Contemporary Trends and Issues in Science Education 49

Vaughan Prain
Brian Hand *Editors*

Theorizing the Future of Science Education Research

Springer

Contemporary Trends and Issues in Science Education

Volume 49

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ISSN 1878-0482 ISSN 1878-0784 (electronic)
Contemporary Trends and Issues in Science Education
ISBN 978-3-030-24012-7 ISBN 978-3-030-24013-4 (eBook)
https://doi.org/10.1007/978-3-030-24013-4

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Part III Review

Chapter 1
Introduction: Theorizing Future Research for the Science Classroom

Vaughan Prain and Brian Hand

1.1 Interpreting Complexities

Why compile a book on how possible futures in science education research can or should be theorized? After so much intensive research over decades into what, how, and why students learn (or fail to learn) in school science, what remains to be speculated upon, investigated, tested, understood, and justified? We think there are many reasons why such a book is timely. They all relate to the current state of play around multiple theoretical accounts of how this learning is explained and promoted. These accounts draw variously on cognitivist, sociocultural, socio-semiotic, neuroscientific, cultural materialist, and pragmatist theories to justify reputed high-gains approaches to science learning. As noted by Tainter (2006), human efforts at problem-solving (in this case, enhancing science education) tend to generate increasingly complex explanations and solutions in the face of the partial success of past approaches.

The theoretical landscape in science education is now congested. Diverse, complex, multidimensional, and, at times, conflicting prescriptions are made about the how and why of science learning. It is timely then both to revisit these theoretical claims, to consider the possibilities of synergies between them, and, where appropriate, to extend or set new agendas arising from these theories. New agendas may also require fresh research methods. Given the modest success rates of many attempts to reform and improve science learning in recent decades, it is timely to consider the extent to which activity in this field (and its theoretical warrants) needs

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*,
Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_1

incremental change, fine-tuning, elaboration, reinvention, or a marked recalibration of theories of practice.

In addressing these questions, we invited both high-profile and emerging researchers to offer speculative insights into how effective future school science education should be theorized. While varying in proposed strategies and theories drawn upon, our contributors broadly agreed on several key issues. There is consensus that if theories are to be useful, they must address both epistemological and engagement issues in science learning. They should explain what and how students come to know in science as well as the conditions that enable them to invest in and value this learning. Contributors stress the importance of both (a) the roles and tasks offered to students and (b) the cognitive, symbolic and material tools and resources students need to use to learn and value science. There is also the ongoing question of what teacher perspectives and practices optimize student uptake of these experiences and resources.

Another recurrent theme, in the face of theory proliferation, is the call by several contributors for more dialogue across competing and divergent theoretical perspectives. As is so often noted over the last 20 years, traditional (and more recent embodied) cognitivist perspectives do not always align easily with sociocultural accounts of contextual cultural factors influencing student learning. Researchers within a cognitivist orientation have tended to focus on the key role of mental processes in individual learners, where studies have researched how to optimize student attention, perception, language, reasoning, and problem-solving, to support conceptual change and metacognition (see Duit & Treagust, 2003). By contrast, socioculturalists have tended to focus on broader contextual conditions such as the influence of the forms of inquiry, the purposes for activity, the roles of learners, and the interaction with material tools on learning within groups (Roth & Barton, 2004). Contributors in this book point to the need to acknowledge generative insights across this theoretical divide and the need to undertake the challenging work of researcher-informed theoretical inclusiveness and agility. There is also broad recognition of the socio-semiotic dimension to learning, in that quality meaning-making depends on guided student induction into all the sensemaking resources in science lessons. In identifying the real complexities entailed in understanding (and enacting) positive influences on this learning, we now need to develop workable multi-theoretical perspectives that engage insightfully with these complexities.

1.2 Overview of Chapters

The first three chapters provide big-picture perspectives on key issues. They focus on the range of resources students need to acquire and refine if they are to develop as engaged, successful learners in this subject (Webb & Whitlow, Chap. 2, this volume), meaningful learner roles, purposes and processes for doing science (Gee, Chap. 3, this volume), and multidimensional structural supports needed to optimize cognitive engagement and success in this learning (Graham, Chap. 4, this volume).

Webb and Whitlow (Chap. 2, this volume) note that science education has been broadly influenced by two divergent traditions. The first broadly cognitivist perspective assumes that learning entails restructuring an individual student's mind through guided conceptual growth, expressed through developing representational competence. The second sociocultural approach assumes that students' learning is facilitated through group enculturation into scientific practices. Such learning is therefore context-dependent and specific to the purposes, collective experiences, and tools used for particular practices. As noted by these authors, these differences lead to contrasting views about what should be researched, how, and why. Cognitivist-oriented researchers seek to test and explain conceptual change in individuals, whereas sociocultural researchers seek to explain learning through microanalyses of learner activities, including teacher-guided discussion. In seeking to combine insights and outcomes from both approaches, Webb and Whitlow (Chap. 2, this volume) propose that cognitivist analyses should be applied to the processes and outcomes of immersive sociocultural approaches.

For Gee, science education has a long history of failure to engage learners, with quantitative research methods symptomatic of sophisticated sleepwalking in this and other education domains. As a pragmatist socio-semiotician, his solution to this story of failure is to claim that learning in science should be fundamentally refocused to engage with the ultimate purposes for meaning-making in this subject. Drawing on Wittgenstein (1958), he proposes that science should be understood as a "form of life," a set of values, norms, and actions rather than as the subject-specific knowledge arising from these practices. He claims that the ultimate purpose of science education should be to enable us to participate in "a better form of life with each other." To achieve this, learning experiences in science education should encourage students and citizens to be committed testers who respect evidence and critical discussion. They should encourage humility and a tolerance for the partiality of human judgments and therefore encourage a collaborative rather than adversarial approach to truth-seeking and truth-testing.

In theorizing the many influences on students' writing development in science, Graham (Chap. 4, this volume) draws mainly on cognitivist accounts of learning processes but integrates these insights with sociocultural perspectives on broader conditions that affect all text production in this subject. Learners are embedded in evolving writing communities that shape what they do, with these communities reflecting broader networks of historical, societal, cultural, and political and institutional influences. At the micro-level, his model of writing development incorporates a detailed account of the necessary knowledge bases or resources that guide what and how individuals write, but he also notes that motivational beliefs, emotions, personality traits, and physiological factors play a part in a writer's sense of self. In naming key ways in which writing development can be promoted, he points out how research is still needed on how these ways interact in science learning and how broader influences play out on this development.

Subsequent chapters in different ways take up this challenge of integrating cognitivist perspectives on learning growth within a theorized account of contextual influences. Contributors propose how particular purposes, resources, and learning experiences can be theorized at the micro-level of individuals, and within groups as the basis for understanding (a) current practices, but also (b) to inform how future learning opportunities should be designed, enacted, and reviewed to promote student engagement and learning. While there is a recurrent focus on theorizing the role of writing in science as a key tool for learning, the theoretical discussion is applicable more broadly to learning in the science classroom.

Lamb, Hand, and Yoon (Chap. 5, this volume) note that the theory espousal of what influences learning in school science continues to outstrip theory testing, with many studies generating competing descriptive models based on qualitative evidence. To address this problem, they propose the use of neuroimaging to identify cognitive processes and dynamics more directly than is usually proposed through retrospective testing of learning, interviews, or student self-reporting. They argue that neuroimaging offers real-time measurement of brain activity in writing tasks, and therefore provides more precise evidence for claims made for learning outcomes from different writing tasks. On this basis, through image analysis, they report that summary writing tasks make more demands on critical thinking abilities than argumentative writing. They suggest that this research technique for tracking cognitive processing, when aligned with other contextual research methods, provides (a) testable outcomes to confirm and complement models of learning arising from different writing tasks and (b) offers further leads for research that is process-oriented rather than product-dependent.

In acknowledging the complex dimensions to scientific practices in and beyond schools, Tang (Chap. 6, this volume) proposes that actor-network theory provides a useful framework to theorize human/nonhuman and linguistic/non-linguistic influences on student learning in science. This theory seeks to integrate cognitivist, sociocultural, and semiotic perspectives. Students here are understood to engage in a sequence of connected multimodal literacy events in learning any science topic, where multiple influences shape and reshape what is learnt. These influences include the students' own purposes and inquiry processes, as well as their interactions with teachers, peers, material resources, and revisable inscriptions during the course of the topic. Tang suggests that future research is needed to identify how and in what ways this network of classroom "actors" aligns with or differs from the practices of scientists. This research agenda aims to focus more precisely on what are generative alignments between the two set of practices, with implications for future design of science learning experiences.

Hand, Cavagnetto, and Norton-Meier (Chap. 7, this volume) claim that there is a need for future research to develop theoretical constructs related to the development of epistemic cognition when students are immersed in argumentation in this discipline. They propose that epistemic cognition (or knowing how and why to generate knowledge claims in science) should be conceptualized as drawing on four knowledge bases. These are science content knowledge around relevant concepts; argument knowledge or how claims are made in science and viewed as valid or invalid; language knowledge or all the representational forms of concepts; and knowledge of the learning environment or knowing how and why to participate. These bases together provide the grounds for students to "live the languages of science." The researchers argue that more research is needed on all the influences on the science classroom environment to determine what affects the development and use of the proposed knowledge bases. On this issue, like other contributors, they see the necessity to acknowledge the value of multiple theoretical perspectives. These include cognitive, linguistic, representational, sociocultural, and epistemological frameworks to interpret conditions for effective student immersion in science practices.

In conceptualizing writing as an epistemological tool for learning in science, Chen (Chap. 8, this volume) proposes three interlocking perspectives. Writing can be a form of personal sensemaking (cognitive perspective), a form of disciplinary induction, and a sociocultural resource within a community of shared practices. From the first perspective, individuals learn from writing in science depending on the degree of perceived challenge and cognitive work entailed in the writing task. From the second perspective, students learn from writing when they learn how and why to use its disciplinary forms and purposes in science. From a sociocultural perspective, writing is one communicative resource among many for students to enact roles in a disciplinary community. He asserts that further research is needed to identify what individuals and groups draw upon, and how, to learn, when this learning is conceptualized as interactions across these three perspectives.

Yoon (Chap. 9, this volume) suggests a model for the development of individual and collective student reasoning capabilities in science based on the complex interplay between learning resources and task demands in this subject. Resources include cognitive, sociocultural, semiotic, and material supports in a particular situation or inquiry, whereas demands are conceptualized as the expected scientific literacy practices to be achieved through the use of these resources over time. The context in which all these resources are used to address demands is characterized as a "discourse space," with learning outcomes dependent on the extent to which students utilize all possible resources to address the developmental demands implied in scientific literacy practices. Yoon suggests further research is needed in micro-level analyses in how individuals learn in this space and the role of representations in this learning. By implication, such research can support future design of pedagogical approaches to guide the development of learners as scientific reasoners.

Prain (Chap. 10, this volume) analyzes the multiple roles of representations in student learning in science, focusing particularly on student generation of these signs. He notes that the divide between cognitivist and sociocultural theories about learning from this sign-making has generated persuasive diverse insights, and that both perspectives, despite differences, converge on the catch-all explanatory value of affordances in this learning. He argues that researchers need to continue a focus on what kinds of tasks, representational challenges and choices, teacher guidance, and student improvisations (a) strongly engage students in creative claim-making and critique dimensions of scientific practices and (b) support student learning through utilizing particular affordances in this activity.

Emerson (Chap. 11, this volume) focuses on negative influences on the formation and maintenance of teacher and student beliefs and attitudes toward writing in science. She attributes this pattern to both early and subsequent school experiences but also to how curricular documents tend to view writing as a communicative rather than an epistemological tool. In concurring with many other contributors to this book, she argues for the need for teachers to understand and enact a focus on student writing as a crucial resource for knowledge speculation, clarification, and sensemaking in science.

Kelly (Chap. 12, this volume), in reviewing key themes in the preceding chapters, suggests that contributors engage in three crucial types of critical dialogue to advance science education research. The first discourse entails specifying groups' central theories, assumptions, and empirical scope. The second discourse entails assessing the value of different research traditions, and the third focuses on what can be learnt from analyzing differences and potential complementarities across contrasting traditions.

1.3 Concluding Remarks

These brief chapter summaries offer at best an orientation to the complexities covered by contributors around theorizing the future of research into school science learning. However, they also point to many broad areas of agreement despite the diversity of theoretical starting points, assumptions, and proposed foci for research and research methods. All contributors recognize that learning science should be about students engaging in meaningful ways with the purposes, processes, values, and multiple cognitive, semiotic, and sociocultural resources of this domain. This engagement is theorized as both individualized and collective. If students are to be more than reluctant bystanders in this subject, then they need sustained, guided immersion in how particular practices in science enable them to generate, judge, share, and value knowledge in this subject (Prain & Hand, 2016). The focus of this book is on student rather than teacher learning, but many chapters, by implication, point to the key roles of teachers in designing and facilitating student learning.

In recognizing the real complexities in theorizing future research in school science learning, our contributors do not converge on a single agreed theoretical prescription. Rather they identify key dimensions that need to inform theory-building, multi-theoretical reasoning, and enactment. Our book is intended to contribute to theory clarification and renewal, noting that theoretical perspectives and research tools are needed that are multi-focused and supple enough to explain the complexities of learning in this subject, and facilitate future pedagogical strategies and design.

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Part I

Mapping the Big Picture

Chapter 2
Merging Cognitive and Sociocultural Approaches: Toward Better Understandings of the Processes of Developing Thinking and Reasoning

Paul Webb and J. W. (Bill) Whitlow

2.1 Introduction

We think the most exciting future prospect for educational research is the convergence of two different conceptualizations of education. One conceptualization comes from the early founders and advocates for the emerging discipline of psychology such as Hall (1909) and Thorndike (1906, 1931), who emphasized measuring attitudes, aptitudes, and cognitive abilities of students, then using those measures of individual characteristics to develop tailored interventions to improve the cognitive competencies of individual students. The other major conceptualization comes from the founders of a sociocultural approach to psychology such as Vygotsky (1978) and Cole (see Cole, Gay, Glick, & Sharp, 1968), who emphasized the importance of the social context of education and the role of language in developing cognitive competencies.

In the first conceptualization, constructing knowledge and shifting learners' understandings from naive to accepted representations of phenomena provide the developmental psychologists' framework for understanding teaching and learning. Increased knowledge through domain-specific restructuring in an individual's mind is seen to lead to more sophisticated conceptual structures, understandings, and representations, as illustrated by the work in science education by Posner, Strike, Hewson, & Gertzog (1982) and DiSessa's (1983) history of conceptual change. Changes of individual conceptions and representations can be investigated using a number of methods including pre-post-tests or via qualitative discussions of chil-

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*,
Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_2

dren's knowledge as they develop (Carey, 1985; Vosniadou & Brewer, 1987). In contrast, the sociocultural approach emphasizes that what is learned is specific to, and grounded in, the situation in which it is learned. Learning is seen as an enculturation in a community of discourse, practice, and thinking (Greeno, Collins, & Resnick, 1996). For socioculturists, knowledge is a cognitive apprenticeship activity in a community context, which can be researched via microanalysis of learners' activities over a period of time (Mason, 2007; Rogoff, 1990).

Sfard (1998) uses "acquisition" as a metaphor to summarize the cognitive approach. "Acquisition" implies that knowledge, content, and concepts can be obtained, applied, shared, or transferred to another situation. She uses "participation" as the metaphor to illustrate the sociocultural approach where learning takes place in a disciplinary community of practice and discourse. Concepts are not seen as mental entities in individual heads which reflect internal representations of the world but are part of social practices and the appropriation of new ways of reasoning based on concepts defined by a community of discourse (such as among physicists or mathematicians). Appropriation enables reasoning using these conceptual tools in a particular context, but is not knowledge that can be transferred to an unrelated task or context.

These two approaches are grounded in ontologies and epistemologies that appear to differ so greatly from one another as to seem incompatible (Packer & Goicoechea, 2000). The cognitive approach is based on internal processes and functioning of the mind, while the sociocultural approach is based in the notion of a context-situated, nontransferable sociocultural appropriation of knowledge. Such differences seem to suggest that researchers would be sensible to locate their research in one or the other, but not together. Nonetheless, the question of whether seeking compatibility between the two might result in better understandings of learning processes was the topic of extended conversations in 1994–1998 in terms of science and mathematics education. This question was examined again at a symposium at the annual meeting of the American Educational Research Association (AERA) in Montreal in April of 2005 (Mason, 2007) with arguments made for and against the compatibility of the approaches and discussion of whether there are integration opportunities in science education.

However, there appear to have been few such conversations since then, and little to no consensus either on ways forward toward integration or how to disseminate such ideas within the science education community. As such we suggest that the trajectory of science education research over the past four decades has not moved toward a more integrated position, and we believe that the question as to whether these two views can be reconciled remains a neglected and long overdue issue for consideration.

In this chapter we briefly reflect on pertinent issues that have come under scrutiny in science education over the past 40 years to support our assertion that a more integrated position has not evolved. We then examine an important sociocultural refutation of cognitive assumptions, namely, the demonstration of "far transfer." Thereafter we provide insights as to how cognitive approaches can be mutually supportive and make suggestions for future research that could possibly fruitfully integrate the two approaches.

2.2 Developments in Science Education

In science education there has been a change in emphasis over time in terms of how research should be framed on these two conceptualizations of how learning takes place. Constructivist perspectives, which viewed learning to be a change in conceptual structures via the successful integration and restructuring of knowledge and which values the active interpretation role of the learner, were commonplace in the late 1970s and 1980s. Changes in personal cognitive and conceptual change were initially the focus of research to investigate mental representations which arose as a result of instruction and knowledge restructuring (Duit, 1999). Research on the notion of "intuitive knowledge" and "alternative conceptions" became popular in the early 1980s and dominated the literature until the late 1990s. Alternative conceptions were seen by some to be internally consistent but naive theories by some (Posner, Strike, Hewson, & Gerzog, 1982) and by others as pieces of knowledge that needed to be framed coherently (diSessa, 1983).

Then, in a seminal paper in 1993, described by Mason in 2007 as "a remarkable event," Pintrich, Marx, and Boyle called for work on conceptual change to include affective, motivational, and situational factors. Attention to such noncognitive variables, and how they might interact with cognitive variables in particular contexts, gave rise to consideration of dual-process models (Dole & Sinatra, 1998). Mason (2007) saw the inclusion of different types of variables as an important step to better understandings of "knowledge restructuring." Conversely, other researchers argued that conceptualization of science ideas should be viewed as the construction of multiple representations in appropriate contexts with one representation being better than the other depending on the particular situation (Pozo, Gomez, & Sanz, 1999; Spada, 1994). The discursive nature of scientific knowledge and the fact that learning science is an enculturation process were recognized fairly early on by science education researchers like the iconic Rosalind Driver and her colleagues (Driver, Asoko, Leach, Mortimer, & Scott, 1994). At the time both personal and social processes were seen to be important; the two theoretical perspectives were not considered to be mutually exclusive.

The most radical criticism of the cognitive tradition came via the views held by "sociocultural researchers" of how learning and teaching should be researched. As mentioned earlier, the sociocultural approach sees the essence of conceptual change not as modification of conceptual structures but as the successful participation in discourse practices (Wertsch, 1998). Concepts are discursive tools which are used when people think and communicate (Säljö, 1999). Knowledge does not transfer between tasks as it is wedded to the context of its use (Lave, 1988). Examples have been put forward of children who are very good at the arithmetic of everyday buying and selling in the street but who have poor mathematical abilities in the school context (Carraher, Carraher, & Schleiman, 1985).

The long-standing, but only recently burgeoning, body of research on "productive discussion" in classrooms appears to both support and challenge sociocultural assumptions. For example, Matthew Lipman, who founded the Philosophy for

Children Project in the early 1970s, was particularly interested in developing children's reasoning skills by getting them to talk about science. He believed that children possess the ability to think abstractly from an early age and that by talking about issues they could learn logic, and his belief was supported by results of multiple studies (at least ten) of his project, which all showed that his participants did better than other children of the same age in terms of reading, reasoning, and thinking in general (Trickey & Topping, 2004). Similarly the Cognitive Acceleration through Science Education (CASE) project, developed by Michael Shayer and Philip Adey at King's College London in 1981, used an approach which focused on group work and discussions in science classes. Not only did participating children achieve better than expected in science, but their mathematics and English grades also improved (Shayer & Adey, 2002).

Similarly, a review of a number of studies revealed that discussion in science classrooms resulted in simultaneous improvement in English and mathematics (Webb, 2010). What we consider important about findings from classroom discussion studies (which are clearly sociocultural in their design) is that so many allude to the possibility of transfer of skills between tasks that are not wedded to the context, sometimes in no apparent way at all. Indeed, an AERA-sponsored research conference in Pittsburgh in 2011 revealed how dialogic forms of teaching and learning raised student achievement and retention of knowledge over years on traditional tests in virtually every school subject (Resnick, Asterhan, & Clarke, 2015). Resnick and her co-authors consider these findings to be "startling." We agree.

The findings suggest that sociocultural activities promote transfer, a cognitive outcome. If "far transfer" can be observed, i.e., when learning in one context is transferable with success to new material in seemingly unrelated circumstances, the educational paradigm becomes even more intriguing, and one may be forgiven for wanting to understand what might be happening in an individual's head. Similarly, it would seem natural that one might want to try to find explanations as to how these processes may have effected the changes that take place. We suggest that reconciling aspects of cognitive and sociocultural theorizing is a viable option to better understand how people learn to think and reason, to provide testable hypotheses, and to highlight the multiple variables that may affect (accelerate or retard) the processes that develop these attributes.

