sphere on SSIs. However, instruction in argument skills cannot solve content-transcendent goals; Gaon & Norris, 2001; Norris, 1995, 1997). Indeed, a false attitude of competence can lead one astray. For example, in recent years we have witnessed massive denial of scientific consensus by those who assert their "intellectual independence." They imagine that they are skilled enough to make conclusions about climate change or vaccine safety based on a single graph or study, or a handful of isolated findings. From their own perspective (shaped largely by a diet of cherry-picked data), they are being good scientists, faithful to the evidence, and skeptical of suspicious or outlandish claims. They are blind to and blithely dismiss their own epistemic shortcoming. Somewhere, they learned scientific hubris, not scientific humility and respect for expertise. Science education must consider instead how to help students understand and cope responsibly with the discomforting insecurity of epistemic dependence.

Students might first come to appreciate the nature of the problem through a very broad, or "bird's-eye," view of the creation and dissemination of knowledge in society (Höttecke & Allchin, 2020). That view would include understanding the distribution of our collective knowledge across many individual experts (including in science), as well as the system of communication, trust, and exchange whereby we share that knowledge. That might lead, most concretely, to lessons in media literacy. Yet it might also be coupled with a conceptual understanding of social systems of trust. For example, how did cooperation evolve among humans (if natural selection is so "selfish")? That involves trust in reciprocity. Evolutionary biologists can explain the conditions for instituting individual trust and maintaining it through social structures that regulate cheaters and enforce accountability (Allchin, 2009; Boehm, 2012; Heinrich & Heinrich, 2007; Nowak, 2011; Sigmund, 2010). As noted by Merton, Bourdieu, Hull, and others (see Section 4), science has developed such a system: mutual accountability, when mediated by empirical evidence engenders a specific kind of trust: *epistemic* trust (the ostensive antidote to epistemic dependence). Science works, in part, because it has a social system that rewards individuals for empirical discovery and reliable results, and motivates them accordingly. That is, there is a concrete social architecture to trust, far more important than easy catchphrases about skepticism (Allchin, 2012c; Goldman, 1999; Shapin, 1996). The deeper question here is how such a system can function more broadly to include non-scientists, especially for the special case of *epistemic* trust. To some, this discussion may seem very academic and abstruse. But it describes the challenges that students negotiate in their everyday lives. Who can they trust to repair their cell phone? Who can they trust to know the answers to the science homework? Who can they trust to know how to get tickets for a sold-out concert? As conceived by Zemplén (2009), students may inquire into these questions from their own familiar universe and, in a constructivist style, develop on their own the requisite principles of expertise and trust. Once grounded in personal experience, such lessons can be generalized to science: Who can say if cell phones cause cancer? Who can be trusted to determine if the climate is changing? What are the risks of the coronavirus and the reliable strategies for managing the pandemic? In these very real cases, the arguments function secondarily. They gain meaning *only within a social system that determines who to trust.* That is the NOS lesson which students need as context before addressing the arguments themselves.

NOS education may highlight two essential strands to scientific credibility: expertise and honesty. First, expertise. Philosophers and sociologists have recently explored the meaning of expertise and its diagnostic features (Collins & Evans, 2002, 2007; Selinger, 2011; Selinger & Crease, 2006; Zemplén & Kutrovátz, 2011; see also Allchin, 2012c). Like know-how in a lab (Section 2), expertise is a repertoire of skills or competencies, not expressed linguistically or through argument. Experience is important, but it comes in many forms, both formal and informal (Allchin, 2012c; Oreskes, 2019). It may include depth of background knowledge. One key feature (echoing the theme of error-reduction in Section 4), is one's ability to detect possible errors and recognize mistakes when they occur. Sometimes (especially in fields other than science), expertise may be validated socially or institutionally through professional certification (e.g., the bar exam for lawyers, medical boards for doctors, or registered licenses for tradespersons). Those credentials become part of the social architecture of trust. They function as indirect

