ISSUES AND TRENDS

Reconceptualizing nature-of-science education in the age of social media

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Abstract

Individuals are increasingly relying on social media as their primary source of scientific information. Science education needs to adapt. Nature of science (NOS) education is already widely accepted as essential to scientific literacy and to an informed public. We argue that NOS now needs to also include the NOS communication: its mediation, mechanisms, and manipulation. Namely, students need to learn about the epistemics of communicative practices, both within science (as a model) and in society. After profiling the current media landscape, we consider the implications of recent major studies on science communication for science education in the 21st century. We focus in particular on communicative patterns prominent in social media: algorithms to aggregate news, filter bubbles, echo chambers, spirals of silence, false-consensus effects, fake news, and intentional disinformation. We claim that media literacy is now essential to a complete view of the NOS, or "Whole Science." We portray that new content as an extension of viewing science as a system of specialized experts, with mutual epistemic dependence, and the social and communicative practices that establish trust and credibility.

KEYWORDS

media literacy, nature of science, science media literacy, social media

1 | INTRODUCTION—THE CHALLENGE SOCIAL MEDIA POSES TO SCIENCE COMMUNICATION

Culture is changing dramatically. And science education needs to adapt, to accommodate those changes. We focus, in particular, on the remarkable shift in communication patterns and networks that have resulted from the rapid rise of the Internet and social media. We are especially concerned about the displacement of traditional media gatekeepers who help ensure the reliability of scientific claims in public discourse. Our chief concern centers on empowering students in such a media context to be informed citizens and consumers, able to assess the reliability of scientific claims (National Research Council, 2012; OECD, 2016; Roberts, 2007; Ryder, 2001). In particular, how can the public discern scientifically justified claims amidst a rapidly growing body of false and distorted assertions, disinformation, fake news, "alternative facts," counter-narratives, science con-artistry, and other mischief—all now widely propagated through the Internet and social media? The central problem is distinctly epistemic: what knowledge claims (or sources of expertise) can be considered credible? The challenge is thus closely related to current educational approaches to the nature of science (NOS; although the emphasis on epistemics varies: Allchin, 2013b; Bell, Abd-El-Khalick, Lederman, McComas, & Matthews, 2001; Erduran & Dagher, 2014; Hodson, 2008; Höttecke, 2017a; Lederman, 2007; NGSS Lead States, 2013). At the same time, the critical new epistemic problems do not involve the familiar scientific practices found in research laboratories, but arise from the communication networks through which science and other forms or expertise are inevitably *mediated to the public and transformed*. The problem is thus simultaneously about *media literacy*, conventionally construed as external to science proper and hence not part of NOS. Our aim here is to present a broad conceptual framework that bridges and unifies these perspectives: namely, a structure to guide instruction on *science media literacy* as a significant extension of NOS in our new media environment.

First (in the next Section 2), we characterize the nature of the problem, in particular contextualizing it in the familiar traditions of scientific literacy and NOS education. Next (section 3), we present a general framework for conceptualizing science communication, as the interface between three relatively autonomous domains of discourse of communication: (a) the scientific community (scientists as experts generating, communicating, and evaluating knowledge); (b) the media (as functional mediators and, traditionally, "gatekeepers"); and (c) the general public (citizen-consumers). We then address the features of each domain of discourse, in turn, and the interfaces between them. We describe the significant epistemic processes and practices that convey and transform scientific information and that, ultimately, yield *what counts as science* in the public sphere (Sections 4–6; Allchin, 2012a). Throughout, we focus primarily on the epistemic dimension, or how scientific claims retain their integrity and reliability as they move through the long pathway from labs and field sites, through communities of expert scientists, to public discourse and especially through social media—"from test tubes to YouTube," "from lab book to Facebook." We conclude with a brief summary, reintegrating the principles, sketching a broad program of work yet to be done (Section 7) and point to the need to foster *science media literacy* as a largely underappreciated goal in contemporary science education (see also Hodson, 2011; Jarman & McClune, 2007; Reid & Norris, 2016; Zimmerman, Bisanz, Bisanz, Klein, & Klein, 2001).

2 | FROM SCIENTIFIC LITERACY TO SCIENCE MEDIA LITERACY AND NOS

Science educators are not strangers to exploring how students interpret media reports involving science (e.g. Glynn & Muth, 1994; Jarman & McClune, 2007; Korpan, Bisanz, & Bisanz, 1997; Norris, Phillips & Korpan, 2003; Phillips & Norris, 1999; Reid & Norris, 2016; Zimmerman et al., 2001). However, such concerns have generally focused on traditional mass media, such as newspapers, magazines, radio, television and film, and other institutional settings, such as museums and science centers. In today's culture, such media—and, more important,

their role as informed gatekeepers—are threatened. They are being displaced by unregulated open access through both the Internet, which bypasses experts and certified authorities, and social media, where misinformation can spread rapidly and widely through existing social networks (Vosoughi, Roy, & Aral, 2018). Scientific information received through such media can vary tremendously in quality. Journalists, lawyers, historians, and others have now documented the effect of bias, spin, and even deliberate deceit—all on a large-scale (Allchin, 2012c, 2018; Goldacre, 2010; Höttecke, 2017a; Markowitz & Rosner, 2005; Michaels, 2008; Mooney, 2005; Oreskes & Conway, 2010; McGarity & Wagner, 2008; Rampton & Stauber, 2001; Steindl, Lauerer, & Hanitzsch, 2017).

Primary (or even exclusive) reliance on social media and/or the Internet is becoming ever more common (Allensbacher Markt- und Werbeträgeranalyse, AWA, 2017; Brossard, 2013; Matsa, Silver, Shearer, & Walker, 2018; Neuberger & Quandt, 2010; Schweiger, 2017). Under such conditions, how do citizens assess the reliability of scientific claims relevant to public policy or lifestyle choices? Ultimately, being a scientifically well-informed citizen or consumer in the new age relies critically on enhanced media literacy. Without a traditional professional gatekeeper, how does the individual sort truth from falsehood or deceptive half-truth? What epistemic understanding and practical skills are needed in this emerging new context? Specifically, searching, selecting, and interpreting *scientific* claims, we contend, necessitates distinctive approaches to media literacy (see also Hodson, 2011; Jarman & McClune, 2007; Reid & Norris, 2016; Zimmerman et al., 2001).

Where do such concerns fit in science education, if at all? Perhaps media literacy is most appropriately addressed in communication or rhetoric studies, or discussions of current events in social studies classes? In our view, the core issue of public understanding of science is situated firmly in the widespread goals of scientific literacy in general and NOS education in particular. Scientific literacy itself is variously characterized, but typically viewed as a baseline understanding of "science in the service of citizens and consumers" (Toumey et al., 2010; see also Hodson, 2008, 2011; National Research Council, 2012; OECD, 2016; Rutherford & Ahlgren, 1991).[1] Citizens are to be informed, so as to participate in community discourse and active decision-making when science intersects with public policy. They are to be empowered to make informed individual consumer decisions and to protect themselves from environmental or health risks. Namely, an average person should be able to assess the reliability of scientific claims and arguments that one might encounter in everyday life (Allchin, 2011, 2013a, 2013b; Kolstø, 2001; Ryder, 2001). In our view, this applies most conspicuously to the scientific claims reported (or misreported or wholly fabricated) in the public media.

While basic science content is acknowledged as contributing to scientific literacy, the central goal is to nurture epistemic understanding and skills (viz., the core of NOS). Thus, in the past two decades, NOS has been widely adopted as a core element in most international curricular frameworks aimed explicitly at scientific literacy (Hodson, 2008, 2011; National Research Council, 2012; NGSS Lead States, 2013; OECD, 2016; Rutherford & Ahlgren, 1991). While there is ongoing debate about the particulars of NOS (e.g., *Canadian Journal of Science, Mathematics and Technology Education*, volume 17[2017], issue number 1), there is nonetheless a general consensus that students need to understand, on a general level, "scientific practices" (NGSS Lead States, 2013), knowledge acquisition (KMK, 2005), procedural, and epistemic knowledge in science (OECD, 2016) or, simply, "how science works." These are certainly central to the issue here: interpreting science in the media.

However, we see two challenges. First, in practice, the teaching of NOS in the classroom often reduces to a narrow list of descriptive tenets *about* science (Lederman, 2007; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003; see critiques by Allchin, 2011; Clough, 2007; Erduran & Dagher, 2014; Matthews, 2012). Teachers do not always aim to build competences or socially relevant skills. Recent curricular documents, at least, have shifted the focus to "scientific practices" and conceptual epistemic understanding (e.g., NGSS Lead States, 2013; OECD, 2016). Importantly, this new emphasis is not about fostering scientific inquiry skills (for *doing* science as a professional), but about developing an understanding for *analyzing and assessing* scientific claims made by scientists and others (Roberts, 2007). These NOS-based analytical skills are what is relevant for the new challenges in *science media literacy*.