2.3 Barriers to Reconciling the Two Approaches

Sociocultural assumptions have a profound effect on the way in which research is conducted. Sociocultural researchers are more likely to use microanalyses of learner interactions which focus on issues of interactional achievements shaped by the sociocultural context rather than analyzing changes in individual understanding (Mason, 2007). The basis of the cognitive science and sociocultural approaches noted earlier are illustrated in Table 2.1. The contents of this table are admittedly a highly simplified presentation of a much more complex and nuanced situation but

Table 2.1 Basic comparison of the underpinning assumptions of the cognitive and sociocultural approaches have been taken in science education

	Cognitive	Sociocultural
Knowledge	Knowledge develops as individual learners move from naive to accepted representations of phenomena	Knowledge is not an entity in the head of an individual. Developing knowledge and representations is seen as a process of enculturation in a community of discourse, practice, and thinking
Transferability	Knowledge may transfer through domain-specific restructuring in an individual's mind toward more sophisticated conceptual structures, understandings, and representations	What is learned is specific to, and grounded in, the situation in which it is learned
Ways of researching	Changes of individual conceptions and representations can be investigated using a number of methods including qualitative discussions or through pre-post-tests of children's knowledge as they develop	Sociocultural learning is researched via microanalysis of learners activities over a period of time
Metaphor	Acquisition	Participation

can be used to illustrate fault lines between the two approaches which have to be bridged if they are to be integrated in a meaningful way.

While cognitive scientists do not disagree that learning is a sociocultural activity steeped in language, they question the sociocultural stance that what is learned is specific to, and grounded in, the situation in which it is learned and is not transferable. This position stands in direct contrast to the notion that transferable cognitive skills can be learned (both individually and in groups). It is the disagreement as to whether "transfer" actually exists, and the accompanying notion that changes in cognitive processes can be rigorously tested that underpins the main "cultural differences" between the two positions. These differences affect both what should be researched and how it should be researched.

2.4 The Problem of Transfer and Its Measurement

Many curricula expect teachers to be able to prepare their students to perform well in new situations, adapt what they have been explicitly taught, and solve problems that are new or different. However there is little evidence that they are able to do so, a problem that goes back to one of the earliest examples of empirical research on education. Thorndike (1906) conducted a wide range of studies in an effort to test the claimed benefits of "formal discipline," in which training in one task, like learning Latin, was expected to benefit performance in other tasks, ranging from general problem-solving skills to more specific tasks like mathematics problems or writing critical essays. As students of psychology remember these efforts, Thorndike failed to find evidence that training in one set of problem conditions led to transfer to different though similar sets of problems (like estimating areas of one set of rectangles to estimating areas of another set of rectangles). Lehmann, Lempert, and Nisbett (1988) point out that Thorndike summarized his work as showing that “training the mind means the development of thousands of individual capacities” (quoted from Thorndike, 1906, p. 246, by Lehman et al., 1988) and concluded that transfer of training depended on “common elements” (Thorndike & Woodworth, 1901).

In terms of science education, however, we argue that there are a plethora of studies that reveal that sociocultural practices such as productive discussion result in children performing better on tests than students who had not, with better retention of knowledge (up to 2–3 years) and of examples of transfer to a different domain (e.g., from science to English literature). These examples include the aforementioned studies by Lipman and Shayer and Adey and a number of other projects that incorporated classroom discussion (Webb, 2010). However, the dismissal of the existence of transfer as reflected by sociocultural assumptions remains.

Arguments against transfer include the charges that only a small number of studies showing positive results have involved measures that were standardized and independent of the texts discussed, or used designs with multiple groups, or that only small effect sizes have been recorded (Wilkinson, Murphy, & Binici, 2015). It has also been pointed out that a number of studies of dialogue-intensive frameworks have failed to find positive results (Reznitskaya et al., 2012) or only reported delayed transfer (Kuhn & Crowell, 2011; Morehouse & Williams, 1998). Another criticism is that in some studies there was little to no clarification as to exactly what was transferred, or how the claimed transfer was measured. This criticism is particularly important when one tries to claim that “far transfer” takes place, for example, claiming that talking about subject-specific topics in science and/or mathematics can lead to abstract reasoning abilities.

Barnett and Ceci (2002) have developed criteria based on a content and contextual framework to clarify the nature and measurement of near and far transfer. The question, however, remains as to whether there are studies which meet all of the theoretical and methodological criticisms of studies which claim transfer and which might “open the door” for the integration of cognitive and sociocultural approaches to educational research. We believe that there are and introduce our argument by describing our own research in science education that we believe provides robust evidence for far transfer while using a sociocultural approach, namely, classroom discussion.

2.5 Evidence for Successful Far Transfer

We (Webb, Whitlow, & Venter, 2016) reviewed a collection of pre-post-test studies from South Africa which provided robust evidence of far transfer by meeting the criticisms of previous studies already mentioned. In our studies we used standardized tests that were independent of the material discussed in class, involved large numbers of participants, followed a consistent methodology, and produced results that both were statistically significant and showed large effect sizes (Webb et al. 2016). These studies represented a group of research projects undertaken over a decade by a special interest group at the University of Port Elizabeth (now Nelson Mandela University) in South Africa. They all focused on the development of scientific literacy in learners from historically disadvantaged communities through the use of exploratory talk (a form of productive discussion). The studies examined changes in content knowledge but, more importantly, also examined changes in fluid intelligence, using the Raven's Standard Progressive Matrices test, a nonverbal measure of abstract reasoning skills. The nonverbal, abstract reasoning nature of the Raven's test makes it a good measure of far transfer effects when employing an intervention such as exploratory talk because the participants would not be expected to show improved test scores when they had not been specifically trained on nonverbal reasoning.

Teachers in the experimental groups were introduced to, and trained in, the use of exploratory talk, while teachers in the control groups were not. Moreover, one of the critical ingredients in this work was direct measurement of the efficacy of the teachers using exploratory talk. That is, not only was a pre- and post-measure used for a far transfer test (the Raven's test) and a comparison of control and treatment groups on both near and far transfer tests, there were also measures of the degree to which students engaged in exploratory talk. The same classroom observation tool was used in each study, and a four-point classroom observation scale was used to record the classroom activities. These activities were either video- or audio-taped. On-site discussions with teachers and pupils were also used as an indicator of whether exploratory talk had taken place, and analyses of classroom observation records provided deeper insights into the types of discourse and interactions that took place. The criteria used to determine whether classroom discussion had taken place were the ability of learners to engage in the lexicon (use the words appropriately), use scientific explanations (apply connectives), and engage in discourses that included descriptions, predictions, explanations, and arguments.

All of the studies were done over a period of one calendar year and involved a 6-month period of implementation of the strategy with the students from March to September in each case. Two studies were replicated as first and second studies over two calendar years (Webb & Treagust, 2003; Villanueva, 2010). The changes in the Raven's pre-post-test scores of the experimental groups were all highly statistically significantly better than the pre-post-test scores of the control groups, with a large effect size in most cases. These results are consistent with other works done from a sociocultural perspective (e.g., Wegerif, Mercer, & Dawes, 1999) that emphasize the importance of a cognitive apprenticeship in which students are learning how to think and communicate with others rather than simply absorbing information.

2.6 Why Evidence for Far Transfer Is Important

While there are many forms of productive discussion, e.g., exploratory talk, collaborative reasoning, critical discussion, accountable talk, dialogic argumentation, etc., there is a considerable agreement among scholars as to the nature of the discourse that characterizes productive discussion (Resnick et al., 2015). Typically, productive discussion is structured and focused, but not dominated by the teacher. It is framed in a series of open-ended questions, individual and collective reasoning, and a high degree of agency and control in the co-construction of knowledge within a group. Students have opportunities to engage in individual and collective reasoning about issues and to provide explanations for their claims by drawing on their experience and prior discussions. They are able to listen and react to each other's ideas, reason together, and co-construct understanding (Wilkinson et al. 2015).

As noted earlier, the constellation of general approaches to instruction mentioned above that can be loosely characterized as using productive discussion (Kuhn & Crowell, 2011; Reznitskaya et al., 2012) has been found to promote learning not only of studied material but the ability to transfer that learning to new material and situations (for a recent broad description of such approaches, see Resnick, Asterhan, & Clarke, 2016).While what is learned is specific to, and grounded in, the situation in which it is learned, it is also clear that knowledge may transfer through domain-specific restructuring in an individual's mind toward more sophisticated conceptual structures, understandings, and representations – see the transferability aspect of the comparison of the underpinning assumptions of the cognitive and sociocultural approaches in Table 2.1.

It is also important to note at this stage that a common goal of teaching is "to prepare students to perform well in new situations, adapting what they have been explicitly taught so they can solve problems and produce outcomes that are new or different from their specific training" (e.g., see the United States Common Core Standards for English Language Arts). This goal implies that "transfer" is an important aspect of learning to many.

2.7 Looking to the Future

In looking to the future of education, we think that three developments are particularly exciting and encouraging. The first, as noted above, is the evidence that certain social-constructivist view interventions can attain the cognitive goals of general improvement in thinking, reasoning, and problem-solving. A second development is the increasing sophistication of cognitive theorizing, linking specific components of cognitive processes to measurable performance and even brain activation (e.g., Anderson, 2007). Finally, the third development is the increasing focus on rigorous assessment of the efficacy of educational interventions, the evaluation of proposed linkages between cognitive components and performance, and some of the promising advances in approaches and technologies that support an optimistic vision of what educational practices will be able to achieve (Roediger, 2013; Clark & Mayer, 2016). We have discussed aspects of the first development already in this chapter and therefore move to measuring performance and cognitive theorizing.

2.8 Explaining Findings

The core of the scientific enterprise is to be able to describe, explain, and predict. Both the cognitive and sociocultural approaches to research quite easily result in findings that describe what was found out during the research. The validity of cognitive research is determined by accuracy of predictions (such as improved scores on the Raven's test after measured efficacy of teachers to facilitate productive discussion). Theoretical frameworks come into play when one attempts to attribute causality to findings, and it is here that we feel that a fresh look at the complementary roles of cognitive and sociocultural research can make a contribution to better understanding of processes and outcomes. We start on the premise that the mind acquires "conceptual agency" through participation in "conversations that matter" and recognize that thinking is something that is developed through openness to the ideas of multiple "others" (Greeno, 2006). We also believe that this "agency" can be measured in meaningful ways.

One of the critical ingredients in the work we did (Webb et al., 2016) was direct measurement of the efficacy of the teachers using exploratory talk. That is, not only was a pre- and post-measure used for a far transfer test (the Raven's test) and a comparison of control and treatment groups on both near and far transfer tests, there were also measures of the degree to which students engaged in exploratory talk. This program of research illustrates one contemporary trend that seems likely to accelerate, which is the use of video recording to provide detailed feedback to teachers with respect to how well they have achieved their instructional goals. For example, measurement of the amount of student use of dialogic argumentation is a hallmark of recent work by Reznitskaya and Wilkinson that focuses on teacher training (e.g., Reznitskaya & Wilkinson, 2015a, 2015b; Wilkinson et al., 2016; Reznitskaya et al., 2016). These investigators have developed an "Argumentation Rating Tool" (ART) to evaluate dialogic argumentation in language arts classes for upper elementary school children. As the technology to support these efforts improves, such feedback becomes increasingly useful and practical.

The second issue is the measurement of "conceptual agency," for example, strengthening working memory. However, what we suggest is that rather than developing teaching and learning programs based on cognitive theories of conceptual agency, and then looking for evidence of far transfer, researchers in the field of cognitive psychology should examine what is being achieved via research using sociocultural theory that promotes far transfer and then look for evidence that there have been changes in the cognitive machinery. We took this approach, guided by Samuel Moulton's summary of effective learning techniques (Moulton, 2014), when we suggested several possibilities for explaining the cognitive effects (Webb et al., 2016).

In his summary, Moulton (2014) attempts to identify the most robust and well-documented findings from the cognitive research literature that seem to him to have significance for education. He organizes his review of key findings with respect to three domains – effective learning techniques, mental architecture, and motivation and persistence. The following paragraphs briefly examine sociocultural activities such as classroom discussion in relation to two of these domains in an effort to identify what are probably the most promising avenues for future research.

2.8.1 Effective Learning Techniques

Evidence-based assessments of effective learning techniques have shown that certain ways of presenting information are robustly more effective than other ways. In particular, (1) giving students opportunities to practice retrieval of what they've learned (usually by means of testing) rather than by giving them additional study, (2) giving them practice that is spaced over time rather than occurring all at once, and (3) giving them practice with multiple topics intermixed rather than with one topic at a time are all more effective in promoting learning than the alternatives (Roediger, 2013). Productive classroom discussion might be effective because implementing it also embodies retrieval practice. That is, in order to make an argument, one has to remember the facts and concepts that one has studied to construct the argument. Productive classroom discussions might also implicitly provide distributed practice in that the process of developing and presenting argument is likely to involve coming back to the same material at different times. Similarly, developing an argument often requires a combination of reviewing past history, analyzing data from current findings, and constructing a coherent narrative, a process that interleaves different tasks to complete a project. These tasks underpin the "educative ability" noted by Raven and Raven (2003), namely, problem identification, reconceptualization of the field, and monitoring proposed solutions for consistency within all available information.

These speculations about how classroom discussion might provide implicit support for effective learning techniques seem reasonable, but it seems to us unlikely that discussion enables far transfer effects primarily through this route. One reason is these techniques are primarily useful for learning material that is actually presented. Hence, the benefits produced by these means would primarily be expressed in tests of near transfer, rather than far transfer. In addition, studies of dialogic argumentation have sometimes found clear evidence of improved argumentation without finding evidence of improved cognitive performance (e.g., Reznitskaya & Wilkinson, 2015b).

2.8.2 Mental Architecture

The “cognitive revolution” began with acceptance of the principle that human processing capacity, like the capacity of all information processing systems, is limited. Thus, effective teaching practices must reflect both the cognitive limitations of students and our understanding of the mental architecture that is involved in learning and memory. For example, the fact that the capacity of working memory depends on how information is organized (e.g., Miller, 1956) means that a teacher’s judgment of the cognitive load of a lesson may be far different from a student’s judgment of the cognitive load of the same lesson (Moulton, 2014). That is, while teachers may believe that they have created organized and coherent lesson structures, their students often struggle with what they experience as a fragmented and disjointed set of facts. In our view, the most likely source of benefit from productive discussion is the way that it explicitly teaches students how to structure an argument and use that structure to organize their thoughts so they are not faced with sets of disconnected, disorganized facts.

Another possibility we have considered is that productive discussions provide practice in how to manage working memory capacity more effectively and thereby reduces cognitive load. Our consideration of this possibility was prompted by two kinds of findings. First, there are the well-established associations between working memory capacity and measures of problem-solving and fluid intelligence (see, e.g., Ackerman, Beier, & Boyle, 2005; Kane, Hambrich, & Conway, 2005; Oberauer, Schulze, Wilhelm, & Suss, 2005). Second, Jaeggi, Buschkuehl, Jonides, and Perrig (2008) reported that extensive training on an adaptive working memory task yielded significant improvements on the Raven’s test. With this result, one could speculate that if productive discussion increased working memory capacity, the increased capacity might translate into higher levels of problem-solving ability. That would still leave the problem of explaining how exploratory talk might increase working memory capacity, but at least that problem can be addressed with a collection of known research tools (e.g., Miyake et al., 2000). That is, one could measure working memory capacity and other executive functions before and after learners are engaged in exploratory talk.

As an explanation productive discussion may facilitate working memory efficiency by providing clear guidelines to achieve the goals of a good argument. Toulmin’s argumentation pattern (Toulmin, 2003) specifies in a straightforward manner a set of components for an argument and how they are related to each other. The task for students using this framework becomes not one of “making an argument” but of identifying data that can be offered to support a claim, establishing the assumptions needed to connect the data to the claim, acknowledging any limits to the claim, and considering counterarguments. Breaking down the larger task into manageable components is a widely recognized strategy for solving complex problems. A germane point to consider, however, is that recent efforts to replicate Jaeggi et al.’s (2008) findings have been inconclusive. Harrison et al. (2013) and Redick et al. (2013) found no improvement in measures of fluid intelligence after extended adaptive training with working memory tasks, even though these tasks yielded substantial gains in working memory capacity. Reasons for these failures of replication remain unclear, although there are probably a number of methodological differences that have not been identified, including the particular structure of the adaptive memory task. While these findings suggest caution in assuming that acquired increases in working memory capacity will translate into better problem-solving abilities, it still seems reasonable to suggest that it would be useful and interesting to determine how working memory capacity is affected by lessons using productive discussion and whether such talk works, at least in part, through the medium of working memory.

Finally, productive discussion might also act to increase students' abilities to sustain their attentional focus. Research has shown that several different kinds of training reduce "mind-wandering" and lead to better learning (e.g., Mrazek et al., 2012; Mrazek, Franklin, Phillips, Baird, & Schooler, 2013; Szpunar, Khan, & Schacter, 2013; Szpunar, Moulton, & Schacter, 2013). Perhaps most intriguingly, Mrazek, Schooler, and their colleagues have shown that learning mindfulness meditation techniques not only helped reduce "mind-wandering" but led to both improved working memory capacity and improved general aptitude. Here too it would be interesting to examine whether lessons using productive discussion diminish the amount of mind-wandering seen in the students and whether the reduction of mind-wandering was a mediator for changes in fluid intelligence. The overall question is: does productive discussion have a positive effect on reasoning skills because of transfer of these skills?

As can be seen from the above, there are more questions than answers, but it is precisely this situation which motivates us to advocate for the integration of sociocultural and cognitive approaches. As such we briefly mention some of the cognitive science approaches that may provide fruitful ways of further investigating and providing affordances for widening possible explanations for the findings of sociocultural activities. Naturally the affordances of such approaches are limited to what researchers consider to be meaningful depending on the context of the both the activities and the learners.

2.8.3 Cognitive Neuroscience

Several extraordinary developments place us perhaps on the cusp of remarkable advances in educational research. First, great strides have been made in understanding the biological bases of learning and memory at a synaptic level (a readable overview of some of this research is found in Rudy, 2013). Second, similarly great strides have been made in understanding the biological bases of learning and memory in terms of computational models of brain activation (see, e.g., Anderson, 2007). Third, controlled studies in classrooms have begun to inform ideas about what cognitively based learning strategies are effective; an excellent example of this is the review by Dunlosky, Rawson, Marsh, Nathan, and Willingham (2013), summarized by Roediger (2013).

On the one hand, we can expect a continuing upsurge of new technologies that enhance or enable alternative learning strategies and constantly increased understanding of how the brain works. At the same time, the need for clear-eyed appraisals of what actually is known about education and learning has never been greater. The history of educational reform is littered with the debris of misguided applications of "brain science" to education, from Samuel Orton's claims about visual reversals as the primary cause of dyslexia to the right-brain/left-brain dichotomies of abilities in the 1990s. Moreover, we are mindful that basic elements of the learning capacities that set humans apart from other species are not likely to have changed much. However, there is much to be gained by thoughtful integration of neuroscience with education considerations. One example of such integration is expressed in a recent article by one of us on the application of "brain-based learning" to a curriculum for teaching computer programming (van Niekerk & Webb, 2016). In a comparison between students who had standard instruction and students who had a "brain-compatible instruction," they found better long-term retention by the latter group of two measures of programming ability. However, a critical ingredient for the success of such an approach is a sensible selection of principles and a thoughtful application of such principles to the design of curricula. The point raised by van Niekerk and Webb has been applied systematically by Richard Mayer and his colleagues (e.g., Mayer, 2009, 2011; Fiorella & Mayer, 2015, Clark & Mayer, 2016, Mayer & Alexander, 2017) to making multimedia presentations more effective. They have used cognitive principles to explain why some multimedia presentations are more effective and others are less effective.

With advances in knowledge about how the brain changes as a result of learning and how different parts of the brain are involved in the creation, storage, and retrieval of memories, the use of brain science as a guide for teaching practices becomes more and more a realistic and productive possibility. We use our brains differently compared to the ways in which our parents, grandparents, and great-grandparents used them, and we have probably altered some aspects of their functioning by doing so. Maguire, Woollett, and Speirs (2006) measured the brains of London taxi drivers and showed that they have enlarged hippocampi, the area used for navigating three-dimensional space, which shows that our brains change as a function of task demands. One wonders if the hippocampal enlargement is still the case for young London taxi drivers who rely entirely on Global Positioning Systems for navigating the city. Of course, one must be careful not to oversell this potential, but brain science, when buttressed by sound psychological science, should probably be at least a touchstone for how to design, measure, and explain effective educational strategies.

One of the simplest and most direct applications of brain science to education is to emphasize the importance of exercise and physical health as a major contributor to sound educational practices (van Praag, 2009). One of the exciting developments is the possibility of targeting specific nutrient supplements to aid in learning under particular conditions or for particular populations. Some interesting early work on the effects of glucose on decision-making (e.g., Gailliot et al., 2007) has matured into a more nuanced view suggesting that the beneficial effects of glucose are dependent on both context and content (Orquin & Kurzban, 2016). Many other possible influences of nutritional supplements have been explored, including the effects of vitamins, stimulants, proteins, and even amino acids (e.g., Benton, 2008; Gomez-Pinilla, 2008; Smith & Farah, 2011; The NEMO Study group, 2007). Interestingly, the benefits of nutritional supplements were just as evident in a well-nourished population as in an undernourished population, suggesting that nutrition alone is not the source of these results. That finding is consistent with recent evidence that L-tyrosine yields benefits in cognitive performance for individuals under stressful conditions (Whitlow, Rowe, & Wigley, 2017; Deijen & Orlebeke, 1994; Owasoyo, Neri, & Lamberth, 1992). In this case, the line of reasoning is based on recognizing that stress calls forth the depletion of dopamine, which is also the most active neurotransmitter in the prefrontal striatal cortex (Backman et al., 2011), which is the region associated with working memory functions in humans, and L-tyrosine is a precursor amino acid for dopamine synthesis. Thus, L-tyrosine supplements might be expected to augment dopamine synthesis and thereby help working memory functions for people under stress.