A second major concern for credibility and trust is honesty. For example, conflict of interest threatens reliable science and science communication. Motivated by ideology, power or profit, many parties try to "bend" science (Markowtiz & Rosner, 2002; McGarity & Wagner, 2008; Nestle, 2018; Wagner & Steinzor, 2006). While appearing to follow epistemic rules, researchers with conflicts of interest may deliberately mislead. They may cherry-pick evidence, hiding relevant information that does not support their aims. They may stop a clinical trial early, using an unrepresentative small sample size. They may manipulate statistical categories and analyses in a way that most experts would regard as misrepresenting the patterns in the data. Consider one recent study that offered recommendations on meat diet (Johnston, et al., 2019). The authors appeared to base their assessment on associated health risks. Yet they also incorporated personal dietary preference as a factor (not directly related to health). At the same time, they did *not* consider other equally valid dietary decision factors, such as concerns about the environment or world hunger. While the authors were all university faculty and presumably experts, they were also meat-eaters (with one exception) and two of the lead authors had a history of ties to the food industry (Parker-Pope & O'Connor, 2019). Their study exhibited a conspicuous conflict of interest. Nevertheless, the recommendations were reported in the news with great fanfare as apparently important results of a "scientific" study (Kolata, 2019). Conflict of interest has plagued other recent dietary studies, for example about sugar in soft drinks and the healthiness of organic foods (Nestle, 2015; Smith-Spangler et al., 2012). Again, conflict of interest does not announce itself in an argument. You have to know something about the author and the context of the argument. A full understanding of NOS needs to make clear those contexts, and alert students to the uses of argument, and the potential for dishonest or misleading reporting that may appear as valid arguments.

In the last century or so, public science communication has benefitted from professional science journalists as mediators. Like other news media, they function as "gatekeepers" between experts and non-experts. Because they aim chiefly to preserve the reliability of scientific claims, their role in mediation—and the corresponding issues of expertise and epistemic trust—may escape the notice of many consumers. However, in exercising their editorial (or curatorial) role, they actively filter and transform information. They select news for relevance. They reconfigure jargon and technical issues for intelligibility. They adjudicate debates. They also respond to the contexts of news publication, such as the interests of advertisers and the readers' desires to be entertained and impressed by the value of the information. What "arguments" one finds are thus not the original scientific arguments. They have undergone transformation. Accordingly, several educators have already advocated for science media literacy (e.g., Jarman & McClune, 2007; Reid & Norris, 2016; Zimmerman, Bisanz, Bisanz, Klein, & Klein, 2001). Namely, media users need to understand both the virtues and practical limits of media gatekeeping. But because this process has significant epistemic import, such efforts should now be integrated into standard NOS education (Höttecke & Allchin, 2020).

6 | THE EPISTEMICS OF "SCIENCE IN THE WILD"

For the purposes of scientific literacy, the nature of "science" does not end with scientific publications or the development of a consensus among scientists (Section 4), or even with the communication of those findings to the public through the news media and elsewhere (Section 5). Scientific claims relevant to personal decision making and public discourse have a further trajectory. Recall the relevant scope of NOS: "from test tubes to YouTube," "from lab book to Facebook," "from field sites to websites" (Section 1). A good deal hinges on what scientific claims ultimately reach citizens and consumers (as well as policy makers, legislators, and judges). Claims originating from scientists must somehow win the endorsement or acceptance of non-experts (see Figure 1). At the same time, not all the purported "scientific" claims in the public sphere originate from genuine scientists. Indeed, many voices in including subterfuge and outright deceit. We live in a world of imitators and science con-artists (Allchin, 2012b, 2015b, 2018; Dean, 2017; Kenner, 2015; Michaels, 2008; Mooney, 2005; Oreskes & Conway, 2010; Rampton & Stauber, 2001; Toumey, 1997; Union of Concerned Scientists, 2019). This is science beyond the boundaries of the epistemic community of scientists. Hence, the claims can escape the accountability of the system of checks and balances (Section 4). It is also beyond responsible media gatekeepers and science journalists (Section 5). This is "science in the wild." And the epistemic challenge is to discern and sort the trustworthy scientific claims from the imposters' junk.