Second, and more important perhaps, most current approaches to NOS focus narrowly on matters only internal to science. They disregard external factors, such as funding, public understanding of science, and the impacts of scientific knowledge on economics, ethics, environmental sustainability, politics, and other aspects of culture

(Allchin, 2004; Erduran & Dagher, 2014; Kelly, Carlsen, & Cunningham, 1993). These dimensions have already been well and generally highlighted in the heritage of Science, Technology, and Society and approaches based on socioscientific issues (SSIs; e.g., Raveendran & Chunawala, 2013; Sadler & Zeidler, 2005; Solomon, 1993; Wong, Wan, & Cheng, 2011; Zeidler, Sadler, Simmons, & Howes, 2005; Zeidler, Walker, Ackett & Simmons, 2002). These now need to be integrated into updated NOS frameworks. Beyond current NOS, we need to teach about the mediation and transformation of scientific claims as they are used (or misused) and understood (or misunderstood) by consumers in society. In short, we need to reconceptualize NOS as a more expansive nature of *science-in-society* (or NOSIS).

The expanded view of NOSIS includes, most notably for our purposes here, scientific claims in the media. Epistemic issues do not end with a scientist publishing a paper or the scientific community reaching a consensus. Conveying and establishing that knowledge in a broader public is equally important. We can no longer accept a simple model of "dissemination" or "diffusion" of scientific knowledge. Knowledge becomes actively transformed, reconfigured, and recontextualized as it travels through communication networks (Knorr-Cetina, 1981; Latour, 1987). Namely, how an individual applies and interprets scientific claims matters just as much as how the claims are generated originally (Allchin, 2012a). Most current approaches to NOS limit their focus to just how science is embedded in society in a rather general sense (e.g., as a source of funding) and how scientists justify claims in a professional context. They follow scientific claims only so far as publication in journals, peer review, and consensus, not beyond (Figure 1, white box). Nothing about their fate in a cultural setting. That is, in most existing educational NOS models, once the claim has been established by scientists, the remainder seems unproblematic. We are now keenly aware, however (as noted above), how monied interests try to "bend" science, present pseudoscience as science, portray reliable science as "junk science," or foster an image of uncertainty even where scientific experts have reached a solid consensus. Some claims have no basis in research at all, but are hearsay or deliberately designed to compete with or obfuscate genuine science. If the scientifically literate citizen-consumer is important, then the epistemic questions about how credible claims make their way from a scientific community to the individuals who use those claims are equally important. One can no longer view the transmission of information as inevitable or transparent. We need to consider the reliability of claims as they traverse a large and continuous trajectory, "from test tubes to YouTube," "from lab bench to judicial bench," "from field sites to websites," "from lab books to Facebook" (an approach aptly dubbed "Whole Science"; Allchin, 2011, 2013a, 2013b). A NOSIS approach to NOS includes *science communication* and equally, in the familiar tradition of NOS education, the *epistemics of* science communication (Figure 1, shaded box).

Acknowledging the epistemic problems of the science consumer introduces major new issues into NOS education (as we detail more fully below). Foremost, it invites a broader cultural view of the generation, transfer, and integration of expert knowledge. Most notably, all public scientific knowledge is inevitably *mediated*. Knowledge is generated in one domain of expert discourse (among professional scientists) and consumed in another (the everyday discourse of individuals in society). How do scientific claims effectively bridge the implicit gap? How do they interact with imposter claims? What is the "social architecture" that justifies trust or allows it to function effectively (Allchin, 2012b)? In addition to learning about how to interpret data or evidence, students need to learn how to address such social questions as Who is an expert? Whose testimony should be deemed credible? What happens when experts seem to disagree? In what ways does science, with its own internal social system, establish trustworthy knowledge as a community? How should someone (who is not a scientist themselves) ascertain scientific consensus?

Many of the evaluative and filtering functions have historically been performed by science journalists and the news media as professional mediators. However, with the rise of electronic and social media, such traditional "gatekeeping" is waning. Individuals are now left to distinguish reliable from unreliable science largely on their own. Good scientific information is certainly readily available if one knows where to find it and who to trust. However, the challenge is deeper than merely interpreting jargon or complex evidential reasoning, or understanding graphs or scientific reporting style (as addressed by the NGSS, e.g., NGSS Lead States, 2013). Namely, who exactly can one
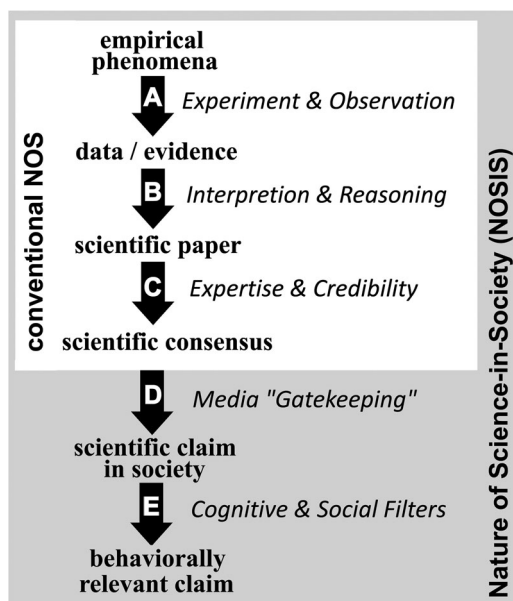
FIGURE 1 The full trajectory, or "ontogeny," of a scientific claim. Each claim passes through a series of epistemic steps, "from test tube to YouTube" or "from lab book to Facebook." Arrows indicate information flow (not any form of direct causality or necessary trajectory). Arrows may thus be best read in reverse, as mapping the origin or provenance of a claim as it is relevant to assessing the claim·s reliability, or trustworthiness. The limited domain of conventional NOS (internal science) is compared to the more expansive domain of the nature of science-in-society (including "external" factors; see text). Information is conveyed and transformed at several points, each posing specific epistemic challenges, including (A) observations, experimental measurements and the instruments that mediate them; (B) scientific, statistical and theoretical reasoning; (C) peer review, correspondence among scientists, and epistemic checks and balances, often mediated by assessments of credibility; (D) "external" publications and testimony to media professionals and public institutions (legislatures, courts, government agencies); and (E) various communication media (print and broadcast, news and entertainment, Internet, social peer-to-peer networks). The many cognitive and cultural factors that shape how individuals interpret and communicate their claims are not shown

trust as a spokesperson for science? By contrast, who might be biased by a potential conflict of interest? Why, indeed, should one care about science or evidence at all? In our view, therefore, students need to appreciate a "bird's-eye" perspective of the system of knowledge generation and its mediation, including their own role as consumers. This is the essential context for understanding the vantage point of the citizen-consumer and his or her and inescapable responsibilities. And this is the profound reorientation in conceptualizing NOS that we feel is now necessary for science educators (even those already partially oriented to the role of "science communication").

3 | A FRAMEWORK FOR INTERPRETING THE MEDIATION OF KNOWLEDGE FROM SCIENCE TO THE PUBLIC

In our view, to address current challenges of how the public becomes scientifically informed, students need more than cautionary disclaimers about evaluating sources (e.g., NGSS Lead States, 2013; University of California Museum of Paleontology, 2020). They need more than a handful of core concepts in media literacy or the now-familiar litany of diagnostic tools for analyzing sources (such basics as profiled, e.g., by the American Press Institute, 2019; Center for Media Literacy, 2018; Kellner & Share, 2005; or News Literacy Project, 2012).

It demands more than blind skepticism or mere caveats about messages on social media. Rather, students need to understand, more holistically, the epistemic structure and provenance of scientific claims that they encounter in everyday life. That includes the "ontogeny" of such claims, "from test tube to YouTube" or "from field site to website." Thus, our approach to science communication and to *science media literacy* builds on conventional NOS themes about epistemics. We seek to unify the NOS and the *nature of science in the media* in one integrated framework. Here, our purpose is to present the framework as a theoretical guide to instructors and as a structure that can help students contextualize and organize the relevant concepts.

This begins with understanding the very role of scientific knowledge and the whole research enterprise (which has its own internal social dimension). In our modern culture, we find a division of intellectual labor and specialization. Different people learn about different fields (medicine, law, auto mechanics, plumbing, financial planning, etc.). The body of collective knowledge is thus *distributed* across various domains in society (Luhmann, 1977). That *distribution of expertise* poses challenges for how knowledge is shared, or communicated, both between experts and from experts to nonexperts (Goodman, 2014; Zemplén, 2009). Science is one of the domains of expertise—crudely, knowledge of the physical world, its organization and causal structure, accessible through empirical investigation.[2] We turn to scientists (as specialized experts) to tell us, for example, about the safety of new drugs or consumer products, what causes (or might cure) a disease, how a change to the environment might affect us in the long-term, where we might find mineral ores, how to generate energy more efficiently, how to manipulate matter into new substances, and more.