2.9 Conclusion

On the key issue of whether cognitive science-based training programs produce benefits in tasks that are different from the training tasks, a careful review by Simons et al. suggests that while many studies show near transfer, the attainment of far transfer remains elusive. In contrast, multiple sociocultural interventions have produced evidence of both near and far transfer which have not been explained in terms of cognitive mechanisms.

We therefore suggest that a better way of meeting the challenge of understanding how to prepare students to perform well in new situations, and adapt what they have been explicitly taught so they can solve problems and produce outcomes that are new or different from their specific training, is to adopt a different approach, namely, to take an intervention that produces far transfer and attempt to diagnose what changes in the cognitive machinery are associated with the application of the intervention. In this regard, a very promising new development is the emergence of studies of multi-brain synchrony in the classroom (Szymanski et al., 2017).

In other words, rather than using cognitive theory to select components for a training intervention (like strengthening working memory, for instance) and looking for evidence of far transfer, we have an opportunity to use sociocultural theory to create interventions that appear to promote far transfer and then look for evidence of changes in cognitive machinery. In this way there are benefits for cognitive scientist in that they can examine sociocultural research results in light of understandings of factors that may affect cognitive development, for example, nutrition, cognitive load theory, short-term memory aspects, brain physiology and architecture, etc. In turn sociocultural researchers have an opportunity to access understandings and theories that may help them understand the outcomes of their interventions in new and different ways, particularly where interventions work in one context but not another. However, bridging the gap between these two views of the world requires mutual respect and the type of productive discussion between scientists that enables openness to the ideas of multiple "others" (Greeno, 2006), in essence a sociocultural activity.

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Chapter 3
Frameworks, Committed Testers, and Science as a Form of Life

Jim Gee

3.1 Introduction

My assigned task is to identify "key theories that should guide future research into teaching and learning in school science." What I offer here is an "opinion piece." While I hope my opinions are true, they are contentious. More importantly, the reader will, in the end, see that the "key theory" I propose necessitates that I should not have too much confidence in my opinions until they have been tested in critical discussions with others. So, this paper is meant to start, not finish, such a critical discussion. I will begin by arguing that we should see that there is a crisis in science education today, though few people do. After discussing this crisis, I will offer some ideas, based on rather old theories in the philosophy of science, about how to proceed, if we ever agree—or agree in time, since we may well have limited time to deal with our problems—that "business as usual" is bankrupt.

3.2 The Crisis

The word "science"—and individual names for sciences like "biology" or Z"physics"—has two different meanings. The word can mean the contents ("facts" and principles) that are created by the values, norms, actions, practices, tools, methods, and theories of some branch of science. Or it can mean these values, norms, actions, practices, tools, and methods themselves. Let us call the first meaning the "content meaning" and the second "the form of life meaning" (adapting a term from

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*,
Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_3

Wittgenstein, 1958). I will further explicate my view of the "form of life meaning" in the next section.

School science tends to focus on the content meaning of "science." It is very hard to implement the form of life meaning in schools (Gee, 2004). Schools do sometimes give science a third meaning: they introduce science-related activities (e.g., labs, trips to a local pond, experiments in fast-growing plants, and so forth). Such activities rarely if ever truly introduce—let alone replicate—science as a form of life.

Science as content—though it is what school science is mostly about—is almost entirely irrelevant to people's lives when separated from science as a form of life. Nothing much turns on knowing how the seasons change. Even people who have been introduced to this knowledge at school rarely master it or remember it if they do. Science as content in the absence of science as a form of life is much like having a manual to a video game one will never see or play. Doing science-related activities at school in the absence of science as a form of life is mistaking grape juice for wine—it may be good for you, but it is not the real thing (and, yes, the real thing is a good deal more dangerous).

Whatever one thinks of science education and school science today, it is pretty clear that it does not work well. Our society—and most of the rest of the world—has no deep commitment to evidence, let alone science. This problem has been endemic to humans forever. After all, lots of research has shown for decades that humans are prone to confirmation bias and a great many other "brain bugs" that make them more tropic to mental comfort than to truth (Buonomano, 2011; Gazzaniga, 2011; Gee, 2013; Kahneman, 2011; Macknit & Martinez-Conde, 2010; Marcus, 2008). Furthermore, research has shown that educated people are no less prone to confirmation bias—and to further entrenching their beliefs when confronted with counter-evidence—than are less educated people (Kahneman, 2011; Lewis, 2016; Stanovich, West, & Toplak, 2013).

However endemic brain bugs like confirmation bias are to us humans worse today than ever. We live in a world fractured into ideological and religious echo chambers, as we have for most of human history, but today we also live in a world where interacting complex systems are running amok, a phenomenon caused by human ignorance, greed, and the disavowal of evidence and science as a form of life (Gee, 2013). This ignorance may—in the not too distant future—bring the world to ruin (it is already bringing on one of the largest mass extinction events in the history of the earth). It matters little that some people master science as content in schools only to live in a society replete with the disavowal of evidence, science, or even basic logic.

While I can note that science education and science in schools would have long gone out of business, if it were a business (given the minimal impact it has had on society in terms of beliefs and epistemic practices), I cannot predict what will replace it in the future. I can, however, argue that it is time to change the very paradigm of science education as we know it. As with so many other things in our current world, time for "business as usual" has long passed if we want actually to solve our problems.

Let me be clear, before I propose "my" alternative paradigm (really not mine, actually an old and forgotten one), that, in my view, the current mess of science and society was caused as much by liberals (especially academic ones) as conservatives. In my decades as an academic, it has been my experience that liberal academics in the social sciences and education have as deep a disdain for evidence and science as a form of life as any conservative, maybe more. It is an irony that while many postmodern academics have disavowed science as a rational activity devoted to truth, many right-wing ideologues today celebrate a "postfact" or "post-truth" world. In Karl Rove's famous words to a journalist:

> [people like you are] "in what we call the reality-based community," … [people that] "believe that solutions emerge from your judicious study of discernible reality." … "That's not the way the world really works anymore. We're an empire now, and when we act, we create our own reality. And while you're studying that reality—judiciously, as you will—we'll act again, creating other new realities, which you can study too, and that's how things will sort out. We're history's actors…and you, all of you, will be left to just study what we do." https://en.wikiquote.org/wiki/Karl_Rove

The term "the judicious study of discernible reality" is about as good a shorthand as I can think of for science as a form of life. Rove must have studied science well in school, since his disavowal of it is so well aware of what it is. On the other hand, I would claim that the realities created by Rove and his associates are excellent examples of why it is important to study discernible reality judiciously.

As if these problems were not enough, there is today a crisis in much academic science research, though one that is, by and large, ignored in the service of business as usual. Numerous books and articles have argued powerfully, over the last few years, that our standard statistical procedures (based around p-values) are highly suspect and often invalid. Indeed, some prestigious scientific journals have tried to ban these statistics (Cummings, 2012; Reinhart, 2015; Weisberg, 2014). Yet in education, we refer to such work as "evidenced based" and the "gold standard." The claim that our traditional statistical methods are bankrupt is further backed up by important work that has shown that such statistical studies—even meta-analyses of such studies—cannot be replicated in a great many fields, including medicine, psychology, and education (Baker, 2015, 2016; Green, 2016; Young, 2016). Much work in science education is based on just such methods, methods that—it has been argued—survive more because of our need to publish copiously and get tenure than because they are valid or have led to real understanding. Sources such as Cummings (2012) and Nielsen (2012), Reinhart (2015), and Silver (2012)—as well as a great many others—discuss remedies to our statistical woes, but we also need to keep in mind that controlled studies do not apply to complex systems and, often, when we study people in teaching and learning situations—not least in classrooms—we are, in all likelihood, studying a complex system in the technical sense.

3.3 A Theory About Science as a Form of Life

I will use the word "framework" for an interconnected set of ideas from which a person draws conclusions about the world. Depending on context, the word "framework" can be replaced by a great many other terms: theory, model, perspective, folk theory, mental model, cultural model, discourse model, figured world, and others.

We live today in a world where people with different frameworks, stemming from different families, educational backgrounds, communities, religions, cultures, institutions, and nations, not only disagree with each other but too often dismiss, denigrate, or even seek to harm others with different frameworks. Since people often cherish their own frameworks, they are not only reluctant to change them but even to discuss them with people who disagree with them for fear they will lose their faith in what they cherish and need.

In a world like the one we live in today, there is a pressing need for teachers who know how to teach people, young and old, to care about and learn from what I will call "reflective discussions" (Popper, 1994; Soroush, 2000). Such discussions involve people respectfully discussing differing frameworks on important issues. The goal of such discussions is not to convert other people to "our side." It is not even to reach truth in the short run.

The goal is for each party to such discussions to come—over time—to understand their own frameworks better, be better able to argue for them at a conscious level, and maybe modify parts of them as they learn from others. The goal is also to appreciate the overall shape of other people's frameworks, not just as isolated claims but in the contexts of their lived experiences. The ultimate goal is to test whether people, over time and with good will, can gradually converge, even if only partially, on frameworks that lead to a better world for all people and, indeed, all living things (because all of us living beings are in this together).

What stands in the way of reflective discussions is the view, common on the right and left politically, that the goal of argument is to show someone else that they are wrong (and even stupid or evil). This does not work well to move people closer together and certainly not to recruit them to a common cause. Reflective discussions are based on thinking about truth not as a final destination, which we frail humans will reach any time soon (or even ever), but as a journey where, over the long haul, we may gradually converge on truth or, at least, a better form of life with each other.

Reflective discussions also crucially require that people respect the world in the sense that they seek to test parts of, or all of, their frameworks by acting in the world and paying respectful attention to what world "says back" to their actions. The world that speaks back to us may be the natural world or the world of other people and social interactions.

Respectful attention to the how the world "talks back" means two things: first, asking honestly whether the results the world gives back to our tests (actions followed by reflection) really support our beliefs and values and, second, consulting with other people who differ from us in regard to how they assess the world's response to similar sorts of actions (this is one way to counter confirmation bias).

This is just what "evidence" really means and it is basically the process that science formalizes. Again, the goal is not to prove someone—even yourself—right or wrong, once and for all, but for each of us to improve our frameworks in terms of the quality of our own lives and those of others with whom we share this planet.

If people do not respect the world's responses to their actions and beliefs, they cannot really have a reflective discussion with others because they are not open to change. And, too, the response of others to us in reflective discussions is also aspects of the world "talking back." These others, like us, were developed by the society and world in which we all live. One way or another, their frameworks are reflections of and insights into that society and world.

I am not saying that we should never criticize and never agitate against what we see as error or evil. But we can hardly understand other people's frameworks deeply enough to criticize them if we have not respectfully listened to them and reflected fairly on their frameworks. Furthermore, none of us are in possession of anything like any final truth.

People who have enough goodwill to commit themselves to reflective discussions and to respecting the world and other people's responses to their actions are what I will call "committed testers." Such people realize that all frameworks and all cultures have flaws. As the Iranian philosopher Abdolkarim Soroush (2000) has said, "…each culture must disavow certain elements of itself." Soroush also captures well what it means to be a committed tester:

> We can have two visions of reason: reason as destination and reason as path. The first sees reason as the source and repository of truths. The second sees it as a critical, dynamic, yet forbearing force that meticulously seeks the truth by negotiating tortuous paths of trial and error. (pp. 89–90)

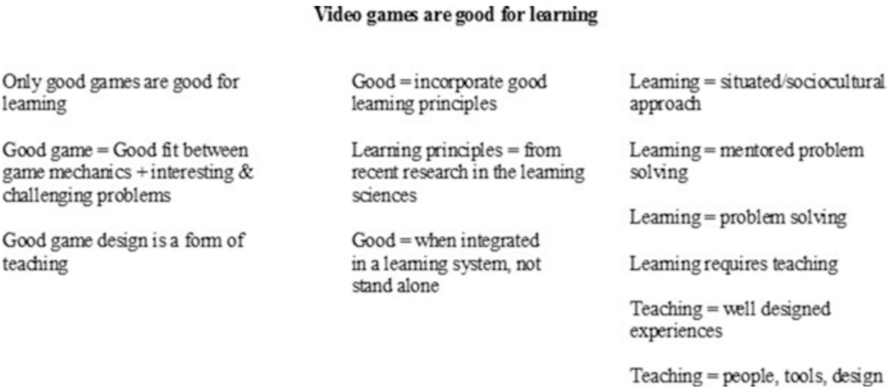
Let me say at the outset that though some may claim science education as we know produces committed testers, it does not or we would not be in the mess we are currently in. At the least, I would like to see studies that show science education transfers to civil and civic argument and discussion (Sadler, Barab, & Scott, 2007). What I am going to argue here is that teaching people to be committed testers means engaging science with public life and getting people to see that science just formalizes in certain areas what is, in fact, a much wider commitment to a "form of life" that respects evidence, critical discussion, human frailty, and uneven progress to (little "t") truth.

3.4 Comparing Frameworks

Meaningful reflective discussions across different frameworks in science, religion, politics, or culture are not about vetting individual claims (Popper, 1994; Soroush, 2000; Quine, 1951). They are about testing whole frameworks (all the claims in them as interrelated claims) against different ways of talking about and looking at experience.

In a reflective discussion, we need to discuss and compare networks of claims that support each other, not a single claim out of the context of its supporting framework. We do not, for example, want to know whether someone thinks abortion is (or is not) murder. Rather, we want to get at the whole network of ideas, values, and knowledge claims in which this belief resides and from which it gets its meaning and support for a given person.

Let me give a specific example of what I mean when I say that we do not test our frameworks claim by claim but only in terms of a whole set or system of interrelated claims that compose the framework. For years now, one area in which I have worked is on the affordances of video games for good learning (Gee, 2007). I have made the claim that "video games are good for learning" (in and out of school). But this claim is one part of a set of claims that make up my framework (theory) about games and learning (Gee, 2011). Here is a simplified picture of my framework (really this be learning and teaching):



Video games are good for learning

Only good games are good for learning

Good game = Good fit between game mechanics + interesting & challenging problems

Good game design is a form of teaching

Good = incorporate good learning principles

Learning principles = from recent research in the learning sciences

Good = when integrated in a learning system, not stand alone

Learning = situated/sociocultural approach

Learning = mentored problem solving

Learning = problem solving

Learning requires teaching

Teaching = well designed experiences

Teaching = people, tools, design

When people do research to test my claim that video games are good for learning, they often have the view that science is about testing claims one by one to see if they are "true" or "a fact." But imagine someone argued that they had shown my claim to be false based on evidence from their research. My claim is connected to a whole set of other claims. Faced with their evidence, I can change or adjust any one or more of these other claims and keep my claim that video games are good for learning. Perhaps I will say that the game they tested was not a "good game." Even if it was, I can modify my definition of "good game." I can adjust any of my claims or their relationships in my framework in a myriad of ways.

Any statement in my framework could have been bolded as the one people wanted to test or discuss, but things would still work the same. Any one statement brings all the others with it, and the results of any test can be spoken to by a myriad of different adjustments. All we can ever do—in science, religion, politics, or culture—is honestly look at our frameworks (or have critics do it), draw logical consequences from the claims in our frameworks, and then ask ourselves honestly whether these consequences are good for our purposes and good for the world we share with others.

3.5 Clashing Frameworks

Words in our critical discussions of frameworks with others need to be interpreted. And that interpretation requires effort, education, and the realization that interpretation is a social—and, yes, historical and political—act. The study of language, culture, history, texts, and interpretation should be at the very heart of the education of any citizen in a society that wants to stay both civil and free. The humanities are core to the study of interpretation, but educational reformers have left the humanities withering in the dust in contemporary America and much of the rest of the world in the favor of "STEM." The results are predictable.

I want now to discuss an example of what happens when frameworks clash, and there are no reflective discussions to mitigate this clash (see Gee, 2014 for the data). Years ago, I worked in the town of Worcester, Massachusetts. Worcester is a fascinating place. It has been a town since long before the USA became an independent country. For hundreds of years, Worcester has defined itself against Boston (the bigger, more prosperous, and prestigious city near it). In the colonial era, Worcester was "free soil" (opposed slavery and the return of escaped slaves), while Boston was much more tepid in these matters.

By the early twentieth century, Worcester was a successful industrial working-class town. Its population was a mix of nineteenth-century "white" immigrants (from places like Poland, Russia, Ireland, and other parts of Europe) and African-Americans whose families went back to the Underground Railroad (the secret routes and waystations to freedom from slavery). This population "melted" (as in the "melting pot") into "Americans" primarily by becoming common citizens of Worcester first and foremost. Many teachers in Worcester's public schools had used teaching as a way to enter the middle class from working-class family backgrounds.

By the 1970s, Worcester's industrial base was beginning to decay, a victim of the outsourcing of jobs. A once vibrant working-class community became financially depressed. Furthermore, the population of Worcester was fast "browning" due to a new wave of immigration from Asia, South America, Mexico, and the Caribbean. The teachers in the public schools, themselves a product of immigration, viewed the "brown" children in their classrooms as "Worcester kids" and felt it was their job to help them become citizens of Worcester and, thus, in that sense, to "melt" as had their own families.

Worcester has a number of good colleges, and some years ago, there was a project in one of them where university history professors and middle-school public school teachers worked together to design and teach a new history curriculum based on students engaging in local oral history. I was part of a team facilitating the meetings between the professors and teachers and also involved with studying their discourse practices (Gee, 2014).

The project went on for many meetings, and eventually a curriculum was made and taught. However, the meetings were often contentious. From interviews, it became apparent that the professors thought the teachers were racists and the teachers thought the professors looked down on them and did not trust them. At one meeting, a professor asked a teacher if she had much diversity in her classroom (which was, in fact, made up of white, Asian, South American, Mexican, African-American, and Caribbean students). The teacher said, "No, they're all Worcester kids."

The professors wanted the middle-school kids to study their own neighborhoods (so, e.g., a Vietnamese student would engage in oral history within a largely segregated Vietnamese neighborhood, which not so long ago had been, perhaps, a Polish neighborhood). The teachers wanted students to focus on the downtown of Worcester ("the center") and the people who went there from the socially and culturally diverse neighborhoods of Worcester. The professors and the teachers never overtly discussed their conflicts or the possible sources of those conflicts. Eventually we noticed, however, that over the course of many meetings, the professors had used the words "diverse" and "diversity" many times, but never used words for having things in "common." The teachers, on the other hand, rarely used the word "diversity" but often used terms for having things in common as citizens of Worcester.

It became clear that the professors and the teachers brought two different frameworks to the meetings. Of course, people do not normally formalize their frameworks in explicit claims, and so I cannot know the full details of their frameworks. However, as a discourse analyst, based on various sources of data, I can make hypotheses about their frameworks, given how the professors and teachers talked, interacted, acted, and expressed values.

Here are simplified versions of the two different frameworks:

Professors

1. Honoring diversity is the primary goal in schooling.
2. Diversity is defined in terms of race, class, and gender, but with a primary emphasis on race.
3. Stressing commonality over diversity is a form of colonization.
4. Failing to orient to a child's race or ethnicity is a form of racism.
5. Academics have privileged insight into the politics of race and diversity.
6. Larger macro-level power structures systematically victimize "people of color," thereby severely limiting their agency at a local level.
7. Larger macro-level power structures are where the important causes and effects actually happen though most people do not have the insight or knowledge to see this or really understand it.
8. Diverse neighborhoods should be the focus of Worcester, not the downtown, which is possibly unsafe anyway.
9. Teachers and the American public in general are not sophisticated intellectually or politically.
10. Teachers are locally focused; academics are nationally and globally focused.

Teachers

1. Honoring commonality is the primary goal of Worcester public schooling.
2. The earlier "white" immigrants (their own families) "melted" into being co-citizens of Worcester, and the new "brown" immigrants need to do so too.
3. One key goal of schooling is to make students become citizens of Worcester.
4. Placing children in large social groups effaces their individuality.
5. Teachers are there to teach individual children not "abstract" groups.
6. Class is more central than race or ethnicity in terms of people failing to get ahead.
7. The primary causes of people's success and failure are at the local level and a matter of their individual agency.
8. In a community where new immigrants are poor and often (the teachers believe) have dysfunctional families, teachers must not just teach but nurture the children as individuals.
9. The downtown of Worcester needs to be a focus for everyone because that is where all the people of Worcester used to come together as citizens of Worcester. It needs to be revitalized.
10. Though college professors teach, they are not teachers.
11. Academics live in an ivory tower and do not know what is going on "on the ground."

Note that it will not do much good to pick one claim and ask whether it is true or pick one word and ask what it "really" means. This is so because each claim and each key word is inextricably linked to many of the other claims and words in each framework. It is not surprising that the professors felt the teachers were hiding things or even lying and the teachers felt the professors looked down on them and attributed racism to them.

What might have happened if the participants in this project had seen the value of a reflective discussion comparing both frameworks in their entirety, with the goal not to convince each other or settle in any final way a given claim or word meaning? The goal would have been for each party to come to a better understanding of their own framework, learn better ways to argue for it and explicate what it means, face new questions, and discover what parts of their framework, if any, they want to change or reformulate.