Conventionally (as described above), we have relied on a system of gatekeeping through science journalists and other media professionals. But gatekeeping is not perfect, and media users need to be aware of the benefits and flaws. Moreover, with the advent of the Internet and the meteoric rise of social media, the role of traditional gatekeepers seems to be waning. What does that portend? Misinformation is now on the rise. Lies spread rapidly via electronic and social media. And they travel faster, further, and more broadly than facts (Vosoughi, Roy, & Aral, 2018). Fake news abounds. Yet fake news has real consequences. Consider the man who heard about purported child sex-trafficking led by a U.S. Presidential candidate—with abductees held captive in tunnels under a neighborhood pizzeria with the light-hearted name Comet Ping Pong. "Pizzagate," they called it. Absurd and amusing on the surface, perhaps. But the reports motivated one man to pack up his rifle, drive 350 miles to rescue the children, and fire shots inside the family restaurant (Fisher, Cox, & Hermann, 2016; Lipton, 2016; Siddiqui & Svrluga, 2016). Later (a little late, perhaps?), the gunman admitted that his "intel on this wasn't 100 percent" (Goldman, 2016). Lies and fraud certainly occur within the scientific community, too (Broad & Wade, 1982; Chevassus-au-Louis, 2019; Judson, 2004). But the internal system of checks and balances tends to clear them out relatively efficiently. Not so for science in the wild. The consumer and citizen in the modern age, unaided by gatekeepers, thus has a profound challenge indeed. Once again, who is an expert, and how does one know? Which sources, which media are credible? Ironically, that matters to science, or to *what counts as science* in modern society (Allchin, 2012e).

The temptation may surely be just to say, "trust the scientists." Or "trust a *trustworthy* media source." But these are precisely the fundamental epistemic problems of credibility that the citizen-consumer cannot answer. One may have learned what demarcates science from pseudoscience in the abstract, but still be unable to discern which is which in any given instance. After all, the imposters are using every cheap trick and symbol of science they can find to appear scientific (Toumey, 1997). Students thus need to learn how to recognize science con-artists and their various wiles and stratagems (Allchin, 2012b, 2018, forthcoming). Imitators endeavor to foster confidence. They use style, disguise, social emotions, doubt, or sometimes just flooding the media to give a false appearance of the "wisdom of the crowd." These are all forms of persuasion—outside the standards of scientific argument, yet effective at convincing ordinary folk of scientific truths. Simply knowing how to construct or dissect a well-structured argument is not enough. One must understand the con-artists' "playbook" (Kenner, 2015; Union of Concerned Scientists, 2019)—an effective form of "inoculation" against deceit (Cook, Lewandowsky, & Ecker, 2017).

In addition, individual citizen-consumers need to understand their own role in science communication. They are not passive listeners or receivers. They decide which media to follow. They actively filter what they hear, see, and read. And they are just as susceptible as scientists to cognitive missteps (Section 3). They exhibit confirmation bias, the WYSIATI syndrome, and ideological filters, and succumb to faulty appeals to nature. Electronic media now amplify the problem: web-browsing history is used to filter online searches and customize news feeds, leading to "filter bubbles," an electronically amplified form of confirmation bias (Geschke, Lorenz, & Holtz, 2019). In some cases, "motivated reasoning" fueled by ideology takes over, and leads to outright dismissal of genuine scientific evidence, as in the case of climate change or evolution denial (Kahan, 2013; Kahan, Jenkins-Smith, & Braman, 2011; Kraft, Lodge, & Taber, 2015). Students need to be aware of these cognitive tendencies, particularly in the context of