That is, even idealized independent thinkers capable of basic scientific reasoning can know very little on their own. We inevitably depend on learning from others, on the evidence collected, evaluated and interpreted by others, and on the experience of experts. The concept of *epistemic dependence* (as described by philosophers) is foundational in how we build and share knowledge, including scientific knowledge (Hardwig, 1985, 1991; for implications in education, see Gaon & Norris, 2001; Norris, 1995, 1997). Because cultural knowledge is inevitably distributed across many individual knowers, knowledge has an inescapable social (interactive) dimension (Giere, 2002; Kitcher, 1990; Luhmann, 2014; Shapin, 1994). Accordingly, communication and trust are essential elements, both within science and in consuming science. What is the "social architecture" that justifies this trust or allows it to function effectively (Allchin, 2012b)?

In this paper we reduce our analysis to the scientists, the consumers of science in the public sphere (who depend on them epistemically), and the interfaces between them.[3] In recent history, the role of an interface between science and a wider public has usually involved another group of experts: the media, epitomized by professional science journalists. We visualize the system as a set of three domains of discourse and the interfaces between them (Figure 2, top row). Communication also occurs between individuals in the public sphere (Figure 2S), including via social media, the occasion for so much recent concern (see Section 6 below). While we acknowledge that science, as well as the media, cannot be strictly separated from other social subsystems, we regard the simplification as fruitful for instructional orientation.

We present this as a prospective conceptual model to (re)organize and guide NOS education. Each of the following three sections (4–6) profiles one of the discursive domains and its interfaces with others. Throughout, we consider climate change science as a timely and significant case for illustration. Finally, we apply this model to argue for an integrated educational approach to NOS that newly incorporates *science media literacy* and which encompasses a conceptual understanding of the mediation of scientific knowledge, as well as specific skills to cope with the challenges of interpreting the reliability of scientific claims in our new age of social media.

4 | HOW SCIENTISTS COMMUNICATE

To repeat, our vision for *science media literacy* is not to simply alert students to the wily stratagems of science con-artists and the purveyors of fake science news, nor to simply train students in a prescribed list of skills for
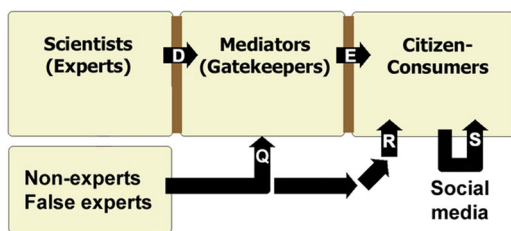
FIGURE 2 A simple conceptual structure for interpreting science communication from a "bird's-eye" view. Reliable scientific claims typically flow through three relatively independent domains of discourse (top row). Science journalists and other public media professionals function as "gatekeepers" who assess and interpret claims from experts (D), and regulate and limit unjustified claims from nonexperts and false experts (Q). Consumers and citizens face the responsibility of identifying trustworthy media (E) and managing claims from other questionable or unreliable sources (R). Citizens and consumers may further convey information through informal, peer-to-peer social networks (S). They must recognize and regulate the effect of their own cognitive biases and filters (E, R, S)

critiquing science reports in the media. Rather, we advocate fostering a deeper understanding of how scientific knowledge is created and communicated. What are the epistemic principles that govern its reliability, or trustworthiness at each stage of creation and communication? What do students need to know? We begin with the basics of traditional NOS: the generation of scientific knowledge among the scientists themselves (Nielsen, 2013; Figure 1, white box).

To begin, consider the periodic reports of the Intergovernmental Panel on Climate Change (IPCC). In many ways, they transparently reflect typical scientific practices, or how science works (the core of traditional NOS lessons). The researchers present evidence gathered through material experimentation, other causal investigations, and systematic observation: scientific knowledge is empirically based (Figure 1A). The IPCC studies also use mathematics and computational thinking, and may rely on reasoning through models (Figure 1B). The evidence is considered in light of possible sources of error and alternative explanations (Figure 1B). Revisions to earlier IPCC reports (based on deeper evidence) are noted, illustrating how scientific knowledge is historically contingent, or "tentative". These familiar NOS features are all highlighted in current models of NOS in science curricula (Allchin, 2013b; Erduran & Dagher, 2014; Hodson, 2008; Höttecke, 2017a; Lederman, 2007; NGSS Lead States, 2013; see Table 1), and we concur about their significance. They help characterize scientific knowledge as rooted in the observable, material world, its ultimate standard for evidence.

The IPCC reports also exhibit an important social dimension, usually *not* included in conventional characterizations of NOS (Allchin, 2004; Höttecke, 2017b; Zemplén, 2009). For example, IPCC scientists achieve and express an explicit *consensus* (Figure 1C). Individual scientists sometimes disagree, based on varying theoretical orientations or cognitive backgrounds. Philosophers of science accordingly highlight the role of *robustness*, or agreement across diverse perspectives (Solomon, 2001; Wimsatt, 2007). Thus, an individual climatologist giving testimony to the U.S. Congress is not necessarily a legitimate voice of science, unless that individual reports consensus views (Allchin, 2015). To be trustworthy, scientific knowledge must reflect the *epistemic checks and balances* of diverse perspectives (Harding, 1991; Longino, 1990; Solomon, 2001). Scientific knowledge is socially embodied in a *consensus* (Oreskes, 2014, 2019), although rarely formal or stated explicitly, as the IPCC does.

Equally important, the consensus must be a consensus *of experts* (Collins & Evans, 2007; Oreskes, 2014, 2019; Selinger & Crease, 2006). Science is not a democracy of casual personal opinion. The views that matter are from those who have relevant background knowledge, skills in interpreting particular results, and awareness of potential flaws in reasoning (Figure 1C). Thus, a petition or declaration denying global warming is meaningless if the long list of signers are not scientists with expertise *in climate science* (Allchin, 2015). For example, a much-publicized 2008 document supposedly endorsed by over 30,000 "scientists" ultimately included only 39 climatologists (Angliss, 2010; Grandia, 2009; Hoggan & Littlemore, 2009). Expertise matters just as much as consensus. In support

TABLE 1 Features of information flow in an epistemic account of NOS (On the "consensus list," see Lederman, 2007; on "scientific practices," see NGSS Lead States, 2013; on "Whole Science," see Allchin, 2012b)

Element of NOS	Relevance to epistemics of science communication	"Consensus List"	NGSS "Scientific Practices"	Whole science
Empiricism	Figure 1A	#1	#1,3,4	(+)
Accurate observation	Figure 1A		#1	(+)
Tentativeness		#2		(+)
Models	Figure 1B		#2,5	(+)
Errors and alternative explanations	Figure 1B	#3	#3,7	(+)
Statistical analysis	Figure 1B		#6	(+)
Expertise	Figure 1C,D			(+)
Peer review	Figure 1C	#5	#7	(+)
Communication by scientists	Figure 1D		#8	(+)
Science media	Figure 2D,E			(+)
Role of social media	Figure 2S			(+)

Abbreviation: NOS, nature of science.

of scientific literacy, then, these two sociological dimensions—*consensus* and *expertise*—should be added to pedagogical profiles of NOS.

The IPCC reports exhibit another important sociological dimension of science relevant to public understanding of science. Namely, the report is an amalgam of findings from many fields. Different researchers study atmospheric temperatures, ice core samples, wind and ocean current patterns, island topography, habitat displacement, atmospheric composition, ocean chemistry, paleobiogeography, and so forth. Climate science, like all science, is a mosaic of specialized expertise. Scientists depend on each other·s results to build on earlier work and to integrate information from various fields. Indeed, no scientist can be expert in all things. Whenever scientists perform an experiment, they have already implicitly decided to trust their coworkers, laboratory assistants, technicians, and the manufacturers of their laboratory equipment. Knowledge is *distributed* not only among scientists and their predecessors, but also among the multitude of "invisible hands" (Hentschel, 2008; Shapin, 1989). One person or one lab cannot do it all. *Epistemic dependence* is inevitable (Hardwig, 1991). Science is enabled only through managing *epistemic trust* (Goldman, 1999, 2002; Shapin, 1994). While skepticism is often touted as a hallmark of science, epistemic trust is, ironically, essential to science as a social enterprise. This is another important NOS lesson for functional scientific literacy (Allchin, 2012b; Gaon & Norris, 2001; Norris, 1995, 1997).