Each party to such a discussion would respect evidence in the sense of how the world reacts to what they do and say when they use their framework in the world. In the end, they would all settle not for final truth or conversion but for the possibility that transformed frameworks may gradually evolve and at least partially converge, in the course of critical discussions based on goodwill, toward frameworks that are truer, deeper, and more collaborative toward some common good.

I have said several times that what is required for such critical discussions is goodwill. But now we reach our final question: what could possibly be the source of goodwill in our politically, socially, religiously, culturally, and ideologically fractured country and world? Goodwill is precisely what is often missing in highly unequal societies. I do not know the final answer to this vexed question. I do know that the place to start is good teachers and good teaching in and out of school.

3.6 Collective Intelligence

Readers may well wonder now what all that I have said has to do with science and science education. Being what I have called "committed testers" is the basic form of science as a form of life. Without it, there is little point in learning science at all. As we have seen this, basic form of science as a form of life applies to all empirical matters (any situation in which the world has "opinions" when we put our beliefs to work in it as actions). "Empirical" does not mean "establishing facts"; it means "respecting the world's responses and actively countering confirmation bias."

Science as a form of life—in its basic form or in its specific formalized disciplinary forms—today involves something new. Lots of research today has shown that in the face of complex systems and "hard problems," individual siloed expertise is dangerous (Harford, 2011, 2016; Jenkins, 2006; Weinberger, 2012). Such experts too often over-trust what they think they know and ignore what they don't. They too often exist in their own echo-chamber silos engaged in a kind of "groupthink."

Lots of different methods have been developed today to help people (scientists and others) engage in collective intelligence of different sorts (Brown & Lauder, 2000; Leimeister, 2010; Levy, 1999; Nielsen, 2012; Surowiecki, 2004). Any collective intelligence situation pools people with diverse frameworks and skills together and networks them with smart tools so that the group behaves more intelligently than anyone in it could alone. Often such groups require each individual to have deep and specific skills and knowledge to be able and ready to pool these with other people's deep and specific—but different—skills and knowledge. Furthermore, each individual in the group must share an understanding of the big picture in which they are mutually involved and must understand each other's skills enough to be able to keep in synch with them in service of a larger goal. Such groups are sometimes called "cross-functional teams" and are common in modern workplaces, scientific endeavors defined around hard problems or challenges and not a single discipline, and in multiplayer video games (e.g., *World of Warcraft*).

I cannot detail here the large amount of important emerging work on collective intelligence. But interesting findings are coming at a fast pace. For example, Anita Woolley at Carnegie Mellon and Thomas Malone at MIT (Woolley & Malone, 2011) have found that just putting smart people in a group does not make the group smart. They found three factors that significantly predicted a group would be smart. These three factors were (1) the social perceptiveness of the group members, that is, their ability to judge what other people are thinking and feeling; (2) the evenness of conversational turn taking, with no one person dominating; (3) the percentage of women in the group.

The last factor is interesting, indeed. Woolley and Malone found that more women did not mean just some men and some women. Rather, having some women was better than having none, and all women groups were the best of all. They are not sure why this is so, but it may well be due to the fact that, on average, women score higher on measures of social perceptiveness than do men.

It has been argued more generally that the sorts of social intelligence and networking skills many women tend to have are particularly important in the modern world where individual "go it alone" expertise can be dangerous (Newton-Small, 2016). Some have even argued that the 2008 recession was brought on, in part, by the testosterone-fueled, high risk-taking behaviors of young male stock brokers and hedge fund managers (Coates & Herbert, 2008; Newton-Small, 2016). Things might have been different had there been more women involved or, at least, more collective intelligence drawing on a wider array of skills, perspectives, values, and backgrounds.

Current work has shown that even people who dislike or distrust each other—or feel divided in different ways—can people together and rise to the occasion if they face a mutual challenge which can only be overcome if they all pull together. Sebastian Junger in his book *Tribe: On Homecoming and Belonging* (2016) points out that:

> Humans don't mind hardship, in fact they thrive on it; what they mind is not feeling necessary. Modern society has perfected the art of making people not feel necessary.

In his book, Junger tells stories of people who found a greater sense of belonging amidst disaster than they did living in modern affluent societies. For example, when Serbia attacked Bosnia and laid siege to Sarajevo, its capital, nearly 70,000 people were killed or wounded, about 20% of the population. People were without food and water and witnessed violence daily. Conditions were horrific. Yet one woman, talking about Bosnia after the war had ended, told Junger:

I missed being that close to people, I missed being loved in that way, … In Bosnia—as it is now—we don't trust each other anymore; we became really bad people. We didn't learn the lesson of the war, which is how important it is to share everything you have with human beings close to you. (pp. 69–70)

When Junger asked this woman if people had ultimately been happier during the war, she said "We were the happiest, … And we laughed more." Junger also points out that someone spray-painted on a wall—about the loss of solidarity in Bosnia after the war ended—the slogan: "It was better when it was really bad."

Far from being untypical, researchers have repeatedly found that when humans face an existential crisis from wars or natural disasters, they don't fall apart but pull together. Their health often gets better and those suffering from mental illness improve. Again, to quote Junger:

As people come together to face an existential threat, Fritz found, class differences are temporarily erased, income disparities become irrelevant, race is overlooked, and individuals are assessed simply by what they are willing to do for the group. It is a kind of fleeting social utopia that, Fritz felt, is enormously gratifying to the average person and downright therapeutic to people suffering from mental illness. (pp. 53–54)

And now we get some good news: we all *do* now face an existential crisis as humans. My proposal is just this: school science should be about creating committed testers—people committed to science as a form of life in its basic and most important sense. In this sense, every “subject matter” in school is ripe for science. And, too, this “curriculum” is the only sane one in a world facing an existential crisis where we must—struggle though it will be—pull together.

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Chapter 4
Writers in Community Model: 15 Recommendations for Future Research in Using Writing to Promote Science Learning

Steve Graham

When housecleaning the other day, I came across four issues of *National Geographic*. As I considered what to do with them, I was once again reminded of the prominent role that science plays in the world today. The cover of each magazine screamed science: the new science of the brain, the science of death, the new science of solving crimes, and the new science of marijuana. The term "new" in many of these articles highlighted the explosion in scientific methods, technology, and knowledge, emphasizing this is not likely to subside any time soon.

The rapid advances in science present a formidable challenge for schools and science education in particular, as educators must decide what should be learned as well as when and how it should be acquired. These decisions are directly linked to goals to develop students who are scientifically literate, allowing them to understand how science operates, engage in critical discourse about science and scientific findings, and make informed and reasoned judgments about ethical, moral, and social issues involving science (American Association for the Advancement of Science, 1993; National Research Council, 2012). They are also driven by a desire to develop students with an interest in science who are able to engage in the scientific process.

The National Research Council's (Duschl, Schweingruber, & Shouse, 2007) *Taking Science to School* captures these goals by emphasizing that science education should help students "generate and evaluate scientific evidence and explanations" and "participate productively in scientific practices and discourse" (p. 2). This requires that students enter into new and different ways of thinking and reasoning (Driver, Asoko, Leach, Mortimer, & Scott, 1994).

A key dilemma that bedevils science educators is how to meet these goals. Recommendations include directly teaching science, learning science through

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*,
Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_4

observation and interaction, inquiry-based research projects of interest to students, and the use of authentic science learning experiences to name a few of the methods championed by different groups (Goldman, 1997; Moje, Collazo, Carrillo, & Marx, 2001; Rappolt-Schlichtmann et al., 2013). As is often the case in education, one approach is preferred over another by some experts, even though evidence to support claims of differential effectiveness is notably absent or weak.

One possible means for enhancing students' science learning is writing. Writing experts contend that writing about difficult content material can help students gain a better understanding of it, think critically about it, and construct new knowledge from it (e.g., Klein, 1999). Some science educators and researchers agree (e.g., Hand, 2008; Rivard, 1994). This has resulted in a small but expanding body of research examining the use of writing to support science learning in the classroom.

The goal of this chapter is not to conduct a systematic review of the research already conducted but to consider future research needs and directions. I use a newly developed model of writing (Graham, 2018a) to shape my analyses and recommendations. Before turning to this task, I briefly consider if writing does show promise as a tool for supporting science learning in education. This provides the gist for three atheoretical recommendations. Twelve additional theoretically based recommendations are then provided, bringing the total to 15. Because of space limitations, I do not cite past studies that addressed one or more of my recommendations. None of the proffered recommendations, however, have been investigated adequately or extensively.

4.1 Does Writing Support Science Learning?

In 1994, Rivard conducted a qualitative synthesis of the research on writing to learn in science. He examined a variety of different types of studies conducted with school age as well as college students, including case studies, descriptive research, and experimental investigations. He concluded that students using "appropriate writing-to-learn strategies are more aware of language use, demonstrate better understanding and recall, and show more complex thinking about content" (p. 975). He tempered these conclusions by noting that studies testing writing to learn in science were not always well-designed, reported, or conducted in real classrooms.

A decade later, Bangert-Drowns, Hurley, and Wilkinson (2004) conducted a quantitative meta-analysis on writing to learn across content areas, which included science. In contrast to Rivard (1994), they limited the studies they reviewed to true or quasi-experiments conducted in school or college classrooms. They located seven studies that yielded an average weighted effect of 0.32 on measures of content learning. The effects varied considerably for individual studies, however, ranging from 1.48 to −0.77, with only 57% of studies producing a positive effect.

As part of Graham and Perin's (2007) meta-analysis of true and quasi-experiments, seven studies with students in grades 4–12 were located that tested the effectiveness of writing to support science learning. These classroom-based studies produced a statistically significant average weighted effect of 0.18 on measures of content learning. Again, there was considerable variability in effects, and only 57% of studies produced a positive effect.

A final meta-analysis by Graham and Hebert (2011) examined if writing about material read enhanced comprehension of said material. Thirteen of the studies involved writing about science text, and all but one of the studies produced a positive effect. The average weighted effect size of 0.36 was statistically greater than no effect.

These four reviews provide support for the claim that writing can support science learning, but the effects are generally small, and the reliability of the point estimates in the meta-analyses must be viewed cautiously given the small number of studies. It is important to note these reviews did not include all available studies assessing the impact of writing on science learning. For example, the two meta-analyses by Graham and colleagues (Graham & Hebert, 2011; Graham & Perin, 2007) were designed to isolate the effects of writing on reading comprehension and learning, respectively. As a result, they did not include studies that compared the impact of different writing to learn activities, such as research conducted by Hand and colleagues (Hand, Hohenshell, & Prain, 2007) comparing his writing science heuristic to other writing activities. Of course, these reviews did not include studies published after they were conducted (e.g., Gillespie, Graham, & Compton, 2017).

Recommendations Based on these four reviews, I recommend:

1. A new meta-analysis examining the impact of writing on science learning is needed, as the last one was conducted 10 years ago (Graham & Perin, 2007). Such analyses should occur periodically to match the pace of research in this area.
2. Additional research examining the impact of writing on learning is needed as the database is relatively sparse. This research needs to include stronger studies (randomized control trials) that compare the effectiveness of different types of writing activities on science learning, including studies that not only isolate the effectiveness of a specific writing activity but further isolate the role of writing as the active ingredient in promoting learning.
3. Researchers need to explore how to make writing to learn activities in science even more effective, as the impact of such activities led to important but small gains in the meta-analyses reviewed above.

4.2 Writers in Community Model: Implications for Writing and Learning in Science

The scientific enterprise centers on developing and testing theories. Theories in turn give rise to useful frameworks for generating and testing hypotheses. As a result, theories provide a useful tool for considering the direction and nature of future research in a particular discipline. I use this approach here, as I draw on a recently developed model of writing (Graham, 2018a, b) to generate additional recommendations to guide future research on using writing to support science learning.

The Writers in Community model (Graham, 2018a), used to guide my recommendations, reflects both sociocultural and cognitive perspectives on writing. The model not only describes the act of writing in context, but it identifies the factors that shape and foster its development. The basic tenet of the model is that the community in which writing takes place and the cognitive capabilities and resources of those who create writing simultaneously shape and constrain the creation of written text. This concept of complementarity assumes that different approaches (in this case sociocultural and cognitive perspectives), each useful and internally consistent, can be used to more fully and accurately describe a single system such as writing.

It is important to note that my task of deriving theory-based recommendations could be based on a number of different models, including models of learning in science, learning in general, or other models of writing. I do not assume that there is one best model or theory of writing or learning but echo Mitchell's (2003) contention that alternative conceptualizations can be productive, facilitating dialogue and new ways of thinking within a discipline. I am hopeful others will apply this sentiment, using different models to guide the process I am engaged in here. In using the Writers in Community model for this purpose, I focused and expanded it at points (see particularly the section entitled **Production Processes**) so that it more directly addressed the task at hand – using writing to support science learning.

4.3 Writing Community

The Writers in Community model is based on the assumptions that writing is a social activity, situated within the context of a writing community (see Fig. 4.1). The idea of community in this model draws on the concept of activity theory (Lave & Wanger, 1991), where one or more people aim to accomplish a desired goal through the use of specific tools and regular and reoccurring patterns of activities. It also draws on Bazerman's (1994) concept of genre as typified ways of engaging in activities for social purposes.

According to Graham (2018a), a writing community involves one or more people using writing to accomplish specific purposes, such as a science classroom using writing to assess or facilitate learning. As this example illustrates, writing does not have to be the only or even the most central goal of the community. Consequently, a writing community in a science classroom is nested within other communities, such as science classroom itself, the school, district, and so forth, much as wooden Russian nesting dolls of decreasing size are placed one inside the other.

A single person can and likely does participate in many different writing communities, which can vary in size and purposes, ranging from a single writer acting as both author and reader as when writing a personal diary to much larger communities such as a fan fiction website. Writing communities also vary in terms of

Fig. 4.1 Basic components of a writing community

accessibility, as some are restricted such as a typical college writing class, while others are more inclusive, such as the same class offered as a MOOC.

Members At the heart of a writing community are its **members**. Members can produce writing, help others do so, or serve as readers. Some writing communities include individuals who act as a teacher or mentor, such as a teacher in a biology class, helping other members use or acquire needed writing skills to meet the purposes of the community. How power is distributed in writing communities and the status of members vary as well. For example, a writing community can have a hierarchical structure as is common in a science classroom, or it can be more horizontal as when students voluntarily come together to act as a sounding board for each other's writing. Likewise, members within a writing community can differ in terms of their roles and responsibilities; familiarity with the purposes and practices of the community; and their level of commitment, identity, and affiliation and value to said community. To illustrate, one student in a science class may readily accept her role and identity as a student, considers herself a valued and informed member of the class, views herself as a competent learner and writer, and welcomes the chance to learn more about science. In contrast, another student may place little value on her role and identity as a student, feels that she is not viewed as a valued or knowledgeable member of the class, believes she is a poor student and writer, and is generally ambivalent about science and learning more about it.

Purposes Writing serves particular **purposes** within a writing community. In a writing community situated within a science classroom, for instance, purposes for writing are shaped by four factors: (1) goals (e.g., assess science learning and facilitate science learning), (2) norms and values (e.g., stress brevity and accuracy when writing about science), (3) stance/identity of the community wants to project (e.g., values writing as a means for thinking about science), and (4) audience (e.g., share what is written with teachers, peers, and sometimes individuals outside the science classroom). Accordingly, the purpose of a writing community can be singular as when a science class only uses writing to assess learning or it can be multifaceted as is the case when writing is used not only to assess learning but as a tool for generating hypothesis, recording observations, and fostering reflection. Even in seemingly similar writing communities then, such as two tenth grade chemistry classes in the same school, the purposes for writing may not be the same, as there are likely to be some differences in the two teachers' writing goals, norm/values, stance/identity, and intended audiences.

Tools Writing cannot be accomplished in science classrooms or other writing communities without **tools**. There are now multiple modes for writing. It can be produced by hand, dictation, typewriter, word processor, or speech synthesizer to name some of the more prominent options. Some digital tools also make it possible to acquire information through the Internet, share writing broadly, and produce text that combines written, verbal, and visual information. Writing tools influence how writing is used in a community. For instance, if students write by hand, as is the case in many science classrooms (Kiuhara, Graham, & Hawken, 2009), this may restrict potential audience as sharing writing outside the classroom becomes more difficult. While writing on a computer with an Internet connection greatly expands audience options, the utility of this tool depends on the writer's facility with it (see, e.g., Wolfe, Bolton, Feltovich, & Niday, 1996). It is also important to note that some writing tools can act as a collaborator by directly assisting the writer, as is the case with spell and grammar checkers. It is important to note that writing tools can both facilitate and hinder writing, as when feedback is inaccurate.

Actions A writing community then involves a group of people (**members**) who use writing to achieve their **purposes** using one or more writing **tools**. These writing purposes are accomplished through **actions** or typified practices that members of the writing community engage in to define the writing task; structure the writing environment; distribute responsibility; carry out the process of composing; as well as manage the social, motivational, emotional, and physical aspects of writing. To illustrate, a science class may develop a typified pattern of practice to use writing to generate one or more written hypotheses when conducting an experiment, take notes as the experiment is conducted, revisit and revise initial written hypotheses as needed, and write a brief on how the results of the experiment do or do not fit with their previous conceptions. As Graham (2018a) noted, such typified patterns of action are best viewed as temporary structures, subject to change as new circumstances and needs arise. This means that the writing actions of a particular writing community, such as a science class, are not sealed shut but are flexible and permeable.

Written Products As members of a writing community engage in typified actions and practices, they produce **written products**. This includes completed text and not fully completed text as well as other tangible artifacts such as notes, drawings, and figures produced by the writer and their collaborators. They also include source material including text, pictures, and film. When writing in science classes, these products can further include the apparatus and materials used to conduct an experiment as well as the tangible effects of an experiment. Written products can reside physically within the writing community or in a digital environment.

Collective History and Physical/Social Environment To summarize so far, one or more **members** of a writing community accomplish specific writing **purposes** using writing **tools** and **actions** to create the desired **written product**. This does not occur by happenstance but is shaped by a **collective history** and the **physical/social environment** in which writing takes place. As a writing community in a science classroom operates over time, for example, its business becomes codified. The types of writing it conducts, its intended audiences, and how writing is used and conceptualized become more defined. Specific methods for writing as well as certain writing tools become preferred, and members of the classroom community develop specific identities, roles, and responsibilities. While this collective history shapes the purposes, actions, beliefs, behaviors, and writing tool used by the class, it is open to change as the narrative underlying the history and purpose of such a writing community are open to change (as we shall see later in the chapter).

Finally, writing can occur in almost any physical place where people congregate (e.g., homes, classrooms, or offices) or in any digital locale where text can be produced (e.g., email, Facebook). Locale can impact a writing community in many ways, including the number of community members that can be present at a given time, the types of writing tools available, and how writing is executed. Similarly, the social environment, which involves relationships between members of the community, can impact the work of a writing community. Social environments can be supportive, neutral, or hostile; pleasant or unpleasant; competitive or cooperative; controlling or self-governing; or any combination of these. In a science classroom, these factors may influence the social relationships among students and teacher, students' sense of belonging and affiliation, stereotypical beliefs students and teachers hold about each other, and how the teacher and students perceive power and autonomy.

Interactions and Complexity While I have presented the seven interacting features of a writing community separately (i.e., members, purposes, tools, actions, written products, collective history, physical/social environment), they do not operate in an isolated or separated fashion. Instead, each feature can influence the other (e.g., introducing new writing tools into a community can influence purpose, membership, and so forth). As a result, writing communities, even ones in science classrooms, involve considerable variation in terms of type and operation. Even within a specific writing community, such as a sixth grade science class, contradictions, disparate elements, conflict, and multiple voices ensure that heterogeneity exists (Swales, 1990). Graham (2018a) stressed the use of structural elements to define writing community, does not imply permanence. Writing communities are not static entities but are continually emerging.

Recommendations Based on the conceptualization of writing community presented above, I offer the following recommendations for future research:

1. Greater emphasis needs to be placed on context in research involving the use of writing to learn in science. For example, intervention studies in this area need to more fully describe the context in which they are conducted. Or in other words, context should not be treated as background noise with little to no relevance to the findings of a study.
2. Little is currently known about how writing communities operate within science classrooms, including purposes and types of writing undertaken, how teachers and students accomplish these purposes, what tools they apply, how they interact with each other and their audiences, the physical space in which they operate, or the standards and norms that guide their writing. As a result, research is needed to determine how writing communities in different science classrooms are enacted, operate, and change over time in order to identify common and disparate themes within and across classes and within and across students and teachers. Such scholarship will provide a better understanding of how writing is used in science classrooms, providing valuable information for any future efforts designed to make writing to learn more common and effective in science education.
3. Because of the rapid development of new tools for composing, there is a need to investigate if they can be used to facilitate science learning. For example, Rappolt-Schlichtman et al. (2013) reported positive effects for a web-based science notebook that provided supports for recording, organizing, analyzing, and interpreting data during active science learning. The development, application, effectiveness, as well as the limitations of such new tools require greater research attention, as they may make writing and science learning more accessible to all students.
4. Research is also needed to better describe and determine the impact of autonomy and power, roles and responsibilities, as well as commitment, identity, and affiliation. For example, students may be more committed to using writing to support learning if they have some voice in how it is applied, have meaningful roles in its application, and operate in a class that values writing and views all members as capable writers and learners. Likewise, how science teachers view and address these factors will surely influence the operation and success of a writing community in a science class.