Worse, perhaps, receptivity to scientific claims can be significantly shaped by social networks. Students readily appreciate the notion of peer pressure and how it can govern beliefs. Even adults tend to align their beliefs to conform to their group or to perceptions of their identity. Historically, the anti-fluoridationists shared political ideology, not just views on a single science topic (Martin, 1991; Toumey, 1997, pp. 63–80). Beliefs in creationism and even climate change can be strongly shaped by family or community views (Allchin, 2013b; Harmon, 2017; University of Kansas, 2017; Walter, Brüggemann, & Engesser, 2018). Social media merely amplify the effects, leading to echo chambers, spirals of silence, and false-consensus effects. As the use of social media grows to become a major source for science information, the importance of social dynamics in interpreting science media reports also grows (for more discussion, see Hottecke & Allchin, 2020). Again, these psychological and sociological factors contextualize and tend to peripheralize any appeal to the evidence or effort at formal argumentation. Hence, in our view, citizen-consumers vitally need to understand the place of argumentation in a Whole Science view of NOS.

7 | WHITHER ARGUMENTATION?: WHAT ARGUMENTS CAN AND CANNOT DO

As articulated in Sections 2–6, no single model of argumentation aligns with all the epistemic processes in science that are relevant to functional scientific literacy. NOS education would be incomplete if it relied wholly on such models. In particular, the commonplace views of argumentation in science education (assumptions listed in Section 1) are decidedly problematic. Is scientific argumentation rational? Ideally, perhaps. In practice, not always. Cognitive biases intrude (Section 3). At the same time, there are compensating mechanisms (Section 4). Is scientific argument empirically based? Generally, yes (Section 2). But judgments of credibility often displace direct reliance on empirical arguments, for epistemically sound reasons (Sections 4 and 5). Non-experts, especially, are epistemically dependent on experts, relying instead on their credibility to know and interpret all the relevant data (Section 5)—else error can proliferate in cultural settings (Section 6). Moreover, empiricism relies on *observations*, *measurements*, *experimental demonstrations*, and *expert skills* and *competence*, elements not fully embodied in their linguistic counterparts in argument (Sections 2 and 5). Is scientific argumentation logically structured? Does it follow universal structures that transcend context? In the informal discussions in labs, no (Section 2). In formal publications, somewhat. But the style of reasoning is highly context-dependent and the argument styles most frequently promoted as distinctly "scientific" are highly contingent on circumstances. Are published scientific arguments enduring? No. Arguments proposed by one scientist may contain errors or biases that are corrected by others (Section 4). The "tentativeness" or provisional NOS is widely acknowledged, but rarely considered at the level of individual arguments. Finally, are all scientific arguments honest? Within a scientific community, mostly (the fraud that does emerge is typically soon discredited). In the public sphere, however (where arguments are most important for SSIs and scientific literacy), deception and con-artistry currently flourish (Section 6). Indeed, expecting an honest (and rational) argument can easily lead one dramatically astray. In short, the science educators' assumptions about argumentation are not well justified and may, indeed, prove greatly misleading in a context of supporting functional scientific literacy. Ultimately, is proficiency in argumentation sufficient for intellectual independence? No. The mediation of expert knowledge means reliance on others (epistemic dependence; Section 5) and on judgments of who to trust, not what to trust (Sections 5 and 6).

The educators' assumptions (Section 1) tend to reflect the long heritage of rationalist philosophy. However, in the past half-century, studies in the history, sociology, and cognitive dimensions of science have yielded a quite different image of science in practice. The alternative views in education may perhaps best be characterized by views of NOS (Allchin, 2004b): is it how scientists actually achieve their results, or how they "should" achieve them? So, too, perhaps, for science educators' views of the role of normative versus descriptive frameworks of argumentation.