Epistemic trust can extend to, for example, the technical exactitude in executing experimental procedures (Figure 1A); the accuracy of observations and measurements (Figure 1A); skills in statistical analysis (Figure 1B); and insight in interpreting results (Figure 1B)—all the scientific practices in traditional NOS. The reliability of claims can vary, however, based on the level of expertise behind them. Eventually, some works survive criticism better than others; some are more fruitful in leading to further studies; some become an indispensable benchmark in theory development. Trust, therefore, is not assumed. It is earned. Over time, each researcher builds a track record of reliability not only based on formal education, but embodied in an informal reputation. This builds on the quality of their educational background, their mentors and coauthors, and home institutions: their *credentials*. All this becomes evidence for their *credibility*. In the short term, credibility is the indirect basis for extending epistemic trust (Figure 1C; Allchin, 1999, 2012b; Latour & Woolgar, 1979). So, for example, contributors to the report of the IPCC

earn their privilege, and this adds to the credibility of the research team that publishes their benchmark studies on climate change.

Because of the nature of epistemic dependence and the system of checks and balances in building consensus, the development of modern science relies in part on effective knowledge transfer. That is, there is active communication *within* science. Understanding how the system of checks and balances works within science and contributes to reliable knowledge (social epistemology) is another often overlooked aspect of NOS. It turns out to be key to understanding how scientific knowledge also extends outside the scientific community to reach non-scientists. That is why we claim, as described below, that it is essential knowledge for fuller *science media literacy*.

The system of sharing information within science may be viewed as an economy of sorts, with very specific forms of "currency" and exchange (Bourdieu, 1975; Hull, 1988; Latour & Woolgar, 1979). Of course, investigators could very well choose to keep their scientific knowledge private. They might hope to profit from it someday, or use it to their exclusive advantage to guide further research. What motivates them to share it? In this case, the scientific community offers a contingent reward. Ownership of a discovery accrues to whoever publishes it first. Credit for a new idea is determined by priority. That may translate into a patent or royalties, perhaps. But it also means stature among fellow scientists and in the institutions where they work. Through public reporting, researchers trade their private discoveries for professional credit. As a result, scientists compete, in a sense, to make important novel discoveries and make them public as soon as possible. Different scientists, of course, respond to these incentives in varying degrees. But prestige, professional standing, and historical reputation all shape the communication system.

With such potential rewards, one may also see an incentive to lie. Fraud is a potential danger in any system of exchange. Lies do occur in science occasionally (Broad & Wade, 1982; Judson, 2004). Yet liars, like cheaters elsewhere, are held accountable through sanctions. When fraud is unearthed, the individual loses credit and professional stature. Careers can be ruined. Although disincentives are no absolute guarantee, recurrence of scientific fraud by the same person is rare. Liars are labeled and their power to mislead is neutralized. Sanctions are also social and depend on closing loops of accountability within large networks of exchange (Heinrich & Heinrich, 2007; Nowak, 2011).

Scientists have additional aids in assessing the credibility of communication. One is the system of *peer review* (Figure 1C). That is, before publication, a research report is typically read by several experts in the field, who provide recommendations to an editor. Reviewers consider such things as the quality of the design of the experiment and appropriate controls, the validity of statistical analyses, the interpretation of data, and the scope of generalizations. Reviewers do not repeat the experiments themselves, but they function to generally limit professional publications to "responsible" research and commentary. An editorial process is a form of curation, or "gatekeeping" (see also Section 5 below). A second system now growing in importance is the need for investigators to publicly declare conflicts-of-interest and other potential sources of bias (most notably, their sources of funding). These two factors in credibility are important in identifying the deficits of the reports of the so-called Non-Intergovernmental Panel on Climate Change (NIPCC). The publisher is the Heartland Institute, a partisan political organization actively engaged in denying climate change and its consequences. The report lists scientists as authors, but the work is not peer-reviewed by experts in the respective fields. The ideological origin and absence of genuine peer review help expose the NIPCC report as bogus science, even without detailed analysis of the purported evidence it presents (Allchin, 2015; Nuccitelli, 2012).

The systems of peer review, conflict-of-interest statements, and epistemic credibility are all short-term filters (or heuristics). They help to reduce the propagation of errors. In the long-term, of course, scientists must rely on mutual criticism, further research, and more empirical evidence to determine if observed patterns are valid. Scientific theories may change in the long-term, yes. Still, the short-term guides are integral to establishing trustworthy communication within science (Allchin, 1999) and, as we describe below, they are valuable epistemic models for broader cultural systems of communicating science.

Ultimately, how do scientists assess what information to trust? First (briefly), they must be assured that there is no reason to suspect a lapse of epistemic integrity. Communicating information in a community with mutual accountability helps safeguard against such problems. Second, scientists assess the expertise of the person presenting the information. Their surest gauge is the researcher·s and the publisher·s credibility, established through the quality of their past performance. Finally, if their own expertise allows, they may assess on their own the new claims, and the evidence and reasoned arguments for them, especially in light of what they already know themselves. They may also consider the potential biasing effects of theoretical or personal perspectives. They may then contribute further to the expert dialogue towards building a consensus.

The image of NOS profiled above is worth contrasting with the conventional image of the scientific method. Traditional views of NOS are very much oriented to laboratory science, experimentation, tests of explanatory theories, empirical evidence and logic. While such processes are surely fundamental to science, they only function within the larger-scale institutional organization and social dynamics of science. The sociological elements are equally critical to the ultimate reliability of scientific conclusions (Oreskes, 2019; Zimring, 2019). Indeed, in practice, the sociological criteria of expertise and credibility predominate in the day-to-day assessment of scientific claims communicated among scientists. Because these dimensions are echoed in other domains of science communication (discussed next), they are essential elements in NOS curricula.

In summary, scientists epistemically depend on each other. Yet they have established practices, such as peer review and a system for gauging someone·s expertise and credibility, that allow and justify trust in each other·s knowledge claims. As a result, they can build on each other·s results and claims, critically contributing to the growth of knowledge. The system of checks and balances, enabled by distributed expertise coupled with effective communication, also provides a good reason for a nonexpert (outside of science) to regard their conclusions as trustworthy—when there is a consensus (Oreskes, 2019). Most educational approaches to NOS end here. However, another critical challenge remains for the citizen-consumer, parallel to that faced by scientists themselves: who can reliably speak for science? This leads us deeper into the problems of science communication, mediation, and gatekeeping—discussed in the next section.

5 | THE ROLE OF JOURNALISTIC MEDIA IN COMMUNICATING SCIENCE TO THE PUBLIC

Citizen-consumers receive information from science and about science from a variety of sources. That ranges from popularizing magazines (such as *Scientific American* or *Popular Science*) and television broadcasts (such as *NOVA*, *Nature*, or the Discovery Channel), films and books, through exhibits (at science centers, natural history museums, nature centers, and world fairs), to NGO policy reports, legislative hearings, and conventional daily news media. The contexts also vary, from entertainment through guiding public policy issues to informing personal decisions about medications, diet or household products. Only rarely do private individuals read science journals or talk with scientists directly. Too much to read and too many specialized terms and concepts. Nor do even well-educated individuals have the expertise to assess the quality of a research publication, its particular sources of error, or domain-specific methodologies (a competence ironically targeted in the NGSS; NGSS Lead States, 2013). Thus, as the diverse sources above illustrate, science communication is typically *mediated* (Figures 1D and 2; Kellner & Share, 2005). However, several challenges face would-be mediators (Shoemaker, Vos, & Reese, 2009).

One can imagine many approaches to science communication. For example, one may aim to disseminate information, on the one hand, or engage the public in participating in the pursuit of science, on the other; one may highlight policy issues or, alternatively, general understanding and appreciation (Secko, Amend, & Friday, 2013). We will focus on the educational goal of functional scientific literacy: providing reliable knowledge to inform personal and public decision-making (Habermas, 2014). Hence, we begin with science journalism, a professional field which

emerged in the 1930s (Weingart, 2017) and which has developed its own type of expertise and values (Rensberger, 2009).

We invite you to imagine yourself for a moment as a specialized science journalist and envision how you might achieve the stated goal responsibly and effectively. What might constitute an idealized model of science communication? Several factors seem important simultaneously (Figure 2D). First, journalists encounter an overwhelming amount of scientific information. But perhaps not all is directly relevant to the average citizen. Thus, they select. This reflects the customary editorial function of news media. Like editors of scientific journals (Section 4), they "curate" what is worthy for their readers. Here, information is strongly reduced, recombined, and framed to the character of a particular audience. Science media thus play a major role in directing attention and setting agendas for public discourse. Indeed, in terms of public debate and policy-making, the actual scientific consensus can matter less than "what counts as science" in public opinion (Allchin, 2012a; Weingart, 2015, p. 239). In some cases, the journalist serves as a "watchdog," alerting the public to hidden information or dangers, and even triggering alarms if needed (McCombs & Shaw, 1976). Further, science news media may analyze the quality of science in political debates, contributing to public opinion-making and reflection (Schweiger, 2017). Of course, journalistic power does not operate in a vacuum. Responsible journalists respond to feedback (such as letters to the editor and readership patterns) that helps shape editorial practice (Bruns, 2009). This overall function of editorial selection we may call, briefly, transformation for *relevance*.