4.4 Writers and Collaborators

The Writers in Community model (Graham, 2018a) assumes not only that writing is shaped by the community within which it takes place but that writers and their collaborators exert individual and collective agency over what they write in those contexts. In other words, writing is further shaped by the individual actions and cognitive resources of writers and collaborators within the community. For example, when a student is asked to take notes about a chapter in their science class as a homework assignment, she must decide if she will undertake the task, and if so, how much effort to commit, what writing tools to use, how notetaking is to proceed, and the conditions under which the work is executed. Graham proposes that these decisions are driven by the student's beliefs (e.g., how much they value the task), emotions, personality traits, and physical state as well as the cognitive resources she can draw upon.

As the example above demonstrates, writers make a variety of decisions that influence the degree to which they engage in writing and how the process of writing unfolds. The cognitive resources writers and their collaborators bring to the task and draw upon are not benign but bound as well as enable what they can do. The Writers in Community model (Graham, 2018a) is based on the assumption that writing is a cognitively demanding task, and limitations in human's cognitive architecture constrain the process of writing. It also assumes that through participation in multiple writing and learning communities, writers and their collaborators acquire increasingly sophisticated knowledge about writing and the subject of their compositions (e.g., science), become increasingly proficient at the processes of producing text, and establish greater control at harnessing and regulating their attentional and processing capabilities, beliefs, emotions, personality inclinations, and physical states in the service of writing.

In thinking about how cognitive architecture constrains writers and collaborators, it is first useful to consider how difficult writing can be. Even with skilled adult writers, this complex skill does "not simply unfold automatically and effortlessly in the manner of a well learned motor skill...writing anything but the most routine and brief pieces is the mental equivalent of digging ditches" (Kellogg, 1993, p.17). Writing is challenging because it involves the execution and coordination of attention, motor, visual, executive functioning, memory, and language skills (Hayes, 1996). This work occurs within a cognitive system with specific limitations (Pass & Sweller, 2014). For instance, the cognitive processes we use to process information as we are engaged in an activity such as taking notes during a science lecture are limited by how much information can be handled at any given time (about seven elements at a time) and for how long (about 20 s without rehearsal). Likewise, while the amount of information we can retain about science over time is quite large, accessing this information is not always an exact or certain process, as many students can attest to when working on an essay response on a science exam.

In addition, if the cognitive actions writers or collaborators take requires conscious attention that exceeds the capacity of the human processing system, then the result is cognitive overload and interference (Pass & Sweller, 2014). To illustrate, consciously having to think about how to spell a word while writing a journal reflection following a science experiment can tax a writer's processing capacity, as ideas for the current sentence or even the next one being held in working memory may slip away as the student tries to figure out the unknown spelling.

Fortunately, humans are quite ingenious at devising ways of overcoming their cognitive limitations. With writing, for instance, we learn to carry out some production processes such as handwriting and spelling so that they can be done accurately, quickly, and with little cognitive effort. Writers also learn various tactics that are helpful for dealing with processing limitations. For example, when writing a report for a science class, a student may alter the nature of the task by dividing it into smaller tasks, such as developing a basic plan for the report and using this plan to guide the process of producing text. The teacher in the class may also put into play strategies for reducing possible cognitive overload, by distributing responsibility so that one student is in charge of gathering and organizing relevant information for the science report, two other students are charged with writing specific sections of it, and a fourth student is responsible for rewriting and polishing it so that it speaks with a single voice.

The structure of the cognitive architecture of individual writers (or collaborators), as presented in the Writers in Community model, is described next (see Fig. 4.2). It was influenced by previous models of writing (Hayes, 2012; Zimmerman & Risemberg, 1997) as well as current conceptualization of executive functioning

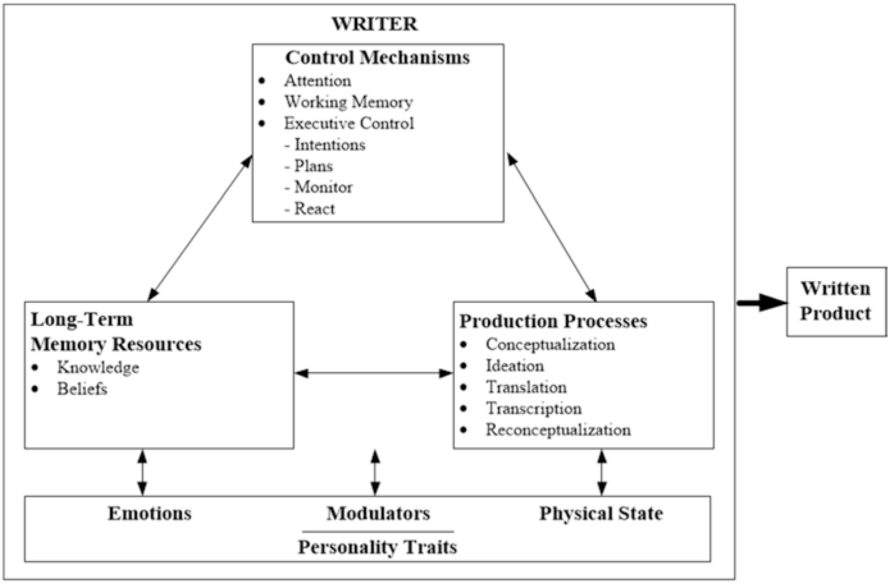

Fig. 4.2 Cognitive mechanisms involved in writing

(Jacob & Parkinson, 2015), motivation (Graham & Weiner, 2012), emotions (Boekaerts, 2011), and personality traits (Zeider & Matthews, 2012).

Long-Term Memory Resources While the resources that writers draw upon can and often do reside within the community (e.g., source material, peer's expertise), writing is also dependent on the richness of the long-term memories of those who produce it. It holds individual's beliefs and knowledge about the value of writing; expectations for success; interests and knowledge about the writing topic at hand; identities as a writer; beliefs and knowledge about various writing communities; knowledge and beliefs about one's emotional reactions and personality traits; specialized knowledge about writing and audiences; and knowledge about how to speak, listen, and read. For students in science classes, some of resources held in long-term memory involve knowledge about science and how to engage in science writing in particular classes as well as beliefs about these communities and writing within them.

According to Graham (2018a), writers and collaborators hold a variety of beliefs in long-term memory that can facilitate or hinder writing in communities such as a science class, as they influence whether one engages in writing, how much effort is committed, what cognitive resources and tools are applied, and how one interacts with other members of the class. This includes the perceived value, utility, and interest in the writing task under consideration; expectations for success; attributions for success or failure; and presumed value of writing as a tool for learning in said class. It also includes beliefs about one's assumed role, identity as a writer and learner, and potential success in this classroom.

What happens during writing is further enabled or constrained by knowledge writers and collaborators hold in their long-term memory. This includes (1) acquired knowledge about language and literacy; (2) specialized knowledge about writing (i.e., transcription skills, sentence construction, text purposes and features, processes for text production); (3) knowledge about the writing topic, the presumed audience, and possible writing tools and resources; and (4) knowledge about the writing purposes and practices of the community in which the writing task is accomplished. Richer pools of knowledge increase the chance that writers and collaborators are able to meet their goals and the writing goals of their community. For example, students with little knowledge of how to construct a report for a particular science class are at a disadvantage unless they acquire such knowledge as part of the process of completing this composition. Similarly, students with little knowledge about the topic of the science report are likely to produce an impoverished essay unless they acquire additional knowledge while writing it.

Production Processes These are the mental and physical operations writers use to create text. Production processes draw on long-term memory resources, such as topic knowledge, language, and specialized writing knowledge, as writers and collaborators construct a mental representation of the writing task (*conceptualization*), draw ideas for the composition from memory and/or external sources (*ideation*), take the most pertinent of these ideas and transform them into acceptable sentences (translation), commit the sentences to paper or digital print (*transcription*), and engage in the act of revision (*reconceptualization*). Engagement and persistence in applying production processes are further influenced by some combination of the beliefs writers and collaborators hold in long-term memory about the value/utility of writing, their capabilities as writers, motivations for engaging in writing, reasons for success, and identities as writers. Greater facility with these production processes enable writers and collaborators to better meet their goals and the goals of the writing community.

Learning in science can occur when writers and collaborators engage in the production processes described above (Applebee, 1984; Bangert-Drowns et al., 2004; Graham & Hebert, 2011; Klein, 1999). For example, writing about science ideas may promote personal involvement, as it requires that writers and their collaborators make active decisions about rhetorical goals, including what will be written, how it will be treated, what form it takes, and who is the audience (*conceptualization*). How the writing task is conceptualized shapes what is learned, as different writing tasks promote different types of thinking (e.g., paraphrasing versus writing an argument). When addressing their rhetorical goals (or the goals established by someone else), writers and collaborators must draw pertinent ideas (*ideation*) from an immediate experience (such as an experiment they are conducting), knowledge about science stored in long-term memory, or both. As they engage with these ideas, more elaborated and even new understandings may occur, as they decide which ideas are most important, explore relations between ideas, organize ideas into a coherent whole, or build conceptual frameworks. When writers and their collaborators commit their ideas to text (*translation* and *transcription*), additional understanding or learning may occur, as they are repeating science content which increases content exposure and time on task. The act of writing further involves transforming and manipulating language, as writers must put science ideas in their own words. This may force them to think more deeply about what an idea means or lead to new learning as they use language to express their understandings. Finally, the permanence of writing makes it possible for writers and collaborators to review, reexamine, critique, and think about science ideas committed to text (*reconceptualization*). This provides them with accessible additional opportunities to evaluate their understandings and possible confusions as well as generate new ideas, connections, inferences, and meanings.

Learning from writing can also be less direct. For instance, students in a science class can each be asked to share their written reflections from an experiment just undertaken. One or more students' reflections may lead other students to develop new science understanding.

Emotional, Personality, and Physiological Moderators Graham (2018a) proposes that writing can further be enabled or constrained by the unique emotions, dispositions, and physical state of writers and collaborators. These factors modulate or influence the working of other aspects of writing. A science student who experiences anxiety (an emotional state) about writing, for example, may judge his text more harshly than a student who is less anxious, affecting how he engages in the production process of reconceptualization. A student who is conscientious (a personality trait) versus one who is less so may be more likely to overcome low interest in writing when a science teacher assigns a writing task, whereas a tired, hungry, stressed, or sick student (physiological states) may have difficulty focusing attention when writing.

Control Mechanisms Three control mechanisms (attention, working memory, and executive control) enable writers and their collaborators to direct, maintain, and switch attention as needed when writing; make decisions about what is composed and how; regulate writing production processes and other aspects of writing (e.g., thoughts, beliefs, emotions, personality traits, behaviors, writing tools, interactions with collaborators, arrangement of the writing environment); and monitor, react, and make adjustments for all of these actions. When writing in a science class, for example, these mechanisms allow writers and collaborators to control and direct the act of writing and engage in cognitive actions such as planning, problem-solving, reasoning, drawing inferences, and making interpretations.

The control mechanism of attention allows writers and collaborators to choose where attention is or is not focused when writing. Working memory provides a limited and temporary storage system where information from memory and the environment are held and acted upon when writing. Executive control involves the processes of setting goals (formulate intentions), initiating actions to achieve them (plan), evaluating goal process and impact (monitor), and modifying each of these as needed (react). These four executive control actions can be applied to all aspects of the writing processes from initially conceptualizing the assignment to regulating thoughts and behaviors when writing to working collaboratively with others.

As noted earlier, the mechanisms underlying the human processing system are finite, and cognitive overload and interference can occur when the actions undertaken by a writer require conscious attention that exceeds the capacity of this system (Baddeley, 2000). This is complicated by individual variations in attention, working memory, and executive control capacities. For example, students who experience problems with attention and executive control are likely to experience greater difficulty learning to write than those without such challenges (Graham, Fishman, Reid, & Hebert, 2016), potentially reducing the effectiveness of writing as a tool for science learning for such students.

Interactions and Complexity Graham (2018a) notes that it is critical to keep in mind that the writing community and the cognitive architecture of writers and collaborators within the community do not operate separately. They interact and influence each other in complex ways. I provide an example here to illustrate this.

Take, for instance, the executive control mechanisms described above. They are not only used by writers and collaborators to direct and mange a writer's thoughts and behaviors, they are also used by them to direct and manage their work within the writing community. This can include using these control mechanisms to make decisions about collaborators, restructuring the writing environment, modifying the proposed purpose of a writing task, selecting new tools for writing, and changing the typical pattern for writing within the community. Of course, such decisions may not be possible in some writing communities, such as a science classroom where the teacher has specified exactly how the writing assignment is to proceed, what form it should take, and who works with whom.

Graham (2018a) further stresses that the cognitive resources and capabilities that writers and collaborators bring to the task of writing in specific writing communities are continually changing and evolving, As a result, writing communities and those who inhabit them, whether this involves a 12th grade physics class or friends on Facebook, will be characterized by complexity, heterogeneity, and transformation over time.

Recommendations Based on the conceptualization of writers and collaborators presented above, I offer the following recommendations for future research:

1. Because students are still developing as writers and science learners, more research attention needs to be given to how individual differences in writing skills and knowledge of science mediates the effectiveness of specific writing to learn activities. Assuming that science learning is mediated by these two individual factors, this could lead intervention researchers to design, develop, and test mechanisms for minimizing their impact (e.g., Rappolt-Schlichtmann et al., 2013).
2. Scholars need to develop a better understanding of how individual differences in beliefs, emotions, personality, and physiological conditions influence the effectiveness of writing to learn activities in science. One way of doing this is to examine the unique and collective contribution of these variables to predicting learning when writing to learn activities are applied in science. This approach can be widened by including additional predictors such as writing capabilities, science knowledge, reading skills, or gender. Conclusions drawn from such correlational research can be strengthened by conducting intervention studies designed to enhance a specific predictor, such as writing efficacy. If writing efficacy improves and there is a corresponding improvement in science learning, then support that one's confidence as a writer is an important ingredient in the success of writing to learn activities in science.
3. Limitations in human processing capabilities have led researchers to examine if interventions designed to enhance control mechanisms such as executive functioning result in improved academic learning. Although the results so far have not been especially promising (e.g., Jacob & Parkinson, 2015), such research is still in its infancy, and its impact on writing to learn in science should be explored.
4. Little research in writing to learn in science has focused on students with special needs or those at risk for school challenges due to trauma, language or cultural differences, or poverty. Research studying these children and writing to learn in science has the potential to provide new and important insights, as has been the case in other areas such as learning and memory.

5. A central tenet of the Writing in Community model is that writing is shaped and bounded by context, writers, and collaborators and the interaction between the two. Future research in writing to learn in science needs to place greater emphasis on studying this interaction. For example, how science teachers use writing in their classroom likely rests on their perceptions of students cognitive and motivational capabilities. Similarly, the success of a writing strategy a student decides to employ likely depends on how well it allows the student to meet the classroom purpose, stance, and norms/values. In fact, the study of what elements of a particular writing activity result in students' meeting the specified learning objectives in science are virtually nonexistent.

4.5 Promoting Writing Development

The Writing in Community model (Graham, 2018a) proposes that writing is shaped by the community in which it occurs and the capabilities of the writers and collaborators within this community. Neither of these, however, are a collection of fixed traits. Instead, each involves an unfolding and dynamic story of change. For example, writing in a teacher's science class changes from the start to the end of the year and from 1 year to the next, whereas the students who pass through these classes develop greater facility as writers with experience and time.

At the level of the writing community, changes occur as a function of shifts in the community itself, as will likely happen in a science classroom when a new teacher takes over or new tools for learning science or writing are introduced. Changes also occur as writing and other socially derived communities impact each other, as when students learn a new strategy for writing in English and apply it in their science class or the science teacher acquires new ideas for writing as a member of a professional development group. Writing communities are further shaped by larger macro forces, as is the case for teaching writing and science for states adopting the Common Core State Standards. The expectation was that writing would be used as a tool to support content learning in areas like science.

At the level of the individual writer, Graham (2018a) describes seven mechanisms that promote writing development:

- Learning by participating in a writing community and as a result acquiring the writing practices embedded in it
- Learning as a consequence of action where a writer applies a specific action and learns if it is successful or unsuccessful
- Learning by expansion where new writing knowledge or skills are acquired through participation in nonwriting activities such as reading
- Learning by observing where writers learn new writing skills or methods by observing other writers
- Learning from other people through collaborative writing practices, feedback, mentoring, or teaching

- Learning through deliberate agency by deliberately deciding to become a more skilled writer, apply what was learned in a previous situation or community to new ones, or build new ideas about writing within the context of old ones
- Learning through accumulated capital where new development as a writer serves as a catalyst for further development (e.g., as writers become more knowledgeable about writing, they value writing more and are more motivated to write, leading to more writing and new development as a writer)

Recommendations Based on the mechanisms of change described above, I offer the following recommendations:

1. A practical and compelling issue involves how to make writing communities more common in typical science classrooms, as writing occurs less frequently in science versus language arts or history (Kiuhara et al., 2009). An especially difficult challenge in studying how to bring to scale writing to learn practices in science is how to facilitate change that is both effective and welcome. One avenue that may be productive is to study science teachers that are particularly adept at using writing to support learning, examining how and why they employ such strategies and how their practices in doing so change over time. Studying teachers' knowledge about the use of writing to support science learning and procedures for increasing this knowledge is likely to prove fruitful too.
2. Relatively little research has focused on how to promote productive change in individual students' acquisition and use of writing strategies to support science learning. While each of the seven mechanisms for promoting writing development described above are supported by research in the general learning or writing literature (e.g., Graham, 2018a), we need to know much more about when, how, and in what combination they are effective in advancing students' skills at using writing to support science learning. It is further important to determine if writing to learn strategies acquired in one context transfer productively to another as well as how to facilitate such transfer.
3. More scholarly attention needs to be directed at how institutional, political, social, cultural, and familial factors influence the use of writing to learn in science, facilitating or hindering its use in classrooms and its effectiveness in promoting science learning.

4.6 Final Comments

It is relatively easy to proffer recommendations and directions for future research, but the ultimate value and utility of this practice depends on two factors: a sufficient number of researchers interested in taking up the charge and enough research funding to make this a viable enterprise. While much can be done by a few dedicated people with sporadic or little funding, more researchers who are interested in the intersection of writing and science are needed as is a consistent and sustained funding base from research organizations like the National Science Foundation. Even if this is not forthcoming, new advances in this area will be made, but at a much slower pace.

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Part II
Theorizing Aspects of Science Learning

Chapter 5
An Exploratory Neuroimaging Study of Argumentative and Summary Writing

Richard Lamb, Brian Hand, and Sae Yeol Yoon

Researchers in science disciplines at all levels focus on gathering evidence to better understand how phenomenon occurs in the natural world. In some cases, working at the boundaries of disciplines allows researchers to make use of tools to augment existing findings or produce additional findings not available in the field previously. For example, in working at the boundaries of language, neuroscience, and education, we can begin to examine writing as a tool for learning as both a product and a process. In other words, how do we as educational researchers bridge the gaps which exist not only on our field but also on other fields as well in addition to making these processes synergistic with one another?

Learning tasks are complex and the degree of cognitive action in these tasks varies, so additional tools may be needed to help us better understand where learning as a process generates a product. We believe that current applications in science education may benefit from a tool that can examine this specific area in learning. Often the development of understanding of learning as a process takes the form of theory building in which empirical evidence is collected and analyzed and predictive models created based upon evidence and underlying theory. The resultant models are then tested against evidence and revised to reflect what is observed. This process is used in many disciplines including science education. In turn, research in science education also seeks to gather evidence and produce descriptions and

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*,
Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_5

models to understand how students learn within the science classroom. However, the current nature of science education research limits the scope of outcomes in terms of empirical evidence that supports emerging theory and model development (Bryman, 2015). In essence, there is considerable theory development without the control of theory testing to refine models of learning in the science classroom. This is often due to the difficulty of the black box of student cognition. Due to this, science education researchers are often left to infer cognitive processes from outward behaviors.

Further research may experience frustration in the development of fully tested theory due to overreliance on the aspects of theoretical frameworks, which disciplinarily isolate researchers from one another in science education (Prior & Thorne, 2014). For example, of the 54 research articles published in 2015, in the top-rated science education journal (Journal of Research in Science Teaching), a significant number of articles were either self-reports or interview-based. Self-report data is defined as a method of data collection in which participants respond to questions either written or oral about latent constructs such as attitudes, beliefs, knowledges, or efforts. Self-report data presents unique challenges with prediction, validity, reliability, ability for triangulation, and participant trustworthiness. Through the addition of neuroimaging or other forms of psychophysiological measurement, it may be possible to tie autonomic nervous responses to data related to self-report responses. This is not to suggest that qualitative or survey-based work should not be considered relevant or is not valuable, but by its nature, it does not lend itself to model testing only description. Thus, we often only see the product not the process. This is particularly evident in discussions of cognition related to student learning.