In response to the normative/descriptive tension, many philosophers have (as noted in Section 3) developed a more pragmatic, qualified, and "human" approach to normativity: a *naturalized epistemology* (e.g., Bechtel & Richardson, 1993; Callebaut, 1993; Wimsatt, 2007). At the same time (as noted in Section 4), many sociologists have moved from descriptive or critical accounts to more normative ones informed by their studies (Bourdieu, 1975; Hull, 1988; Merton, 1973). As a result, one cannot contend that only philosophers (namely, *rationalist* philosophers) defend "good" science—through promoting certain views of argument, say—while sociologists promote only relativism and antiscience, by critiquing and rejecting the traditional norms of argument. Philosophers do not align strictly with normative values. Nor do sociologists adhere only to descriptive values. Ultimately, both approaches—both normative and descriptive, philosophical, and sociological—seem important for informing students about the "nature" of science. The only major caveat is that, without appropriate contextualization or qualification, either model (normative *or* descriptive) may be easily interpreted as—and mistaken for—the other.

One might well imagine that the flaws of the historical rationalist models can be ameliorated to maintain a "preeminent role" for argumentation. Namely, one may mitigate the limitations of the rationalist's assumptions by adopting a family of models familiar to scholars in argumentation studies (Bricker & Bell, 2008; van Eemeren, et al., 2014): some informal, some dialectic, some multiagent, some rhetorical. While currently scarce in science education, such a suite of models could address a larger repertoire of epistemic practices. That is, concern for real scientific practice could open a more pluralistic and fluid approach to argument, neither formulaic nor algorithmic. However, no single model alone would suffice. One would need a set of divergent (and perhaps mildly incommensurable) approaches. One would certainly lose the one-size-fits-all approach and the virtues of conceptual economy that seem so attractive to those who advocate for the elegant "centrality" and "privileged strategy" of argumentation.

Even so, one may justifiably pause before focusing exclusively on argument as the "core" of NOS. The chief concern is that students will mistake argument for science. As noted by Manz (2015), model argument schema can be easily but inappropriately reified as the whole epistemic process. As reflected in many classroom worksheets (whether rubrics for evaluating arguments or guides for critical thinking or media literacy exercises), students are typically habituated into focusing on the argument alone. They are not invited to consider its social context or argumentative meanings. Namely, is the argument made from a position of expertise? What is the author's depth of experience? Who has funded the work? Is there a conflict of interest? Is the evidence generated through technical expertise? Are the claims peer-reviewed and fully vetted by a diverse community? Is this argument intended to reflect a scientific consensus, and what is the evidence for that? Is the writer a credible spokesperson? Instead, students are typically directed to focus on the data (as given), the warrants and the backing, and whether they are merely consistent with the claims. But a well-*formed* argument is not necessarily a well-*informed* argument. The epistemic danger, ultimately, is that the would-be scientifically literate citizen mistakes the former for the latter. As noted in Sections 2–6, there is considerably more to the reliability of scientific claims than "a good argument."

Students may thus master the art of argumentation (composing and/or critiquing arguments), without fully understanding the epistemics of science—a superficial performance that Berland and Hammer (2012) justly dubbed "pseudoargumentation" (see also McNeill, et al., 2018). An apparently "good" argument need not demonstrate depth or breadth of NOS understanding. A focus on arguments typically encourages reasoning aimed at persuasion, rather than at deciphering or interpreting data, even with respect to a theoretical benchmark. Do students reach conclusions based on the evidence (Latour's "science-in-the-making"), or do they compile the evidence on the basis of preformed judgments (rational reconstruction)? Cognitive science reminds us that our minds tend to more process of thinking through contrary evidence (Section 4). Indeed, research indicates that collaborative epistemic approaches, explicitly framed as aiming to develop a critical consensus (rather than to persuade peers), prove more effective in achieving integrative understanding (Berland & Hammer, 2012; Evagorou & Osborne, 2013; Felton, Garcia-Mila, Villarroel, & Gilabert, 2015; Ryu & Sandoval, 2012). The antidote to epistemic dependence (and epistemic hubris) is epistemic humility, respect for criticism and expertise, and an understanding of the contexts and limits of rationalist-style arguments.