Second, "raw" scientific publications can be complex, sophisticated, and filled with professional jargon. As mediators, science journalists help synthesize multiple studies, contextualize the information, interpret its significance, simplify it, and make it more comprehensible and hence more valuable for lay readers (Brennan, 2018). Sometimes, they use analogies and metaphors. The process may seem like mere translation, but journalists fill a creative role here, actively transforming and contextualizing the science for public use. That is, *intelligibility* is an important value-added by the role of mediation.

Third, the media serve a critical role in preserving and conveying the reliability of scientific claims. Accordingly, journalists typically rely on peer-reviewed sources. They check basic facts where possible. They vet their sources, ensuring that the information comes from knowledgeable, well-recognized experts. Science journalists typically consult multiple independent sources and acknowledged critics, to ensure that they understand consensus or the status of uncertainty and debate. This is the critical mediating function of ensuring *reliability* (notably paralleling the similar epistemic practices of peer review, credibility, and robustness by scientists, as described in Section 4).

In these three ways—relevance, intelligibility, and reliability—science journalists fulfill a distinct function formally called *gatekeeping* in 1950 (Shoemaker et al., 2009; White, 1950). These ideals of mediation are embodied as professional norms (Muñoz-Torres, 2007; Saul, Kohnen, Newman, & Pearce, 2012). But even under optimal circumstances, there are inherent trade-offs. Selectivity can risk omissions and being under informed. Streamlined accounts risk oversimplification. Detail to ensure reliability may compete with understandability. Science journalists are thus not merely transparent intermediaries between scientists and the public (Figure 2). They transform information using their specialized expertise either by preserving, removing or even adding information (Brennan, 2018).

Consider how the gatekeeping functions of science news media have shaped public understanding of climate change. First, journalists have tracked scientific interpretations of the severity of the problem and the level of certainty among scientists. In the 1960s and 70s, global warming received modest attention as a theory guiding research. But over time, as the perceived risks of climate change grew, the media profiled its relevance and helped transform the topic into an environmental issue and then into a societal crisis (Weber, 2008). They have helped persuade people about the relevance of the issue, indirectly mobilizing and informing political action.

Second, the media have been persuasive in part by making a complex and long-term problem more intelligible. For example, they transform tedious climate change reports into more concrete and meaningful stories about extreme weather events (such as hurricanes or floods; Weingart, Engels, & Pansegrau, 2000) or the fate of individual species (such as the polar bear or monarch butterfly; Weber, 2008). They have also helped convey an

appreciation of the level of risk, which is long-term, diffuse and, although large-scale, mostly invisible in everyday experience (Beck, 1986). The media help visualize the risks and articulate the meaning of unseen processes and their consequences (Cottle, 1998). For example, through the last decades, journalists (following some scientists) have used the metaphor of a tipping point (van der Hel, Hellsten, & Steen, 2018; Weingart, 2015). This metaphor basically reduces the complexity of nonlinear processes and feedback loops to a yes-or-no question of irreversible impact. The notion of a dramatic on/off switch helps convey the immediacy of finding a solution. Here, the trade-off is between a more accurate scientific portrayal of the problem and an informative understanding that can motivate and guide policy action.

Third, science news media have helped convey the reliability of a scientific consensus about climate change, even amidst a barrage of naysayers. Global warming threatens many industries. In response, one oil company, for example, extensively funded efforts to discredit the science (Mooney, 2005; Union of Concerned Scientists, 2007). Moreover, many U.S. political leaders who favor unregulated industry echoed that position, calling global warming a fraud, a hoax, a scam (Allchin, 2015). These messages have reached both journalists and the public through various media. Yet the core science news media have not carried those messages forward (Figure 2Q). For example, in 1997, one renowned scientist presented an apparent statement signed by 110 scientists (the "Leipzig Declaration") who all denied any problem. However, a journalist for the St. Petersburg Times investigated the signators, one by one. Most were not involved in climate change issues, and none were acknowledged experts. The declaration was not reliable science. Rather, it became newsworthy as an unwarranted political attempt to discount the scientific consensus (Rampton & Stauber, 2001; pp. 276–78). In this way, science journalism has fulfilled one of its most important gatekeeping functions.

Given the rise of antiscience rhetoric in public discourse (fake news, "alternative facts," and disinformation), this last gatekeeping function seems most important now for science educators. Hence, the remainder of our discussion on mediation will focus on gatekeepers as preserving and articulating the trustworthiness of scientific claims (Figure 2D vs. Q). That is, the general problem of epistemology, or grounding claims in evidence, is as fundamental to journalists as it is to scientists (Brennan, 2018; Ekstrom & Westerlund, 2019; Ettema & Glasser, 1985). Thus, the topic of media gatekeeping comfortably extends conventional NOS education.

Our comments so far have assumed an idealized model of journalists as mediators. Of course, journalists practice in a complex social context, where epistemology is not the only (nor always the utmost) concern. Understanding these realities, and the way they shape reliability in science communication, is also important to students. For example, mediation requires resources. Most media are private enterprises that must respond to the economic realities of their markets. They rely on advertising sales, which indirectly means enhancing the attention factor (Hodson, 2011). As a result, media reports tend to highlight the dramatic, personal, emotional, astonishing, novel, controversial, and locally relevant (Boykoff, 2011; Harcup & O'Neill, 2017; Luhmann, 2017; Schweiger, 2017). In this way media contribute to a "second shaping" of science (Feinstein, 2015). Yet using a framework of conflict can lead to oversimplified polarization. Emphasis on extremes can lead to loss of nuance and misleading images. The tropes of "telling a good story" can foster "myth-conceptions" that significantly erode accuracy (Allchin, 2013b, pp. 46–76). The need for media to "entertain" as well as inform can shape the content of the messages. In other cases, reporting can be self-censored if the message conflicts with the interests of advertisers, the source of essential revenue. Thus, journalistic ideals may yield to pragmatic realities.

In addition, in real practice, multiple journalistic norms may conflict. Of particular interest here is the principle of balanced reporting. Normally, news media strive to avoid partisan bias and achieve greater objectivity. They aim for "even-handedness" in debates, to respect the citizen·s autonomy in assessing the respective arguments for themselves. However, in the case of science, citizens are not experts and they do not have the background to make these judgments. This is part of the specialized expertise of scientists (Sections 3–4). Ironically, the "fair-balance" ethos has contributed to misimpressions about the role of humans in climate change. That is, as documented in two studies of newspaper and television reporting from the late 1980s to early 2000s (Boykoff, 2011), the media provided "equal time" to the two views that (a) humans are the primary cause of global warming and (b) their role is

negligible. This actively misportrayed the overwhelming scientific consensus, implying that the question was still widely debated. This was, in fact, a deliberate strategy by environmental opponents, who leveraged the media·s norm to promote the appearance of uncertainty and thereby delay political action (Dunlap & McCright, 2011; Hoggan & Littlemore, 2009; Kenner, 2015; Oreskes & Conway, 2010). The "balance-as-bias" problem has since been recognized by journalists and remedied with more accurate rendering of the consensus, as well as reporting on those very efforts to misguide the public (Brüggemann & Engesser, 2017).

Belief in scientific judgments of climate change may also depend on the subtleties of the media·s use of language, context, and other framing effects. For example, consider the simple difference in referring to "global warming" versus "climate change." The first draws attention to increasing temperatures and stresses human impact and responsibility. Thus, any local or short-term decrease in temperature can become (in the rhetoric of critics) an occasion for a joke and dismissal of the greenhouse effect. "Climate change," by contrast, refers to a broader set of phenomena (such as droughts and blizzards) and appears more neutral. Such framing effects can affect belief in climate change, as well as notions about governmental responsibility (Baumer, Polletta, Pierski, & Gay, 2017; Schuldt, Konrath, & Schwarz, 2011).

Alongside journalistic media, scientific institutions increasingly adopt the role of mediators, or interested gatekeepers. For example, science museums, planetariums, nature centers, along with many professional scientific organizations, such as the American Association for the Advancement of Science or the Union of Concerned Scientists, are establishing their own media roles with websites, podcasts, tweets, Instagram accounts, and so forth. The community of scientists is beginning, at a social level, to adopt the gatekeeping function of traditional media. The question, of course, is who is "listening" (see Section 6).