More to this point, current rates and types of publications in science education provide evidence that a self-report is the dominant form of data collection and that most studies draw conclusions about student learning from self-reports, surveys, and interviews and are not necessarily able to comment on the wider theoretical underpinnings in an effort to test or build learning theory related to cognition. Ultimately, these approaches result in innumerable descriptive “models” with little to offer in terms of actual ability to predict and refine. Of concern is that self-report measures of the kind found in science education research require triangulation in assessing the impact of the cognitive process of learning in science (Antonenko & Niederhauser, 2010; Antonenko, Paas, Grabner, & van Gog, 2010). Importantly, self-report and interview-based studies sometimes leave educators without insights about underlying neurological response as students engage in activities in the science classroom. These neurological responses provide additional insights into the broader ecology of learning and underlying mental processes responsible for cognitive abilities, e.g., production and development of memories, language, and reasoning. As with other self-reporting approaches, subjects are often unable to adequately scale and standardize their responses making comparison between subjects very difficult. For example, self-reports of cognition typically consist of one question completed after a content question, e.g., “Please rate the amount of mental effort invested in the task," and the responses range from "very very low mental effort" to "very very high mental effort" as in the widely used mental effort scale developed by Paas (1992). The question becomes: how does one move to integrate both of these forms of data collection to understand learning in science? One potential solution to this problem is to establish deeper connections between basic and applied research and make use of transdisciplinary tools such as neuroimaging in science education research. More specifically, researchers should adjust the focus away from teacher development as a means to understanding the process of learning and move toward direct measurements of student learning via cognition as a means to understand the process of learning related to science. Essentially the litmus test is this question, what does this (teacher actions) have to do with learning?

Through examination of basic research into the autonomic nervous system's (ANS) responses to learning, one can garner empirical data for a deeper understanding of mechanism of action associated with learning, i.e., models of learning, and ultimately test those models. A mechanism of action (MOA) is defined as the specific interactions through which learning produces effect; these actions typically mention specific cognitive system through which knowledge application and behaviors manifest. More importantly, examination of ANS responses and MOAs can be used to triangulate self-reporting measures. This ability arises as ANS responses are generally not under conscious control of the person (Hussein, 2015). While examination of ANS responses may provide some greater clarity in terms of understanding learning, using ANS measures to solely measure learning would be inappropriate and not recommended as there is considerable difficulty in identifying proximal causal effects. As with any tool, it is the combination and reinforcement of weakness in measurement techniques which will allow us to provide greater clarity of understanding related to the process of learning.

The primary means by which to address weaknesses in science education research approaches is through the establishment of transdisciplinary teams to examine learning (Mertens, 2014). By implementing such transdisciplinary research, we believe that it is possible to move away from only examining student outcomes on behavioral tasks, such as a test or interview, and more directly begin to examine student cognitive processing and underlying tools used to be successful in learning related to science. As is the case in other educational disciplines, science education conceptually engages with the idea of learning being both a process and product, but current research approaches do not enable a rich understanding of the processes to be obtained and thus ultimately rely on retrospective self-reporting. Transdisciplinary approaches such as those found when science education engages with neuroscience or other disciplines create a means to merge the products of learning such as writings and test responses with the process of learning, i.e., underlying cognition, ultimately allowing researchers to test underlying theory. This activity will assist in helping to develop a deep understanding of process of learning. As it stands now, science educators can only speculate through latent factor examinations about the process of learning.

5.1 Educational Neuroscience and Neuropsychology

All around the field of education, sister fields such as behavioral neuroscience, neuropsychology, and human computer interactions are evolving, growing, and incorporating transdisciplinary tools to examine the world around us. These fields are making tremendous strides in understanding learning and as a result may allow them to hybridize their ideas with science education to allow a deeper understanding of student learning of science. Hybridization of ideas between science education and these related fields may promote evolution of research methods in both fields, verification of results, and provide additional research trajectories for researchers (Ravet & Williams, 2017). To promote these additional research trajectories within science education, educational neuroscience provides some novel direction.

The nature of educational neuroscience and computational education requires that we bring together members of multiple communities both inside and outside of education who are interested in exploring As these fields develop, these nascent fields will begin to examine and add to current educational research and provide additional insights. This chapter provides an example of how transdisciplinary work may provide insight into the development and testing of theory in science education and provides an example study which examines not just the products of learning but the process of learning using neuroimaging to understand language use and writing in the science classroom.

Within the context of this example study, the authors make use of the ANS reaction known as hemodynamic response to better model the process of learning. Hemodynamic response is the rapid delivery of blood to active neuronal tissues (Son et al., 2017). This rapid delivery of oxygenated blood is strongly correlated with greater processing due to increased oxygen demands when specific cognitive systems are engaged. The general term for this activity associated with neuronal tissue is known as cognitive dynamics. Cognitive dynamics are defined only in terms of ANS responses, i.e., rapid delivery of oxygenated blood to neuronal tissues, and not in terms of other less well-articulated constructs that would otherwise identify this process as cognitive load or cognitive demand. The measurement of cognitive dynamics as a means to perceive individual student cognitive processing is critical for understanding the role of cognition and systemic brain function related to the process of learning. One recently developed tool that allows examination of this ANS response is functional near-infrared spectroscopy (fNIRS). fNIRS is a portable noninvasive neuroimaging tool used to understand the hemodynamic responses, i.e., broad level cognitive processing of students as they learn and engage with tasks in the science classroom. Due to its relatively small size, noninvasiveness, and robustness to subject movement, fNIRS is capable of being used with students in the natural classroom setting. While neuroimaging equipment such as functional magnetic resonance imaging (fMRI) devices has been widely adopted in the neurosciences and several other field parallel to science education since the 1990s, the field of science education has been slow to adopt this equipment for research. Reasons for lack of adoption range from cost, to lack of expertise, to a lack of recognition of the potential use of these tools to clarify questions and theory and test hypothesis around the process of learning. In other cases, science educators have been outright hostile to the use of this technology, due to a perceived lack of applicability in the classroom or lack of belief in science as a process, i.e., the science education paradox (Gerbier & Toppino, 2015; Sandoval, 2014). Despite this, by having an affordable and manageable method to examine cognitive processes via underlying ANS responses, the fNIRS provides a pathway for educators to characterize the complexity of learning that occurs and influence educational decisions in the science classroom. This study discussed in the chapter provides an example of the application of this technology in the understanding of the role of writing in the science classroom.

5.2 Functional Near-Infrared Spectroscopy (fNIRS)

Similar to electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS) is a noninvasive, safe, and portable optical neuroimaging method that offers a high-temporal resolution to assess cognitive dynamics or changes in the activation of neurons in the brain during various learning tasks (Ferrari & Quaresima, 2012). fNIRS takes advantage of the inherent physical characteristics of the human skin and bone tissue, in addition to the particular light attenuation characteristics of hemoglobin. Specifically, fNIRS makes use of the following: (1) human tissue is transparent to light within a narrow near-infrared spectral range which is from 600 to 1000 nm; (2) light emitted in the near-infrared spectral range is absorbed by pigment chromophores such as hemoglobin or is scattered by surrounding tissue at specified ranges; (3) the scattering of light is 100 times more probable than absorption by hemoglobin (Delpy & Cope, 1997); and (4) the absorption and scattering of light allows discrimination between large (greater than 1 mm) and small vessels due to the near-complete absorption of light in large vessels.

The arterial blood volume fraction of oxygenated blood of the human brain is 30% of the total blood volume in the body. This relatively large volume is due to the brain's high demand for oxygen when metabolizing glucose during information processing (Kim & Ogawa, 2012). The large amount of blood in the brain provides a means to obtain information regarding the ratio of oxygenated blood hemoglobin (O2Hbi) and deoxygenated blood hemoglobin (-Hbi) as well as the location in which the change from one to the other is occurring. Due to the ability of the fNIRS to discriminate at the millimeter level, it is possible to identify localization of changes in the processing locations of the brain with relatively high resolution. As the absorption spectrum of hemoglobin is dependent on the level of oxygenation, it is possible to examine the relative level of oxygen consumption by localized tissues in the brain through examination of the ratio of oxygenated to deoxygenated blood localized in the prefrontal cortex, as is the case in this example study. fNIRS as a measuring device makes use of infrared light-emitting diodes known as optodes. Infrared light is emitted using fiber-optic cables that are placed on the subject's

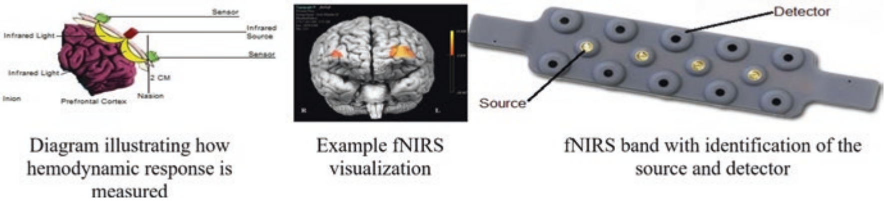


Diagram illustrating how hemodynamic response is measured

Example fNIRS visualization

fNIRS band with identification of the source and detector

Fig. 5.1 Overview of the functional aspects of the fNIRS system

head. The light is emitted at 650 nm from the source optode to the tissue; infrared light is reflected by deoxygenated hemoglobin back to the sensor at 750 nm. The surrounding sensors then detect the change in wavelength, and the ratio between the two is calculated. The coefficient provides the relative intensity of the blood flow in the particular area measured, thus offering localization and intensity which are key pieces of information lacking in other forms of educational measurement. Figure 5.1 provides an overview of the fNIRS band and the resulting visualization. The use of fiber-optic cabling allows researchers to measure oxygenation and deoxygenation in any head position and posture. In addition, the use of fiber optics and light allows the subject to move around in places such as a classroom making this instrument ideal for use with children. The robustness of the fNIRS to movement also allows the use of fNIRS measures in natural environments without the need for restraint and sedation making it ideal to examine student cognitive dynamics in the natural setting of the science classroom.

5.3 fNIRS as a Measure of Cognitive Dynamics

The use of light in the near-infrared spectrum to provide measures of O2Hbi and -Hbi is what allows researchers to examine underlying cognitive dynamics, i.e., the process of learning as a student engages in the science writing process (McKendrick, Parasuraman, & Ayaz, 2015). Several research groups such as Johnson and De Haan (2015) have found a positive correlation between the increase of oxygenated blood and the increase in cognitive effort and localization of the processing. Banville and Falk (2016) showed that the accuracy of fNIRS-based classification of mental workload and localization reached 82% when distinguishing between two workload classes, i.e., high and low. With three classes, high, moderate, and low, the fNIRS was less actuate and able to only conclusively distinguish 50% of cases into the three classes. In a similarly designed study, Harrison et al. (2014) were able to predict whether the subject was experiencing no workload, low workload, or high workload. Additionally, they were able to distinguish between mental workload on low spatial working memory tasks and high spatial working memory tasks with 70% average accuracy. In another study, Herff et al. (2014) showed that frontal cortical oxygenation as measured by fNIRS increases with working memory load, task engagement, and demand. Specifically, average oxygenation changes were observed at optode 1 and 2 due to task engagement and memory demands. For reference, optode 1 and 2 are near position AF7 in the international electroencephalography 10–20 system developed by Jasper in 1958. More importantly, scaling of the hemodynamic responses measured by the fNIRS was associated with task difficulty and increased monotonically with increasing task difficulty. While activation may occur for multiple reasons, there is some evidence that activation intensities change due to changes in difficulty. The AF7 region has been implicated in several previous critical thinking studies using positron-emission tomography (PET) (Justen, Herbert, Werner, & Raab, 2014), fMRI (San Martin & Huettel, 2013), and fNIRS (Gefen, Ayaz, & Onaral, 2014). Given these findings, fNIRS appears to hold great potential for the monitoring and assessment of localized cognitive dynamics associated with critical thinking and memory as students make use of them during writing.

Examination of hemodynamic response as a proxy for cognitive dynamics can help address the problem of cognition as a “black box” which has plagued educational researchers seeking to examine student cognition and learning as a process. fNIRS data related to cognitive dynamics can contribute to our understanding of the processes underlying critical reasoning and memory among other aspects of cognition through examination of intensity of effect and localization of the effects. In short, fNIRS can provide direct real-time measurement of brain activity as students engage in writing in the classroom.

Assessment of cognitive processing by educational researchers has traditionally been achieved using the self-report and behavioral response paradigms, i.e., content testing and effort assessments. In these paradigms, reports of content knowledge are contingent upon an assumption that the content and the students’ assessment of their mental effort adequately reflect cognitive processing which occurs as the student answers questions (Perry-Smith, 2014). In these cases, ratings are collected immediately after each task, i.e., retrospectively and not in real time. While the student may be able to respond to a question on a content test and their response may reflect cognitive action, this does not necessarily allow for the scaling of the cognitive action in real time because it necessarily occurs retrospectively as scaling must occur after the fact. Due to the retrospective nature of self-reports, content tests, and interviews, they do not provide insight into fluctuations in cognitive processing over time as someone engages with the task, unless they are applied repeatedly within the task. More importantly the ability to measure in real time is the problem that application of continuous assessment related to the cognition via retrospective means creates. Continuous assessment disrupts the primary cognitive activity and reduced the accuracy of measurement because the participant must engage in which is essentially an attention shifting task between rating the demand task and the primary task. The shifting dynamic provides only multiple-point assessment which may differ due to attentional dynamics and not continuous assessment (Ayres 2006). In other words, even when applied multiple times, it is unclear whether these self-reports provide a continuous measure of cognitive dynamics and ultimately processing or simply a snapshot. In addition, working memory processes involve interaction with long-term memory schemas, which become automated with practice and may be unavailable for introspection by the participant due to the automation (Peleg-Raibstein, Philipp, Feldon, & Yee, 2015). Antonenko et al. (2010) illustrated that students' self-reports of their cognitive load were significantly less reliable than the electroencephalogram (EEG) data, i.e., ANS data in terms of predicting learning outcomes (Antonenko et al., 2010).

5.4 Critical Thinking and Memory

The frontal lobe is incredibly important to the ability of subjects to retrieve information and make use of that information. Lesion studies illustrate severely diminished performance in semantic memory and application of information when lesions are present in the prefrontal lobe. In addition to lesion studies, neuroimaging studies illustrate that the frontal lobe region is active in several activities related to a large number of tasks under the umbrella of critical thinking and memory retrieval (Fiez & Petersen, 1998). Well-developed critical thinking allows one to understand objective analysis and evaluation and to form judgments regarding courses of action. Critical thinking and memory retrieval occur in distinct and separate areas within the brain topography. This is also indicative of the different cognitive systems used for each facet when answering a question. The separate locations and independent activations temporally illustrate that critical thinking and memory retrieval are two separate processes operating independently are used in tandem to respond to various activities the person may be engaged in such as writing.

Independence of these processes suggests that lower processing capacity in one area may not result in lower processing capacity in the other. Individuals with lower levels of critical thinking capability do not link events, recognize patterns, and illustrate lower levels of discrimination related to judgment. Like other aspects of cognition, the underlying structures and function of critical thinking and memory are present in preverbal children, and these structures are intrinsic component of human cognition. However, critical thinking processes typically develop rapidly between the ages of 3 years old and 5 years old as children begin to acquire the ability to articulate insight and express beliefs about the world. Researchers have shown that critical thinking skills account for a significant amount of variance in the ability to complete science tasks in the classroom (Sá, West, & Stanovich, 1999).

5.5 Writing in the Science Classroom

Over the last two decades, emerging research has looked at how teachers can use writing as a tool to teach science in the classroom. As this research has matured, it has focused on the conditions needed for success in writing in science, the cognitive systems and tools that are part of the writing process, and the success of using writing to learn approaches in terms of student performance in science. Repeatedly, studies have shown a consistent pattern of significant advantage for students in science using approaches such as writing.

Current research into the role of writing as a learning tool within science classrooms has provided evidence of the significant advantages gained by students with respect to conceptual understanding of a topic (Dunlosky, Rawson, Marsh, Nathan, & Willingham, 2013). Researchers inside and outside of science education are beginning to focus on the cognitive tools and process such as critical thinking required by students to be successful (Grimberg & Hand, 2009). A second area of related research is an attempt to understand and characterize the variation in cognitive demand that different types of writing place on writers in science (McDermott & Hand, 2010). While a number of studies have attempted to engage in examining the cognitive processing used within the act of writing, this work has largely occurred using retrospective examination and by looking at the products of the writing task and deconstruction of the text. While this mode of examination provides understanding and insights for educators, neuroimaging may allow researchers to engage in both complementary and confirmatory research for triangulation through examination of the process. This would allow science education researchers to confirm and produce deeper understandings of the actual real-time cognitive dynamics, i.e., the process occurring during text construction by students. This becomes important because in parallel to the rise of writing in science, the Next Generation Science Standards requirements have increased the focus of teachers on understanding underlying cognitive processes used by students as they engage with science learning and not just the products of the student cognition. A specific question, which has yet to be answered related to understanding the writing in science, is: are there differences in processing of science information due to the type of writing, i.e., summary or argumentative, undertaken by the students? The writing tasks presented in this example study are tasks used in an undergraduate science classroom to teach concepts in science. Using fNIRS in conjunction with other techniques such as functional linguistic analysis allows the authors to triangulate results and verify existing predictive models through exploration of product and process. Specifically, the authors seek to examine the underlying cognitive dynamics of students as they engage in these different writing tasks. The examination of both the outcomes in terms of writing and the functional processes via the fNIRS allows science educators to examine not only the products but also the processes of learning in real time. The examination of the combination of the process of learning with the fNIRS and the written sample as products of learning provides greater depth of understanding and confirmation of suspected underlying theorized relationships between types of writing and learning in science.

The two types of writing emphasized within the Next Generation Science Standards are argumentative and summary writing. In argumentative writing, students generate an argument where questions, claims, and evidence cohesively connect to explain the outcomes of an inquiry. Summary writing is a writing that summarizes the conceptual ideas that have been addressed within a unit of work and are written to audiences other than the teacher. For example, as in this study, a student may write a summarization of some science phenomenon to a younger student.

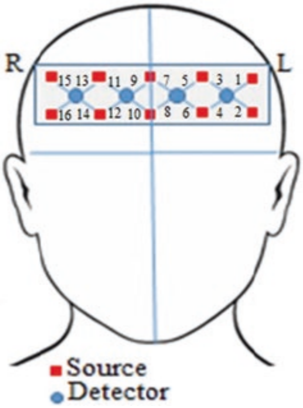
Research into these different types of writing has argued that these two different types of writing place different cognitive demands in terms of intensity on the writer. Importantly, empirical evidence from young writers has shown that shifting the type of writing task and audience type younger authors write to has benefits in terms of performance on end of unit tests and illustrates how evidence in science education research may work in parallel with neurological evidence (Gunel, Hand, & Prain, 2007). Importantly, work by Jang (2011) has shown that summary writing has a greater impact on critical thinking skills than argumentative writing as measured by the Cornell Critical Thinking Test. However, while these results indicate differences in cognitive activity, additional evidence about the manner and order in which cognitive processes play out in the different types of writing is needed and may be supplied through research making use of fNIRS and other similar measurement tools.

5.6 Example Study

Thirty healthy Caucasian, right-handed college-aged students, 15 males and 15 females, participated in an exploratory study designed to examine the cognitive dynamics associated with different forms of writing in science. Lamb, Hand, and Yoon in 2016 conducted this study as a part of a larger series of studies. The mean age of the participants is 19.3 (SD = 0.4). Each of the participants is currently on level in relation to reading. The researchers prescreened participants using the Wide Range Achievement Test-Third Edition (Rohde & Thompson, 2007). Additional screenings for inclusion occurred through extensive interviews and review of histories as suggested in the *Compendium of Neuropsychological Tests* (Strauss, Sherman, & Spreen, 2006). Researchers did not eliminate participants as a result of the screening protocols. Upon completion of the screening, participants were seated comfortably in a chair at an adjustable desk. Participants were asked to sit quietly with their eyes closed and to relax; no limb motion was detected. The authors positioned a 16-channel functional near-infrared spectroscopy (fNIRS) system headband on the participant's forehead. This placement enables the researchers to examine the prefrontal cortex hemodynamic response of the participants. Researchers also activated a video camera at the front of the room to record the session, synchronize events, and identify any irregularities during the session.

The continuous-wave fNIRS device was connected to a sensor pad with 4 infrared light sources and 16 detectors designed to sample prefrontal cortical areas underlying the forehead (Shewokis, Ayaz, Curtin, Izzetoglu, & Onaral, 2013). The four fixed-source detectors are separated by 2.5 cm and generate 16 measurement locations per wavelength in units known as a voxel. A voxel is a unit of graphic information defining a point in three-dimensional space in this case in the prefrontal cortex (Davis et al., 2014). Researchers making use of imaging technologies often locate anatomical positions using this unit of measure. Data acquisition and visualization occurred using COBI Studio software version 1.3.0.19 (Izzetoglu et

Fig. 5.2 fNIRS source (red) and detector (blue) locations



al., 2003). The researchers used fNIRS Soft Professional version for signal processing and data preparation. At a sampling rate of 2 Hz, the researchers generated 120 measures per person per minute. Video and blood volume data acquisition and synchronization occurred using a MP150 data acquisition device synchronized to mark the beginning of baseline I (null condition), the start and end of each of the writing tasks (stimulus), and the post-assessment baseline II (null condition). The stimulus was presented as a block to each participant. This approach replicates a modified single-subject case study design, i.e., A-B-A (baseline I, stimulus, baseline II).

Video analysis was executed post hoc to verify synchronization and to ensure correct marker placement. Figure 5.2 provides a graphical representation of the locations of each source and detector for the fNIRS headband.

5.7 Design

The researchers divided the experiment into three phases: Phase I, preexposure to the task (10 min); Phase II, exposure to the writing task (30 min); and Phase III, postexposure (10 min). During Phase I and Phase III, the subjects performed under null conditions, meaning there was not exposure to the writing tasks. Prior to exposure and Phase I, the subjects were instructed about the upcoming task and told they could make use of pictures and other modes of representation as needed to convey their ideas. During Phase II, participants verbally notified the researchers when they had completed reading the prompt and when they began to write. Subjects were allowed to take up to 30 min to complete each prompt. Writing completion was timed for each participant. Average completion time for the participants was 19.4 min. During Phase III, participants were monitored for the return of the hemodynamic response to baseline levels (Kesterke, Egeter, Erhardt, Jost, & Giesinger, 2015).