Having articulated the abstract relationship between argumentation and epistemics, it may be appropriate for a few comments on possible implications for classroom instruction. First, science teachers should focus primarily on the broad range of epistemic practices ("how do we know?"), not argumentation exclusively. Although argumentation activities may help highlight certain epistemic issues, performance in such activities should not be used as a surrogate for the more foundational epistemic understanding. The theme of knowledge generation and validation should thus always prevail over adherence to any particular prescribed form or scheme of argument. Assessment of student understanding should focus on epistemics and justificatory practices, not on formal "arguments." Students should not conceptualize argument as equivalent to the construction of scientific knowledge. Second, if argumentation models are used to help scaffold epistemic concepts, teachers should engage multiple models in multiple contexts. In particular, the social dimensions and the thorough engagement with counter-evidence or counterarguments (or "oppositional voice," with subsequent documented conceptual change) are essential to avoid reinforcing the native tendencies of confirmation bias and rationalization, which are easily disguised and apparently legitimized by appeals to the standards of rational argumentation. Accordingly, educational documents and discourse should, as a matter of course, no longer use the unqualified label *argumentation*, and instead use such terms as *collaborative argumentation*, *dialectics*, *dialogic argumentation*, or *epistemic discourse* (Evagorou & Osborne, 2013). Third, in the explicit reflection that accompanies the consolidation of constructivist-styled lessons, students should identify the specific reasons and/or evidence ("arguments") that mattered, and articulate how these elements contributed to their changing or modifying their original views or preconceptions. Ideally, they will also be guided to consider how this analysis supports their ability to learn in the future. Collectively, these classroom practices will help shift the emphasis from argumentation back to heterogeneous epistemic practices.

The question may surely arise how best to construct curricula to teach these epistemic practices or to instantiate epistemic cultures in the classroom, in lieu of a privileged focus on argument or argumentation (Ford, 2012; Manz, 2015). Most approaches to "scientific practices" now focus on student-led inquiry. If so, then rather than give students prepared model arguments, teachers should invite them to delve into the nature of "proof," explore the very concepts of evidence, disagreement, and resolution. Provide them the opportunity to *construct on their own* what *they* consider to be the fundamentals of an effective justification, or "argument." (i.e., epistemic processes—including argumentation—should be problematized and taught via constructivist patterns and open-ended questions; e.g., Zemplén, 2009.) There is also substantial value in historical and contemporary cases, where students follow the footsteps of scientists in an authentic manner (Allchin, Andersen, & Nielsen, 2014; Leung, forthcoming). When such cases are (re)framed in an inquiry mode, with richly contextualized problems, students gain the opportunity participate vicariously in selected aspects of the epistemic enterprise (Allchin, 2019a). Such cases, appropriately designed or adapted, provide insight into the authentic practices of scientists, at a scale and cognitive level accessible to students (Allchin, 2012a, 2019b; Hagen, Allchin, & Singer, 1996). Such activities are akin to learning through apprenticeship. Instructors may possibly scaffold learning by offering potential models: argument structures, demonstrations of lab techniques, error checklists, or interpersonal discursive strategies. At the same time, it seems equally appropriate to approach epistemic (NOS) learning from familiar constructivist pedagogical perspectives, and to encourage explicit reflection, seeded with no more than the core thematic questions, "how do we know?" and "how can we be sure?"

engaging in evidence-based discourse. What seems problematic, however, is an undue or exclusive focus on argumentation, which tends to eclipse the wider repertoire of equally important epistemic practices in science. To become scientifically literate citizens or consumers, students need to be informed about Whole Science, "from test tubes to YouTube," "from lab books to Facebook," "from field site to website" (Allchin, 2013b). That includes the material role of instruments, resources and laboratory practices (Section 2), the cognitive processes that bias arguments (Section 3), the social contexts of scientists and their discourse (Section 4), the epistemic challenges of science communication and the mediation of expert knowledge (Section 5) and, finally, efforts to imitate (and illegitimately draw authority from) science (Section 6). In short, while NOS instruction should definitely include argument as a component of science, it should also reflect its very limited role in the larger context of epistemic practices.

ORCID

Douglas Allchin http://orcid.org/0000-0003-4038-5155

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