Having articulated the role and limits of gatekeeping by professional science journalists, we can now reconsider more fully the contrasting case of science communication or media *without* gatekeeping. Namely, some monied interests endeavor to reach citizens and consumers directly with their own version of "science," typically seeking to secure the cultural authority of science without having done any of the epistemic work described in Section 4 (Figure 2R). They exhibit a *conflict of interest*. As anthropologist Chris Toumey aptly describes it, they "conjure" science "from cheap symbols and ersatz images" (1996, p. 6). The recent case of regulating diesel cars and trucks in German cities underscores the potential for misinformation when there is a lapse of media gatekeeping. Nitric oxide as well as fine dust particles from diesel engines pollute the air and affect human health. In many metropolitan areas, the European Union·s official threshold value for nitric oxide was often exceeded. As a consequence, local governments in Germany concerned about public health considered banning diesel vehicles from city centers. The car industry and owners of the older diesel cars, on the one hand, clashed with bicyclists, pedestrians and residents on busy streets, on the other. In January 2019, a group of more than a hundred German pneumologists published a letter questioning the scientific foundation of the current threshold value. Several public media took notice. The issue dominated news coverage and talk shows for weeks. The debate was driven by the questions, "Who should count as a scientific expert on this issue?" and "Who should be allowed to determine safe standards for air pollutants?" Ultimately, investigative journalists checked the expertise of the critics (e.g., Kreutzfeld, 2019; Schnabel, 2019). They found that while the pneumologists were established experts in their own fields, they were not experts in epidemiology, nor had they published any peer-reviewed papers about nitric oxide. Even the calculations to support their assumptions were faulty. Two of the core organizers were found to have links to the auto industry. Ultimately, citizen-consumers depend on gatekeepers able to assess the expertise and credibility behind scientific claims (Figure 2D vs. Q,E vs. R).

False scientific advocates and inappropriate experts (like the pneumologists in Germany) are found in discourses about climate change, as well. For example, in the wake of the discredited Leipzig Declaration (noted above), there have been several similar efforts to present "petitions" endorsed by long lists of self-professed experts. Sadly, the "merchants of doubt" (aptly named by Oreskes & Conway, 2010) have been more influential than many climate scientists in shaping public opinion (Cooper, 2011). Thus, climate change is the most commonly

cited topic among Americans when asked to provide an example of disagreement among scientific experts (Funk, Gottfried, & Mitchell, 2017), despite overwhelming scientific consensus (Oreskes, 2004).

One may also consider how the gatekeeping role is shaped by the form of communication technology. For example, the traditional role of science journalists emerged largely to fit the editorial practices and readership of daily newspapers. Yet as technologies change, one might expect the role of gatekeeping to change as well (Bruns, 2018). Here, we consider briefly a few historical cases, to contextualize and help inform (by comparison) how students might view the particular challenges now framed by the Internet and social media (see also Harsin, 2018; Iyengar & Massey, 2018; Martinez, 2018). For instance, the introduction of radio and later television substantially altered the landscape of mass media. Yet broadcast media were largely able to adapt the journalistic practices and patterns of print media. With the introduction of cable television, however, the number of available channels increased dramatically. That opened the way for news services that did not adopt the public responsibilities of gatekeeping (Figure 2R). Partisan television news shows now host pundits who have no scientific credentials but willingly report falsehoods as though they should be trusted experts (Kenner, 2015). One may also consider the rise of electronic word and image processing, which made "glossy" publication possible without the resources and professional editorial practices of large publishers. For example, one partisan group, the Heartland Institute, has been able to produce bogus scientific reports closely mimicking the style of the IPCC reports that they hope to undermine. These were sent to all science teachers in the U.S., encouraging them to "teach the controversy" (Mann & Schmidt, 2008; National Center for Science Education, 2013; Nuccitelli, 2012). In a similar way, the advent of the Internet has provided an affordable "broadcast" platform for almost anyone, leading now to a flood of antiscience websites that often hide their sources of funding and conflicts of interest (Allchin, 2015).[4] In general, electronic media make it easier to project a false image of a professional and trustworthy gatekeeper. At the same time, the glut of information sources heightens competition for consumer "attention," thereby increasing the bias towards entertainment over informativeness (Harsin, 2018). Another dimension of electronic media is their speed. Faster media shorten the news cycle and challenge the tortoise-like pace of fact-checking and accountability (Ortutay, 2017). These historical examples might provide a context for interpreting how social media present their own set of challenges to the role and form of gatekeeping.

In the past few decades, therefore, it has become increasingly easy for nonexperts to stake a public presence, pretend expertise, and project "truthiness." Science con-artists flourish (Allchin, 2012c; Weeks, 2014). The case of climate change shows vividly how partisan and commercial interests can effectively reach citizens outside the current system of gatekeeping. But just as fraud is regulated within science (Section 4), there are possible ways to disarm the science con-artists. Students need to appreciate that the gatekeeping function of the media is essential wherever self-professed experts or partisan or commercial interests seek to distort science or undermine its authority in the public sphere (Figure 2). An informed citizen thus needs to understand how science is portrayed, presented, transformed or even misused, and how gatekeeping works.

While communication technologies continue to evolve, trust in the traditional news media is eroding in many countries. An international survey indicates that fewer than half the people (44%) now regard the mass news media as reliable (Newman, Fletcher, Kalogeropoulos, Levy, & Nielsen, 2018). The situation varies strongly from countries with generally high trust (Finland, 62%) to low trust (South Korea, 25%). This, too, may have a political basis. In strongly polarized countries like the United States, trust in media varies with political affiliation: 49% for liberals, but only 17% for conservatives. While Republicans and Democrats are equally likely to follow science news, Republicans are less likely to be convinced that media cover science accurately (Funk et al., 2017). Not surprisingly, perhaps, many political critics of the news media seem to criticize science, too. Open information, it seems, can threaten power, profit, and privilege (Harrison, 2018; McIntyre, 2018).

In addition, patterns of media use are shifting, largely in response to the opportunities afforded by the new technologies. For example, adolescents are rapidly shifting to the new internet-based media as their primary source of information. According to a German study, almost all 12–19 years old have Internet access (Medienpädagogischer Forschungsverbund Südwest, 2017). Smartphones are the most important device for going online and are used by 92% of the 12–13 years olds and 99% of 18–19 years old. Social media platforms are the most popular (see also Section 6).

When asked where they search for information, 85% of adolescents indicate that they use Google, 2/3 use YouTube, and about half use Wikipedia. A quarter of them receive news and up-to-date information via social media or online newspapers. Only a fifth use online news magazines. One-quarter of adolescents and young adults (14–29 years) relied on the Internet as their primary source for news, notably more than for people over 30. Overall, the importance of the Internet for attaining information is increasing for German adolescents, but it is not yet significant compared to television (Allensbacher Markt- und Werbeträgeranalyse, AWA, 2017). By contrast, across eight Western European countries, adults aged 18–29 are about twice as likely to get news online than from TV (Matsa et al., 2018). While the competencies of grade-level eight students in using computers and dealing with information vary strongly across countries, students rarely exhibit the highest level of competence, indicating that they cannot securely evaluate and organize the requisite information independently (Eickelmann, Bos, Gerick, & Labusch, 2019). The role of internet-based media is growing significantly, raising important questions about the future of quality science communication. Accordingly, students have much to learn how to deal with media information.

Overall, journalistic media—the traditional gatekeepers—seem, in general, to be in significant decline. People now rely less on journalistic media as distribution channels (Neuberger & Quandt, 2010; Schweiger, 2017, p. 16). Economically, specialized reportage and large-scale investigative journalism receive less funding. The result is increasing opportunity for well-funded political groups, commercial interests, provocateurs, and others to gain influence, aided by advertisers and public relations agencies (Steindl et al., 2017). At the same time (as discussed more fully below), a new generation is acclimating to relying on emerging social media and personal networks for all types of information. The media landscape is changing, with an uncertain future for gatekeepers. Thus, it is also important to understand the role of consumers in shaping the interface between themselves and various media (both with and without gatekeeping), as we discuss in the next section.

6 | THE CITIZEN-CONSUMER'S ROLE IN SCIENCE COMMUNICATION

As noted in the section above, media gatekeepers significantly shape science communication, its content, reliability, and intelligibility. Here, we describe the role of the citizen-consumer as it might appear in prospective NOS curricula. That is, individual end-users also mediate the scientific information and claims to which they are exposed as they interface with mass media (Figures 1E and 2E). For example, they choose their own sources of information (TV/radio news stations, newspapers or news magazines, news feeds, blogs, friends, coworkers, advertisements, etc.). They make their own personal judgments about whether to "receive" that information as relevant and regard it as trustworthy. Sometimes, the mediation is conscious, deliberate, and well informed; other times, not. Here, consumers are vulnerable to deception by science con-artists, akin to fraud within science itself (Allchin, 2012c). Awareness of one·s own role as an agent and the forms of personal cognition one brings to the process is another aspect of *science media literacy*. Psychological processes significantly shape how one consumes scientific information.