A blocking procedure was completed through synchronized manual marking of changes in phase and activities for each of the writing types and each participant. A within subjects comparison was used to examine and compare the forms of writing. To facilitate the within subjects comparison, each participant must complete both prompt types (i.e., summary and argumentative writing). Cognitive demand for each of the writing tasks is defined as the ratio of oxygenated blood to deoxygenated blood per unit time between the start of writing and the completion of the writing task. Time intervals were marked via video analysis, the fNIRS sampling rate, and student verbal affirmations as to the start and end of the writing task. For each of the blocks, Phase I through Phase III, the mean and standard deviation of the cognitive dynamic response, minus the time during the verbal interactions, as identified via hemodynamic response was calculated. In order to account for any individual differences in subject performance, the block was compared to differences from individual baseline in the same way single-subject case study is analyzed. A summary of the design is provided in Table 5.1.

In order to examine the cognitive dynamics associated with these two different forms of writing (summary and argumentative), the researchers made use of the temporal resolution of the fNIRS. This resolution helps to obtain valuable continuous information on the fluctuations and disruptions in cognitive processing during specific activities such as writing, remembering, and evaluation of their writing. This information was obtained through the localization of oxygenated and deoxygenated hemoglobin as the neurons in the brain metabolize glucose during specific task activities such as the tasks of writing, remembering, and evaluating (e.g., Klimesch, 2012). Sensor positioning measurements based on sources and detector locations allows for localization of the hemodynamic response (Kitzbichler, Henson, Smith, Nathan, & Bullmore, 2011). The use of the fNIRS allows researchers to examine the temporal changes in hemoglobin oxygenation that reflect increased mental activity in the frontal lobe. Location of particular interest in this study is in the areas associated with optodes 1 through 4 (see Fig. 5.2). These areas have been specifically implicated in processing related to critical thinking and memory.

Table 5.1 Summary of conditions and study phase breakdown

Condition	Pre-phase I	Phase I	Phase II	Phase III
All participants took part in each condition. Total rest between administrations was 30 min		(Total time 10 min)	(Total time 30 min)	(Total time 10 min)
Summary writing task ($N = 30$, all participants completed)	Instructions given on the task	No writing activity presented	Writing prompt presented	Writing activity completed and removed
Argumentative writing task ($N = 30$, all participants completed)	Instructions given on the task	No writing activity presented	Writing prompt presented	Writing activity completed and removed

5.8 Data Processing

In order to make use of fNIRS data, data cleaning, removal of measurement artifacts, and transformation of the data to standardized hemodynamic responses were required. Data processing began with the removal of the heart pulsations, respiration, and movement artifacts from the fNIRS intensity measurements. Removal was accomplished using a low-pass filter set at a 0.14 Hz cutoff (Meiri et al. 2012). Periods were segmented from the time of stimulus onset to 8 s later and every 8 s thereafter. Eight seconds was selected as the blocking period as this is the time lag between stimulus and response. Standardization of the hemodynamic response in each of the phases occurred using Eq. 5.1. Standardization is necessary to allow comparison between participants and phases.

The standardization equation is:

$$\mathrm{ZO2Hb} = \left(\mathrm{O2Hbi} - \overline{\mathrm{O2Hb}}\right) / \mathrm{SD}\overline{\mathrm{O2Hb}} \tag{5.1}$$

where O2Hbi is the value of the hemodynamic response computed for an i^{th} trial performed during baseline and in each of the subsequent phases. The researchers averaged the standardized values across each of the subjects and each block. This resulted in a composite image and graph representing all participants shown in Fig. 5.3. The standardized values of the hemodynamic response obtained in each phase are the dependent variables of interest.

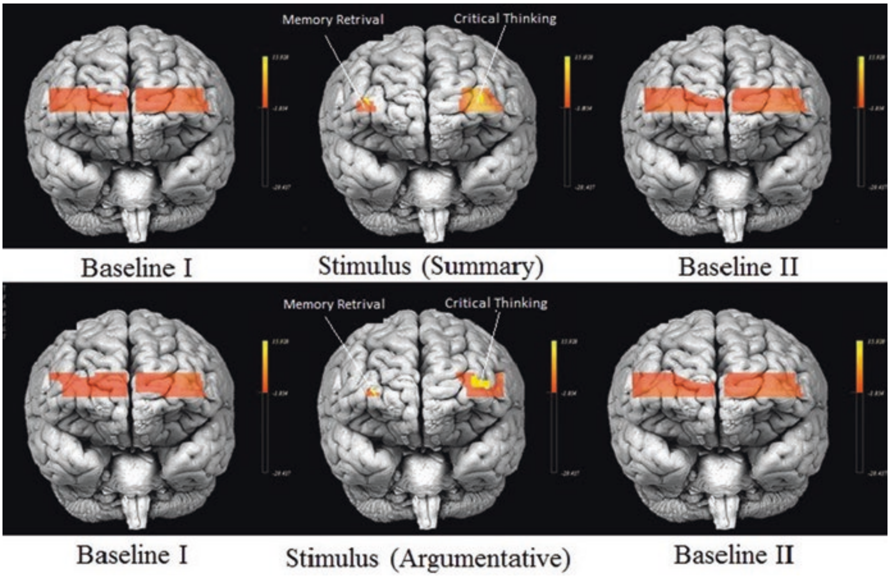


Fig. 5.3 Illustration of neuroimaging results. Activations (orange and yellow) significantly above baseline are illustrated in the portion labeled stimulus (center images). Orange-colored sections illustrated on baseline I (left images) and baseline II (right images) indicate baseline activations during rest periods with no stimulus present

5.9 Statistical Analysis

Statistical analysis of the fNIRS data occurred on the means and maximum attributes of the standardized O2Hbi. The mean standardized hemodynamic responses O2Hbi within subjects were statistically tested for differences using repeated measures ANOVA (rANOVA) and planned post hoc comparisons in SPSS version 23. In rANOVA, the subjects serve as their own internal control making it particularly useful for examining A-B-A designs in studies such as this one. The use of rANOVA reduces error variance and increases the power of the test to detect differences. The rANOVA was used to assess the main effect of hemodynamic response differences between baseline I, stimulus, and baseline II O2Hb*i* levels averaged across the participants. The authors used multiple comparisons to identify specific differences between Baseline I, Stimulus, and Baseline II oxygenated hemoglogin levels. Examination of between condition differences of summary and argumentative writing occurred using a means difference test at a significance of 0.05.

5.10 Characterizing the Complex Responses

Using fNIRS measures of hemodynamic response, the authors topographically (qualitatively) and quantitatively characterized the complex responses in the frontal cortex areas of the brain during two forms of writing in science. Hemodynamic responses were examined using a sampling rate of 2 Hz and triangulated with student writing outcomes using functional linguistic analysis. The oxygenation and deoxygenation of hemoglobin allows us to examine the resultant underlying cognitive dynamics associated with each writing prompt response within subject phase and between conditions. Statistical analysis was carried out through examination of hemodynamic response related to condition type, i.e., summary and argumentative writing, and phase, i.e., baseline I, stimulus, and baseline II. Main effects of writing condition and phase in summary writing and argumentative writing, respectively, were examined. The summary writing standardized hemodynamic response ($M = 3.483$, $SD = 1.05$) occurred at optodes labeled 1 and 3 on Fig. 5.2. In addition, activations were noted at optode locations 13 and 14. Argumentative writing hemodynamic response ($M = 2.112$, $SD = 1.88$) occurred at optodes labeled 1 and 3; activations were also noted at optode locations 13 and 14. Mean comparison of the intensity of the activation between conditions illustrates a statistically significant difference between conditions $t(59) = 3.462$, $p = 0.0012$, CI95%[0.5904,1.361]. Statistically significant activations above baseline I and II also occurred for all participants during both the argumentative and summary writing tasks, Wilks' lambda=0.023, $F(2, 28) = 9.171$, $p < 0.001$. Post hoc comparison illustrates that Phase II or the writing task in each case was greater than phase I and III *t*s > 2.0, *p*s < 0.001. Figure 5.3 provides a visualization of the areas of

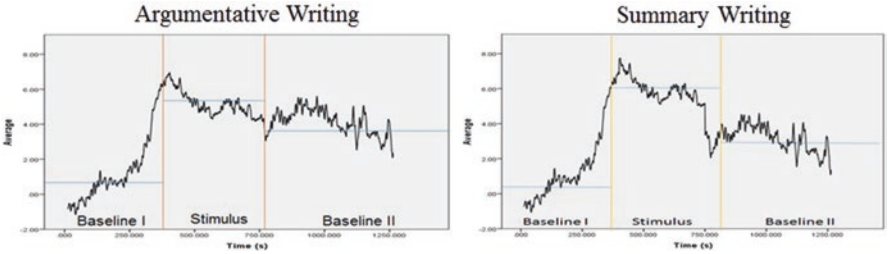


Fig. 5.4 Mean graph of baseline I, stimulus, and baseline II for channels showing statistically significant differences

activation. Figures on the left are illustrations of baseline and figures on the right illustrate activations above baseline.

A more global view of the fNIRS results is illustrated in Fig. 5.3. The graphs in Fig. 5.4 show the timing between baseline I, stimulus, and baseline II. Visual examination of the graph illustrates significant activation as a time of 300 s, which is 8 s poststimulus presentation, followed by maintenance of the elevated response during the stimulus for a total of 1800s. Poststimulus, the activation decreases back toward baseline but does not completely return to baseline; the difference between baseline I and baseline II poststimulus is not statistically significant. While both graphs exhibit similar overall patterns, the intensity of the hemodynamic response is followed by a sharper decline in summary writing when compared to the decline shown in argumentative writing. The intensity of the response is greater for summary writing indicating the students had greater relative cognitive demand. Figure 5.4 illustrates peak activations occurring upon introduction of stimulus. Stimulus activations continue until completion of the problem.

A correlational analysis was conducted to examine the relationship between activation locations and writing (summary and argumentative). Correlational analysis reveals that there are significant relationships between summary and argumentative writing stimulus presentation and activations in location 1 and 2 in Fig. 5.2, controlling for reading ability (rP2W.RA = 0.56, $p < 0.001$, moderate).

5.11 Discussion of Results

In this study, we demonstrated the ability to distinguish between writing types in science using neuroimaging techniques. While summary and argumentative writing appears to activate the same cognitive systems, the intensity of the activations differed. To accomplish this differentiation, the authors compared the relative cognitive demand and localization of each type of writing in science. Imaging results and statistical analysis provide evidence that summary writing tasks in science are more able to increase cognitive dynamics and activate locations in the prefrontal cortex, which are consistent with critical thinking and memory retrieval. The results of this study also indicated that when participants write to younger audiences and summarize their ideas, there is greater activation in the areas of the prefrontal cortex associated with memory retrieval when compared to argumentative writing to a peer.

The process of writing from a cognitive perspective is best understood as a set of distinctive processes organized as the writing progresses. All of which occur in both summary and argumentative writing. In addition to the distinct ordering of processes, writing is a hierarchal process, and the individual process is separated temporally, and downstream processes do not occur until upstream processes are complete. This is indicated through examination of the activations in time sequence. In general, during the writing process, the first aspect the writer must engage is analysis of the rhetorical problem and analysis of the potential environment in which the writing will be presented. As the participant begins writing, the writer must identify and develop strategies to address constraints such as topic, available information, and potential audience. This analysis would initially engage critical thinking (location 1) systems within the prefrontal cortex. Once identification of the constraints is complete, the writer then evaluates the constraints and problem and engages in retrospective and prospective memory retrieval (location 2) to assess possible strategies. Examination of areas 1 and 2 provides evidence of both memory retrieval activations. The graphs in Fig. 5.3 also provide evidence of this process as seen in the sharp increase between baseline I and stimulus at the 300 s mark as the writing brings more processes to bear upon the problem.

It is at this point that deeper examination of the factors influencing the writing becomes important. During summary writing to a younger audience, there is an expectation that greater critical thinking would be necessary, as a translation process is needed to address the relative difference in ability between the writer and the audience. This would result in greater activations in critical thinking when compared to writing in which a person is addressing a peer such as in the argumentative writing process. Comparison of within subject writing conditions, i.e., the same person engaged in summary and argumentative writing, reveals statistically greater response in critical thinking during the process of summary writing. This is evidenced in Figs. 5.3 and 5.4.

As the writer engages with a prompt with limited information and modes of presentation, the writer would rely more heavily on memory to develop response strategies to summarize information. Manifestations of these outcomes are seen as greater activations in both memory and critical thinking when compared within subject phases and between writing conditions. During development of strategies to negotiate summary development in particular to a younger audience, when greater translation is needed, one would expect greater activation in memory retrieval. This is exactly what is seen in the case of this study. If writing is seen as an individual cognitive process such as other cognitively complex human activities, there are integral internal processes that must be understood as well as externalized outcomes and representations. The use of neuroimaging allows for model development and ultimately results in identified testable manifestations such as those outlined in this study. It is the ability to constantly compare expectation with outcome not otherwise under conscience control that allows for model development and testing. Furture studies should address the examinations of new instructional sequences related to writing in the sciences. Once outcome products are aligned to cognitive state, the sequence of writing tasks may promote gradual increases in cognitive dynamics related to specific localizations and intensities.

5.12 Limitations and Potential Future Studies

The prompts are relatively low level in terms of difficulty, and as such the role of difficulty was not explored and should be in future studies. In addition, the fNIRS is limited in its ability to ascertain activations occurring in other systems of the brain located away from the frontal cortex. These areas may be responsible for and capable of compensating for the processing content and memory-based information not otherwise seen in the argumentative writing process.

One particular area of limitation that needs to be explicitly addressed is the inability of neuroimaging to account for learner histories, contexts, and immersive processes. To address these limitations, the research attempt to engage triangulation of results from multiple sources of measurement. Specifically, through interview, video, and neuropsychological work-ups, it becomes possible to explore the effects of individual differences on the cognitive imagining outcomes. A final area of limitation is that this study only examines college-aged students and does not take into account the developmental aspects of learning which may impact outcomes related to critical thinking and memory activation, i.e., does greater experience allow for a reduction in critical thinking and greater activation in memory?

Addition questions which can be addressed in future research are the relationship between structure and function of aspects of the brain systems used in learning and provide means to develop new assessment in education based upon cognitive state, for example, aspects of educational neuroscience can already clearly distinguish between learning from rote and learning from conceptual understanding. Educational neuroimaging work also has the potential to assist in the identification of the physiological markers of learning adding to existing theories of learning. For example, the characterization of dyscalculia and dyslexia from discrete differential causes an identification of underlying mechanisms related to deficits in core cognitive systems. These core cognitive systems are related to the processing of sets and not specifically number sense or reading. Neuroimaging results indicated deeper casual factors related to genetics and resultant development and ultimately moved educators away from intervention that sought to address specific strategies for dyslexia and dyscalculia separately. As the imaging techniques and broader institutional knowledge of how to use the tools developed in science education, a richer and complementary understanding and building of theory of how learning occurs in science will develop.

5.13 Conclusion

Due to the possibility of both confirmatory and complementary aspects of neuroimaging within science education research, it becomes possible to examine not only the products of the education process but also the underlying processes occurring as students develop their products. Imaging work such as that seen with the fNIRS allows researchers to answer questions linking basic and applied research and informing existing theory in ways which have not been possible. This linkage can allow researchers to address the mind, brain, and education in which we collectively move beyond description and address underlying mechanism of action around how learning and understanding occur. Development of these underlying processes creates the explanatory and predictive component of models of learning related to writing in science. As we apply these ANS measurements to other problems of learning, we will undoubtedly find new relationships and strengthen and confirm existing relationships. This example study, using real-time methods to examine underlying processing, provides testable outcomes for theory and model building and provides additional direction to enable further research. From this research, a good number of themes have emerged. The first being that while summary and argumentative writing make use of the same cognitive tools, there are differences in the intensity and temporal patterns which allow identification of different underlying processes and may point to the importance of sequencing of writing and prompting in the classroom. This will continue to be an area of exploration. The elucidation of the underlying processes would not have otherwise been identifiable without examination of the writing process versus the product. This study also provides evidence of an effective but not widely adopted approach through the integration of transdisciplinary approaches to examine the ANS correlates of learning. This example study also speaks the difficulties of self-reports such as interviews in understanding process versus product.

This sample examination suggests greater possibility for educational researchers as the routine availability of optical imaging technologies becomes available to science educators. Use of such technology to examine the process of learning will help to transform our understanding of teaching and learning in the science classroom. These low-cost mobile devices such as fNIRS will drive research, change our understanding of classroom assessment, and move research from product oriented to process oriented. The example application of optical imaging in conjunction with other classroom-based assessment approaches will provide greater data to understanding how science pedagogical approaches may or may not assist in the learning of science.

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Chapter 6
Scientific Practices as an Actor-Network of Literacy Events: Forging a Convergence Between Disciplinary Literacy and Scientific Practices

Kok-Sing Tang

6.1 Introduction

The Next Generation Science Standards (NGSS) has recently introduced the importance of scientific practices for science teaching and learning (National Research Council, 2012). At the same time, recent national curricula around the world such as the Common Core State Standards (CCSS), the Australian Curriculum, and the Norwegian National Curriculum have increasingly emphasised the explicit teaching of disciplinary literacy in all subject areas (see Tang & Danielsson, 2018). Researchers working in the intersection of these two developments have acknowledged the convergence between scientific practices and disciplinary literacy, in particular that disciplinary literacy – as ways of using and thinking with language and representations in a specific discipline – is central to several scientific practices, such as engaging in evidence-based argumentation, constructing explanations and representations, and communicating multimodal information (National Research Council, 2014; NGSS Lead States, 2013).

Although the need for synthesis between disciplinary literacy and scientific practices is clear, there has been little theoretical development that bridges these two areas with a common conceptual frame of reference. Interestingly, both areas have seen a movement from positivistic notions of learning towards more embodied and culturally specific perspectives over the last 40 years (Lemke, 2001; Moje, 2007). In literacy research, the traditional notions of literacy as a set of autonomous and decontextualised abilities are gradually replaced by socially purposeful ways where learners interact with multimodal texts within specific historical, cultural, and institutional contexts (Gee, 2011). Similarly, science education research has also seen many "turns", from behaviourist to cognitive (Posner, Strike, Hewson, & Gertzog,

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*,
Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_6

1982) to linguistic turn (Lemke, 1990) and to the more recent "practice turn" (Ford & Forman, 2006) drawing on perspectives from science and technology studies as well as second generation cognitive science.

In this chapter, I explore the theoretical developments of disciplinary literacy and scientific practices and identity potential linkages across the gap between both areas. Drawing on actor-network theory, I propose an approach that has potential to link several theoretical ideas from literacy and science education research in order to forge a common way of interpreting scientific practices as a network of literacy events distributed across time and space. Some researchers have used actor-network theory separately in science education (e.g. Roth & McGinn, 1998; Roth & Tobin, 1997) and literacy education (e.g. Leander & Lovvorn, 2006). However, my purpose is to synthesise these ideas in the context of theorising the relationship between literacy and scientific practice, as well as understanding what we mean by the term "scientific practices". I start by unpacking some ideas on scientific practices from recent science education literature and followed by some ideas on literacy practices from the literacy education literature. I then give some background to actor-network theory and explain some of its central ideas before I illustrate how an actor-network looks like using examples from a past research project. Lastly, I explain how an actor-network approach offers some ways to connect the ideas between literacy and scientific practices.

6.2 Science Education Research: Scientific Practices and Performances

The recent emphasis on scientific practices can be seen from both developments in curriculum and science education research in the USA and other countries. In curriculum development, the most notable shift came from NGSS which explicitly outlines a list of practices that mirror those of professional scientists and engineers (NGSS Lead States, 2013, p. xv). These practices are, namely, (1) asking questions (for science) and defining problems (for engineering), (2) developing and using models, (3) planning and carrying out investigations, (4) analysing and interpreting data, (5) using mathematics and computational thinking, (5) constructing explanations (for science) and designing solutions (for engineering), (7) engaging in argument from evidence, and (8) obtaining, evaluating, and communicating information.

The use of the term "practice" was a deliberate shift from words like "skills" or "inquiry" that were emphasised in previous curriculum development (Ford, 2015). This development highlights the realisation that engaging in scientific inquiry does not require only a set of domain-general skills but also a range of cognitive, social, and epistemological practices that are specific to the discipline (NGSS Lead States, 2013). Furthermore, the shift denotes an attention to a set of interrelated practices that underpin the epistemology of science in terms of developing theories, building models, and testing knowledge claims (Ford, 2015). What this implies is that practices are not a set of isolated actions determined by the rules or norms of scientific conduct but rather as a broader range of activities that include the conceptual, social, epistemic, and material dimensions of science (Duschl, 2008).

Interestingly, NGSS makes an explicit connection with the Common Core State Standards (CCSS) for literacy in science and technical subjects. With the premise that "engagement in practices is language intensive and requires students to participate in classroom science discourse" (NGSS Lead States, 2013, p.50), a list of reading, writing, speaking, and listening standards from CCSS was linked to each of the practices from NGSS. For instance, to support the scientific practice of "engaging in argument from evidence", examples of reading and writing standard as outlined in CCSS are as follows:

Reading standard: To delineate and evaluate the argument and specific claims in a text, including the validity of the reasoning as well as the relevance and sufficiency of the evidence

Writing standard: To write arguments to support claims in an analysis of substantive topics or texts using valid reasoning and relevant and sufficient evidence

From the connection between NGSS and CCSS, it is clear that there is a mutually supporting relationship between literacy and science; while scientific practices demand language learning, engaging in these practices also simultaneously builds on students' language proficiency.