Conscious choices are easily managed, perhaps. Conventional media literacy lessons certainly underscore the importance of attending to the credibility of sources. How does one sort trustworthy sources from biased or bogus sources (even if one is not considering the more abstract concepts of domains of discourse and gatekeeping)? For example, science teachers already generally try to caution students about the dangers of pseudoscience found in advertisements, entertainment and promotional media (Figure 2R). At first, that may seem to be all that matters.

However, subconscious processes are also relevant to filtering. Personal filtering will occur both for information from nonexperts as well as from gatekeeping sources (Figure 2E,R). Most notably, our minds tend to exhibit *confirmation bias* (Gilovich, 1991, pp. 30–37; Kahneman, 2011, pp. 79–88; Kida, 2006; Mercier & Sperber, 2017, pp. 211–218; Nickerson, 1998; Sutherland, 1992, pp. 135–142). That is concepts or interpretations that are encountered first tend to guide later thinking. Personal cognitive filters develop. Thus, similar instances tend to stand out. They help confirm initial impressions (even if those first impressions are unrepresentative and

misleading). At the same time, one is less likely to notice or give credence to counterexamples. In some cases, apparent counterinstances may even be reconfigured to appear as fitting pre-existing schemata. Standards of evidence are lowered for confirming examples and raised for disconfirming examples. Thus, the important potential of valid evidence to correct faulty impressions is ironically diminished. Selective exposure and mental filtering make it more difficult to assess one·s original beliefs or knowledge objectively, or to change them if they are not fully justified. All of this can occur subliminally, without conscious intent. Confirmation bias also increases susceptibility to "agreeable" fake news from nonexpert, nongated sources (Figure 2R; Braucher, 2016). Scientists, too, may exhibit confirmation bias. However, its influence is kept in check by the interaction of contrasting theoretical perspectives (Section 4). By contrast, in the public sphere, in the absence of mutual accountability or negotiation, the bias can fester.

Confirmation bias now has an electronic dimension, as well, which amplifies the problem (Geschke, Lorenz, & Holtz, 2019). Internet search engines can tap into an individual·s browsing history to yield "user-relevant" results. News aggregators, such as Google News or Yahoo News, also use personal data to select items from disparate online sources. With the shift in news-gathering habits (noted above), unfiltered browsing is declining. Now, the news is becoming tailored to the user·s past behavior and preferences, limiting exposure to new issues, fresh ideas, and critical perspectives. The selective filtering distorts overall information in a way parallel to confirmation bias, increasingly trapping people in what have become known as *filter bubbles* (Schulz & Roessler, 2012; Schweiger, 2017). Recently, YouTube·s similar practice of recommending related videos has been implicated in the resurgence of flat-Earth beliefs (Bowler, 2019). While traditional media present a variety of information, news aggregators and algorithm-driven search engines ironically hide any operative selectivity.

Worse, on some occasions emotions, ideological commitments or self-identities can further amplify the effects of confirmation bias, a phenomenon known as *motivated reasoning* (Gilovich, 1991, pp. 75–87; Kahan, 2013; Kunda, 1990). In such cases, personal desires or beliefs drive inference more powerfully, subverting acknowledged rational norms. For example, partisan beliefs can lead to the rejection of science (Iyengar & Massey, 2018; Kraft, Lodge, & Taber, 2015). Scientific evidence may not be merely differentially accumulated; it may be actively "cherry-picked." When one encounters counterexamples, they may be discounted entirely. More sadly, the credibility of the source of the information may itself be challenged—not based on the customary criteria, but merely on whether the information accords with one·s prior convictions. That is, expertise is not evaluated on the basis of credentials, but on whether one already agrees with the very claims at issue. Customary accountability is weakened, providing opportunities for science con-artists, who knowingly exploit these vulnerabilities in promoting fraudulent claims (Allchin, 2012c; Kenner, 2015). Nor does exposing news as fake always remedy misperceptions. Ironically, when fact-checkers refute them, false claims receive even more attention and can, paradoxically, reinforce the original misimpressions, what is known as a *boomerang effect* (Wormer, 2017).

Thus, students need to learn that the end-users of science communication (citizen-consumers) cannot be regarded as passive receivers, any more than mediators can be regarded as transparent translators. They can play an active role in managing information flow (Figure 1E). This is one reason why we advocate an expanded concept of NOS (Whole Science) that includes science communication and an abstract bird·s-eye-view approach to the domains of discourse: to encourage a more complete, holistic, or systems-level perspective.

Another important dimension in the consumption of science is sociological. How do consumers of science communicate *with each other*? (Figure 2S). That is, how do private peer-to-peer networks link people and form the channels along which information is shared, completely apart from the realm of experts or gatekeeping media? For example, the groups that opposed the fluoridation of public water supplies in the 1950s and 60s tended to share political ideologies and were strongly cohesive socially (Martin, 1991). The same is true today for flat-Earthers and the groups that oppose vaccines or that reject evolution (Allchin, 2013a; Sprenger, Bullock, Healey, Silverstone, & Lamborn, 2019).

Social networks can shape more than the mere availability of information. Groups also foster conformity, whether rooted in ideology or self-identity. For example, user comments on social media strongly indicate what opinions count as a legitimate in that group (Schweiger, 2017). Information flow is thus further filtered, for better or worse. To minimize personal discord and promote social acceptance, people tend to align their ideas and values with their chosen peers (Festinger, 1957; Kahan, 2013, 2017). This effect is now quite well documented in the case of climate change skepticism and denial (Harmon, 2017; Hart & Nisbet, 2012; Lewandowsky, Oberauer, & Gignac, 2013; Santos & Feygina, 2017; University of Kansas, 2017; Walter, Brüggemann, & Engesser, 2018). Science communication through social networks (separate from mass media) can spread disinformation as well as reliable information. Again, gatekeepers that might otherwise provide checks against unreliable information (as they do in scientific communities) are absent. Indeed, social networks may sometimes trump science. The evidence fails to be a basis for rejecting erroneous ideas. Ideologies may become entrenched—ironically, under the mistaken impression that one is heeding the evidence and reasoning soundly.

Having established these sociological factors as context, we may now (finally!) address the advent of social media and their role in science communication. By social media, we refer to Facebook, YouTube, Instagram, Twitter, Snapchat, WhatsApp, Internet chat rooms, blog subscriptions, e-mail listservs, texting, unmoderated user-comment sections on websites, and others. We do not define social media by the type of technology, but rather sociologically, by the structure of the communication networks (see Beck, 2010, p. 29; Treem, Dailey, Pierce, & Biffl, 2016). That is, these media are primarily designed to enhance personal interaction through peer-to-peer contact (with no centralized authority or voice). They tend to emphasize sociality, sharing, engagement, and participation in largely transparent social networks. As such, social media contrast with *broadcast media*, which yield largely centralized, *one-to-many* networks, with editors choosing the content. Social media support instead of *many-to-many* communication networks, often with ample opportunity for *user-generated content*. Accordingly, social media tend to foster an ethos of democratization, while eschewing censorship or any kind of privileged authority. Social media, as typically conceived and used, are inherently antithetical to the gatekeeping notion of filters, or even expertise. In terms of scientific literacy and education, then, we are concerned with how science communication via social media bypasses professional gatekeepers (Figure 2S; Sections 5–6). Social media seem to exacerbate the lack of confidence in scientific expertise (Weingart, 2017) and contribute to a more general crisis of expertise in society (Nichols, 2017).

Given the network patterns, social media raise additional concerns. By collapsing time and distance, the new technologies help accelerate and amplify communication, both of information and disinformation. As a result, false news travels faster, farther, and more broadly on Twitter than true accounts (Vosoughi et al., 2018). Lies are more likely to be retweeted because they appear novel and make a "good story." In addition, because social networks reward "shareability," entertainment-value tends to dominate over informativeness, when compared to traditional broadcast news media (Harcup & O·Neill, 2017). The criterion is not evidence, but what contributes to the sender·s social capital, or apparent social status as a font of valuable information (Gilovich, 1991, pp. 90–101; Steinfield, Ellison, Lampe, & Vitak, 2012). Fake news and social media constitute a toxic combination that undermines reliable science communication.

When added to psychological filters, social media communication tends to consolidate and strengthen networks and limit information. Echo chambers become more isolated (Geschke et al., 2019). People tend to share ideas predominantly with like-minded individuals. Controversial discussions, by contrast, are less common, and less well-informed opinions develop (Schweiger, 2017). While the Internet now provides unprecedented access to a diversity of information and perspectives, the effect of social media can be quite the opposite: reinforcing existing beliefs and peripheralizing dissent. As a result, social networks (using such media platforms as Facebook or WhatsApp) foster so-called *echo chambers*, where false scientific ideas are more likely to be re-endorsed than questioned or challenged. For example, research indicates that a familiar social context can lower epistemic vigilance and the disposition to check facts (Jun, Meng, & Venkataramani, 2017). In a similar way, peer pressure actively suppresses the willingness to voice ideas and opinions against a mainstream view in a particular social

network: a self-amplifying effect called a *spiral of silence* (Hampton, Rainie, Dwyer, Shin & Purcell, 2014; Schweiger, 2017; Walter et al., 2018). At the same time, limited exposure to "alternative" perspectives leads to a perception that the group·s agreement is not artificially limited to a particular subset of the population (participants in the network), but rather seems to reflect the "wisdom of the crowd": called the *false-consensus effect*. Communication becomes further compartmentalized with the effect that isolated sub-communities tend to regard their own version of reality (in general) and of science (in particular) as fully justified. Social media tend to aggravate all the unproductive epistemic tendencies that effective gatekeeping can normally keep in check.

Social networks and uncritical sharing of information also increases the potential for a few voices to dominate the discourse and have a disproportionate effect. For example, while numerous blogs express skepticism about climate change, a recent analysis identified only three as the origin of most opinions (Sharman, 2014). A few key players can have an outsized effect in trying to de-legitimize scientific expertise. Comments on YouTube videos about climate change (arguing either for or against the scientific consensus) reveal a similar pattern: a few key players have a disproportionate public presence (Shapiro & Park, 2018).

In summary, examining science communication from the vantage point of the citizen-consumer highlights how the effectiveness of the gatekeeping role of science journalism is highly contingent on the behavior of the end-user and on how social media is used. Someone in search of reliable information to inform personal and public decision-making is in a precarious position and faces many challenges. In our view, science education needs to articulate these epistemic challenges to students, and contextualize them in a comprehensive NOS understanding of the combined system of science and science communication (4–6). Perhaps traditional science journalism is dying or taking up new roles (Bruns, 2018). Perhaps alternatives to those gatekeepers are being developed. Regardless, the way forward should be informed, if we are to meet the acknowledged aims of scientific literacy, by including science media literacy as an integral part of NOS in science education.

7 | RESTRUCTURING NOS TO INCLUDE SCIENCE MEDIA LITERACY

We began our presentation with the observation that science communication to the public is inevitably mediated. As a consequence, an understanding of NOS should not be independent of an understanding of how scientific information is generally mediated. This leads us to the overall objective of *science media literacy* envisioned as a component of NOS. We focus specifically on the relevance and credibility of scientific claims, as they contribute directly to functional scientific literacy for citizen-consumers. Similar to the notion of *science media education* (Reid & Norris, 2016), the notion of *science media literacy* indicates the necessity to understand science as a publicly mediated endeavor characterized by epistemic dependence and trust among scientists as well as systems of checks and balances. *Science media literacy* stresses the role of constraints that news media generally face and is concerned with a bird·s-eye view of both science and the mediation of science to the public. Science and its mediation are each regarded as communicative practices. A science media-literate person, therefore, has developed a deep under-standing about the significance of media (including those with and without gatekeeping, or curation) and how they contribute in the public sphere to the construction and shaping of scientific knowledge. Science media-literate citizens are well aware of the fact that they might often be trapped in filter bubbles or spirals of silence and might be victims of echo chambers or false-consensus effects. They are keenly aware that filter bubbles can feed their own psychological needs and expectations (confirmation bias, motivated reasoning) and regulate their behavior accordingly.

Based on our analysis, a set of core concepts of *science media literacy* seem essential for students to learn to become scientifically literate by also becoming media literate (introduced in the sections above and summarized in Table 2). These concepts bridge the three major domains of discourse we have described: science, the media, and the citizen-consumer including social media.

First, while we regard the cultural challenges of social media as acute and immediate, our approach is not to provide students with a "quick fix," such as unarticulated cautionary admonishments or a simple checklist for evaluating their sources of information. Rather, we see the need to contextualize the current situation in a fuller understanding of the epistemic problems of expertise and communication—the same issues that form the core of current NOS lessons. Thus, we advocate beginning with a "bird·s-eye" view of the roles of specialized knowledge and epistemic dependence in our society (Section 3). Namely, how does the distributed nature of knowledge pose problems for establishing a social system that warrants epistemic trust? Next, students should learn about science itself and the mechanisms for creating and communicating knowledge among scientists (Section 4). Here, we underscore the need to expand conventional curricular conceptions of NOS to include its social (interactive) dimension, including the topics of expertise, credentials, trust, credibility, peer review, and consensus. Third, students need to recognize the epistemic challenges of public science communication and the role of mediators, as illustrated by science journalism (Section 5). Among other things, they should appreciate the irony that in our apparently triumphant Age of Information, with all its remarkable technologies, there is also great potential for misinformation and conflict of interest in communication. That is, there is an indispensable role for professional gatekeepers, curators or editors. Fourth, students should become aware of the factors in human cognition that affect their own abilities to consume, use and share scientific information objectively (Section 6). This includes, of course, seeing clearly the potential pitfalls and dangers of social media, such as echo chambers and false-consensus effects, and how the psychological dynamics of social networks can shape beliefs and knowledge. This is a "Whole Science" perspective of scientific claims, spanning from test tubes to YouTube, from the lab bench to the judicial bench. Despite their various contexts, all these concepts are unified by a common theme, central to NOS: developing and assessing the reliability of scientific claims—or epistemics. That places them firmly amid the widely accepted values of both scientific literacy and the conventional theme of NOS education.

TABLE 2 NOS concepts that involve the integral role of communication in science and science media

Structure of knowledge and domains of discourse
Distributed knowledge
Epistemic dependence
Epistemic trust
Expertise
Credibility
Credentials
Peer review
Robustness
Consensus
Public communication of science
Mediation
Media gatekeeping
Conflict of interest
Engaging in a discourse of communication
Confirmation bias
Motivated reasoning
Echo chamber/spiral of silence
Filter bubble
False-consensus effect

Abbreviation: NOS, nature of science.

We are certainly not alone in concern about the problems posed by social media or the need to apply media literacy to science. Our primary contribution here (as we see it) is providing a broadly considered theoretical framework to guide curriculum and organize lessons, informed by historical, philosophical, sociological, and cognitive perspectives. We thus emphasize the core concepts (Table 2) and their organizational structure (Figure 1–2). At the same time, we openly acknowledge further needs towards realizing a vision of science media literacy as an extension of current NOS education. At the policy level, fortunately, we see internationally shared views about scientific literacy (noted above in Section 2) as already inherently justifying such an approach. Opportunities are open for further educational research, already well mapped by Reid and Norris (2016). Teacher education and professional development will need to adapt, of course—largely by featuring the principles noted above as additional relevant topics.

In the classroom, we hope to see innovative inquiry-based activities that contextualize problems and questions that motivate fruitful reflection on epistemic dependence, trust, expertise, credibility, credentialing, gatekeeping/curation, and accountability in communication (see e.g., Jarman & McClune, 2007; Union of Concerned Scientists, 2019; Zemplén, 2009). And we do express our hope for NOS lessons that pose engaging, authentic problems and open discussion rather than merely itemize, describe, or illustrate target concepts.

In a parallel companion paper, we elucidate some of our own prospective activities. Here, we merely mention a few: (a) a credibility guessing game, based on strange creatures reported in the 16th century (some real, some not), as well as modern images of "fantastic beasts," some real, some imagined; (b) science-based adaptations of the game shows "To Tell the Truth" and "Bluff the Listener," playfully helping students learn the various strategies of deceit; (c) a science news editor role play; (d) historical cases exploring the situated perspective of social groups that embraced erroneous scientific claims, such as phrenology, mesmerism, antifluoridationism, and a flat Earth; (e) web searches from different computers (with separate browsing histories) to discover and explore the phenomenon of filter bubbles; as well as (f) plain cases of error in science—to understand where science did not work and why (Allchin, 2012d). By engaging students in playful and authentic activities that involve epistemic problems posed by the media, we hope that they will develop skills that will help them negotiate the challenges of social media, the Internet and other technologies that are radically transforming public communication of science.

ENDNOTES

[1] One may note the distinction between scientific literacy (for citizenship) and science literacy (for professional science; Roberts, 2007).

[2] We find a very vague notion acceptable, here. We wish to avoid contention about demarcation or "science as a way of knowing."

[3] Here, we leave aside other important forms of interactions between citizens and the scientific community, such as citizen science (nonscientists participating in or contributing to research; Citizen Science Alliance, 2019; Citizen Science Association, 2019) and new efforts to "democratize" science through citizen participation in granting and funding panels (Epstein, 1995; Kitcher, 2011). Namely, our primary concern (here) is the epistemic status of scientific claims as they move from the domain of professional experts to the domain of public discourse where they shape public policy, consumer behavior, or personal decision-making.

[4] For example: ClimateChangeDispatch.com, IloveCO2.com, GlobalWarmingHoax.com, GlobalClimateScam.com, NIPCCreport.org.

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