Although the direction towards scientific practices and the linkage to literacy was explicit in both curricular documents (i.e. NGSS and CCSS), what exactly constitutes scientific practices remains unclear. Furthermore, the NGSS document describes scientific practices as a set of simplistic, isolated, and prescriptive behavioural outcomes without an underlying theoretical or sociological basis of scientific work (Ford, 2015). A recent special issue in *Science Education* edited by Erduran (2015) attempts to address this issue by drawing on perspectives from science and technology studies (STS). The various contributions bring to attention the kind of practices that scientists actually do in reality, rather than an idealised form of what we think they do or ought to do. The key argument from this special issue parallels others who have critiqued NGSS for not sufficiently and accurately depicting the nature of science by listing a set of so-called scientific practices (e.g. McComas & Nouri, 2016; Rodriguez, 2015).

For instance, Mody (2015) aptly depicts a messier version of scientific work that sees scientists as bricoleurs (or handymen) that constantly put stuff together to make tools and literacy devices on a provisional basis as they progress in their research, rather than following any formula or recipe throughout the research process. One of the literacy devices that scientists generate incessantly is an "inscription" (Latour & Woolgar, 1979), which can range from a note on a lab sample, a graph printed from a machine, to a grant proposal or journal article. Needless to say, the inscriptional process involves a lot of reading and writing (including graphic representations) on the part of the scientists. This messier but more accurate view of scientific practices is not sufficiently represented in NGSS and is something that science education researchers need to expand. Furthermore, the complex literacy work undertaken by scientists cannot be easily broken down into a list of text-oriented reading, writing, and listening standards as specified in the connections to CCSS within NGSS.

Another aspect that is not captured in NGSS concerns the larger network of activities surrounding what scientists do. Ford (2015) regards the list of practices in NGSS not as scientific practice in a broad sense but rather as "performances" or actions that are defined at an operational level (e.g. asking a question, carrying out investigations). These performances are the *constituent activities* of scientific practice, but not the practice in themselves. Defining scientific practices as a list of performances runs the risks of surface mimicking based on similarity, such that a particular performance engaged by students may look "scientific", but is not really meaningful when embedded within the mesh of other performances that constitute scientific practices. For instance, while there are norms and rules that determine whether a particular performance such as carrying out an experiment is deemed scientific, whether or not this performance is judged as appropriate to a scientific practice depends on how it interacts with other performances, such as using the results to persuade one's peers or merely to complete a worksheet for a good grade. In other words, scientific practices should be defined by the mutual interaction of constituent performances within a system of performances, and not just the performances in isolation (Ford, 2015). Therefore, the view from science studies depicts a very different picture of scientific practices as one that is constantly reinvented and emerges from a larger network of activities (Stroupe, 2015).

6.3 Literacy Research: Literacy Actions, Events, and Practices

In literacy research, there is a growing shift from content area literacy towards disciplinary literacy. According to Shanahan and Shanahan (2012, p. 2), while content area literacy focuses on how a novice read or write disciplinary text, disciplinary literacy "emphasizes the unique tools that the experts in a discipline use to participate in the work of that discipline". This emphasis on the "unique tools" arose from the argument that students should be engaged in the epistemic processes undertaken by scientists, rather than passively learn the products of scientific knowledge or genres. At the same time, there has been a shift in literacy research towards viewing literacy not just as the conceptual or linguistic tools to support content or language learning in science but also as a form of social practices to support the epistemic processes specific to a discourse community (Moje, 2007).

A major theoretical contribution towards the focus on epistemic and social practices of a discipline came from the research in New Literacy Studies (Gee, 2005), which adopts a view of language as fundamentally a form of social action, instead of the prevalent view of language as an abstract and static system. Language does not exist as an isolated entity independent from everyday interactions but rather as a cultural resource used to perform a meaningful action with specific purposes and consequences. What this view of language entails is an attention to what people do when they are using language and the actions they are performing when they speak, listen, read, write, draw, graph, or gesture (Coupland, Sarangi, & Candlin, 2014). Focusing on the things and actions that people *do* with *words* is important as it links to our purpose of understanding what scientists *do* with the *inscriptions* they are generating.

In particular, there are two key aspects of the above-mentioned view of language (focusing on the words "do" and "words" respectively) that require further elaboration. The first is the performative aspect stressing on the actions and "doing" with words. This attention towards conversational exchange or speech act as the basis of analysing language has its roots in speech act theory (Austin, 1962) and ethnography of communication (Hymes, 1964). The underlying idea is that meanings and realities are always co-constructed interactionally through the participants' use of language. In other words, language functions as a tool to mediate social interaction, dialogic exchange, and construction of meanings. The second aspect is the semiotic aspect stressing on the "words" that people use to do things. Words are essentially symbols that we use and agreed through social conventions to represent certain objects in and ideas about the material world (Hayakawa & Hayakawa, 1990). This symbolic process is not limited to words of course but is extended to any material objects that can be used as a system of representations (Kress, Jewitt, Ogborn, & Tsatsarelis, 2001).

These premises of language are relevant in order to understand what is meant by literacy practices. A useful idea to introduce here is Heath's (1983) distinction between literacy events and literacy practices. Literacy events refer to specific and observable situations in which people are talking, listening, reading, writing, or drawing or any other activity where language is used. In this sense, literacy is always contextualised to specific activities and performances, as consistent with the view of language as a form of social action. On the other hand, literacy practices are patterns of literacy events, which are not overtly observable but are recognisable from repeated and characteristic ways in the unfolding of similar literacy events. For example, a student reading a thermometer and writing down its temperature on a laboratory report is a literacy event. This event is observable and specific to the particular context. Through the recurring of such events and other related events over numerous times and places, there emerges a general and recognisable pattern which we may call the literacy practice of "school science laboratory work". Literacy events and literacy practices are always mutually constitutive. While literacy practices are manifested in characteristic patterns of literacy events in the way we speak, read, write, and use inscriptional tools, they are developed over time through repeated literacy events in a community. Simultaneously, literacy events are the "observable episodes which arise from literacy practices and are shaped by them" (Barton & Hamilton, 2000, p. 8). However, it is worth noting that literacy practices are not the same as scientific practices, which I will point out subsequently, after the next section on actor-network theory.

6.4 Actor-Network Theory: From STS to a General Ontology

Actor-network theory is often associated with the work of STS scholars who began their ethnographic research studying the life and work of scientists in the laboratory and fieldwork (e.g. Callon, 1986; Latour, 1987; Latour & Woolgar, 1979). Much of their work has demystified common perceptions of science as a “scientific method” to discover a set of universal and abstract rules that determine the behaviour of the natural world. Instead, their findings revealed a social constructionist view of science that is underpinned by huge amount of literacy tasks undertaken by scientists through the use of inscriptions. In light of the recent focus on scientific practices, there is a renewed interest in STS as science educators seek to relate the science curriculum to the practices carried out by scientists in the laboratory or research centres (see Erduran, 2015). As such, the empirical findings on scientists’ practices as revealed from STS have become more relevant. However, the work by Latour and others has also led to the development of core concepts and a general approach (now called *actor-network theory*) that are currently used widely in the social sciences. I will elaborate some of the key ideas in actor-network theory, most notably inscription, translation, non-human actors, and actor-network.

The notion of *inscription* was initially based on Latour and Woolgar’s (1979) study that much of the scientists’ actions in the laboratory (e.g. selecting samples, taking measurements) were translated into some kind of written codification, or inscription, which in turn get translated into another type of inscription, and so on until a scientific article is produced. There are two important ideas in how inscriptions are translated. First, each *translation* involves a multimodal transformation from one medium of representation to another, for example, from measurements to numbers in a table, from numbers to graphs, and from graphs to written text. A translation can be made by a human (e.g. scientist, technician) as well as a non-human machine designed to perform a specific translation task (e.g. data sensor, mass spectrometer). Second, every translation step in the entire chain from laboratory work to published article involves assembling what Latour (1987) calls “allies” to support the justification of the translation process. These allies can range from other people who agree with the interpretation of the data, to data outputs from machines in the laboratory, to published articles in the literature. This is essentially how evidence and arguments are formed to support a scientific claim; in Latour’s ontology, it is simply the translation of data through a network of allies consisting of both human and non-humans.

This network of allies also extends beyond what is happening inside the laboratory to the larger scientific community. To make one’s scientific claim accepted by the community will involve a huge assemblage of allies in terms of convincing peer reviewers, getting citations, winning awards, generating public buy-in, and getting continual research funding. Over time, as the network of allies becomes larger, the claim becomes stronger and more convincing. Eventually, it becomes accepted as a scientific fact when nobody questions the translation processes and assemblage of allies involved in producing the claim. When this happens, the translation and assemblage will be "black boxed" until somebody questions them in light of new evidence. But to open this black box will require the assemblage of yet another network of allies by doing almost the same thing, that is, generating more inscriptions and translating the work in another laboratory to published papers, in order to engage in a "trial of strength" (Latour, 1987) with the opposing network.

Latour's initial description of the scientific community was later expanded into a general ontology that can describe any organisation, community, or social setting (Latour, 2005). An interesting insight is the agency Latour ascribes to non-humans. In terms of the propensity to act within a network, a *non-human actor* has as much influence as a human actor. While this suggestion may seem radical, it makes a lot of sense when we think about the reality of a network that spreads beyond a particular locale and short timeframe. As an individual cannot act simultaneously in multiple places and exist over a human lifespan, it is through non-human actors, most notably in the form of inscriptions, that extend the reach of a network over time and space. For instance, the NGSS document published by the National Academy of Sciences (NGSS Lead States, 2013) is an inscription produced as a result of a network of politicians, bureaucrats, scientists, educators, as well as other inscriptions (e.g. previous versions, frameworks). Once the NGSS as an inscription was published, it has been circulated widely and used to form new networks in many places for various purposes, including the central argument I am building in this chapter.

The last concept I like to elaborate concerns the nature of a network and actor-network theory as a whole. Contrary to common metaphors of a network, an *actor-network* is not a fixed network like a computer or transportation network, nor a social network that focuses on the ties and connections among people. Instead, the network refers to flows and circulations that are constantly assembling and reassembling in a transient manner. The purpose of understanding this network is to examine the cluster and interaction of actors (including non-humans) that come together and how those interactions can create meanings that are both material (as objects) and semiotic (as ideas). There are two interdependent levels of understanding such an actor-network, first by (a) examining the interaction within a particular event and the product of this event (e.g. an inscription) and then (b) following this actor (humans or inscriptions) as it circulates to other sites and examining its role in terms of the interaction with other actors in those sites. In this sense, actor-network theory is more an ontological approach to study what reality is and what it comprises in terms of tracing *tangible* relational ties within a network, rather than a theory or epistemology that explains the nature of the world or how we know about the world.

6.5 An Actor-Network of Literacy Events

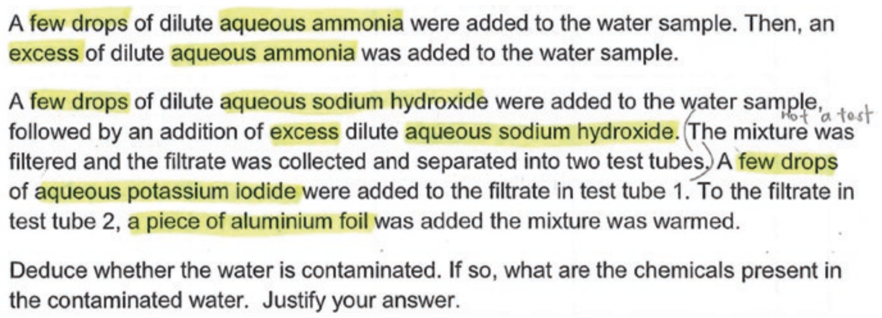
In this section, I illustrate a particular actor-network in a ninth grade chemistry class and use it to make some connections with the ideas of literacy event, literacy practice, scientific performance, and scientific practice that were discussed earlier. The data I use to describe this actor-network are based on classroom videos from a previous study on disciplinary literacy in four secondary science classrooms in Singapore (see Tang, 2016; Tang, Ho, & Putra, 2016; Tang & Putra, 2017). For this illustration, I will focus on a lesson unit on qualitative analysis (QA) and select six episodes from the video data to highlight: (a) how each episode is constructed interactionally as a literacy event, and (b) how the six episodes (as literacy events) are connected as an actor-network. Table 6.1 provides an overview of the six episodes and their occurrence in relation to the lesson unit. As the purpose of this chapter is a theoretical discussion instead of an empirical report, the following illustration will be kept brief.

6.5.1 The Literacy Events

The first episode that I am showing began with the chemistry teacher, Kathryn, revisiting a problem that was first introduced much earlier and iterating it to set the context for the subsequent instructional activities in the next three lessons. This problem involved a "mystery water" that was suspected to be contaminated, and the task required was to conduct a series of QA tests to find out what chemicals were contained in the water. The following excerpt was spoken by Kathryn while she was showing several inscriptions through a visualiser (document camera). This excerpt

Table 6.1 Overview of the episodes in the illustration of actor-network

Episode	Lesson	Video time stamp (hr:min:sec)	Description	Key inscription
1	6	0:07:10–0:09:46	Teacher presented the "mystery water" problem and gave some instructions	Written narrative (Fig. 6.1)
2	6	0:09.46–0:15.06	Students read the problem narrative and wrote the actions needed for the tests	Table (Fig. 6.2)
3	7	0:15:39–0:37:03	Students performed the tests	Table (Fig. 6.2)
4	7	0:42:51–0:50:55	Students drew a flowchart to represent the steps and results of the tests	Flowchart (Fig. 6.3)
5	7	1:00:14–1:02:08	Students wrote their findings and justification	Written justification
6	8	0:08:11–0:18:01	Students presented their findings and justification to the class	Written justification



A few drops of dilute aqueous ammonia were added to the water sample. Then, an excess of dilute aqueous ammonia was added to the water sample.

A few drops of dilute aqueous sodium hydroxide were added to the water sample, not a test followed by an addition of excess dilute aqueous sodium hydroxide. (The mixture was filtered and the filtrate was collected and separated into two test tubes.) A few drops of aqueous potassium iodide were added to the filtrate in test tube 1. To the filtrate in test tube 2, a piece of aluminium foil was added the mixture was warmed.

Deduce whether the water is contaminated. If so, what are the chemicals present in the contaminated water. Justify your answer.

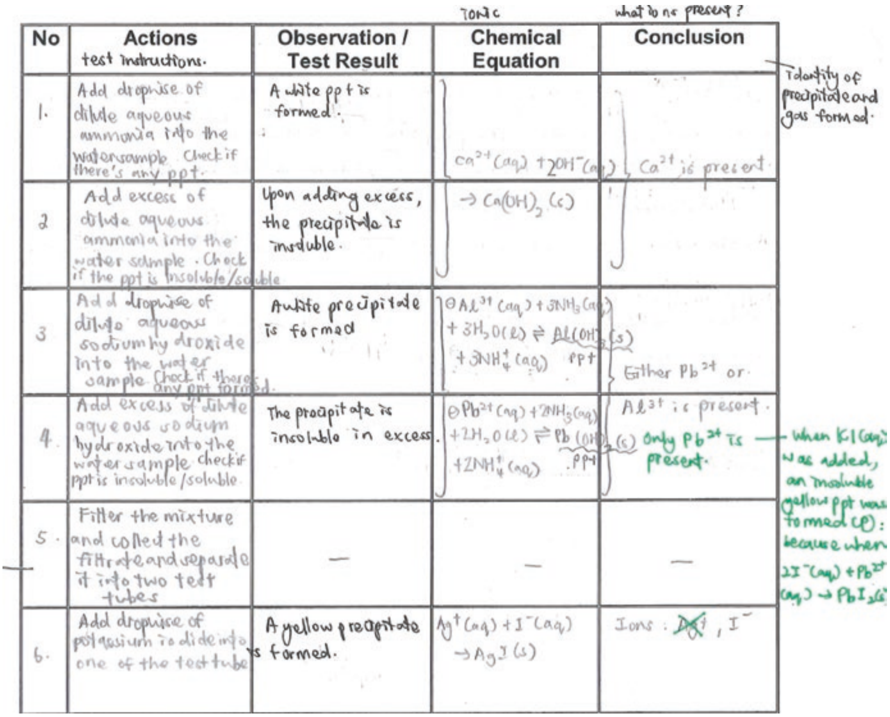
Fig. 6.1 Excerpt from the problem narrative taken from a student's worksheet

(particularly the words in bold) is illustrative of the *literacy events* that would take place after this episode:

> I want you **to read** and as a pair, I want you to **transfer what you know from this passage [pointed to** excerpt shown in Fig. 6.1**] over into actions [pointed to Actions column in** Fig. 6.2]. So what are the **test instructions that you are going to carry out**? So I want you to **write it down on top here** – the chemical test instructions or instructions for the chemical test. If you are not sure, you can make any **reference to your notes**, or to **your worksheets you have done for testing cations and anions**. Observations you won't be able to tell because we are not going to do the practical today, we are **going to do it tomorrow**. Alright, and of course, if there are any chemical equations and conclusions later. **This one [pointed to Conclusion column in** Fig. 6.2**] will come in later**.

In this episode, which is really an observable literacy event, Kathryn was using language (e.g. talking, pointing to written words) to perform a particular social action of giving instructions of what to do next. The students were mostly listening, and many of them were also observed to be coordinating and looking at the various inscriptions used and mentioned by Kathryn (e.g. "this passage", pointing to the table, "your notes", "worksheets"). The performance of this literacy event was guided by a more general literacy practice of "giving/listening to instruction" where Kathryn and students have grown accustomed to after multiple repeated performances of such literacy events. While there is much to say about the actions that were taking place in this literacy event, and how these actions were manifestations of a certain recognisable pattern of literacy practice common in school, it is more important to move on to the subsequent literacy events.

What transpired after this literacy event were more literacy events, which I have selected episode 2–6 to illustrate those events (see Table 6.1 for the chronological sequence of the episodes). Episode 2, which followed immediately after episode 1, involved a pair of students reading and discussing the problem narrative, which contained (a) the scenario of the "mystery water" written in a story form and (b) crucial information and instruction designed to help students perform the tests. Figure 6.1 shows an excerpt of this information text. In this literacy event, the students followed Kathryn's earlier instruction to "transfer what you know from this passage over into actions". Thus, as the students read the passage, they also



Ionic

what ions present?

No	Actions test instructions.	Observation / Test Result	Chemical Equation	Conclusion
1.	Add dropwise of dilute aqueous ammonia into the water sample. Check if there's any ppt.	A white ppt is formed.	$Ca^{2+}(aq) + 2OH^-(aq)$	Ca^{2+} is present.
2	Add excess of dilute aqueous ammonia into the water sample. Check if the ppt is insoluble/soluble	Upon adding excess, the precipitate is insoluble.	$\rightarrow Ca(OH)_2(s)$	
3	Add dropwise of dilute aqueous sodium hydroxide into the water sample. Check if there's any ppt formed.	A white precipitate is formed	① $Al^{3+}(aq) + 3NH_3(aq) + 3H_2O(l) \rightleftharpoons \underbrace{Al(OH)_3(s)}_{ppt} + 3NH_4^+(aq)$	Either Pb^{2+} or
4.	Add excess of dilute aqueous sodium hydroxide into the water sample. Check if ppt is insoluble/soluble.	The precipitate is insoluble in excess.	② $Pb^{2+}(aq) + 2NH_3(aq) + 2H_2O(l) \rightleftharpoons \underbrace{Pb(OH)_2(s)}_{ppt} + 2NH_4^+(aq)$	Al^{3+} is present. Only Pb^{2+} is present.
5.	Filter the mixture and collect the filtrate and separate it into two test tubes	—	—	—
6.	Add dropwise of potassium iodide into one of the test tube	A yellow precipitate is formed.	$Ag^+(aq) + I^-(aq) \rightarrow AgI(s)$	Ions: ~~Ag^+~~, I^-

Identity of precipitate and gas formed.

When KI(aq) was added, an insoluble yellow ppt was formed (P): because when $2I^-(aq) + Pb^{2+}(aq) \rightarrow PbI_2(s)$

Fig. 6.2 An experimental table recorded in a student's worksheet

translated the written text into another inscription, which was an experimental table shown in Fig. 6.2. Subsequently, this table became the key inscription that mediated the next episode.

In episode 3, which took place in the next lesson, the same pair of students were now carrying out the tests following the "actions" they wrote in the table from the previous episode. After every test, they wrote the results on the observation/test result column of the table (see Fig. 6.2). Thus, this literacy event involved the translation from (a) words (e.g. "add dropwise of dilute aqueous ammonia") to (b) bodily actions and performance with objects (e.g. manipulating test tubes and chemicals), to (c) chemical reactions among the ions (the non-humans) that produce a substance with an observable colour and texture, and then back to (d) words again (e.g. "a white ppt is formed"). According to Latour (1987), the interaction of the non-human actors – the chemical ions and apparatus – plays a crucial link in this chain of translation. Too often we see literacy event as solely the use of words and graphic representations by human participants. However, in any science experiment, as was the case in this literacy event, the reactions among the ions in the test tube formed the very basis of what we might call the "empirical" nature of science, without which there will be no experiment. In terms of the actor-network that I will elaborate later,

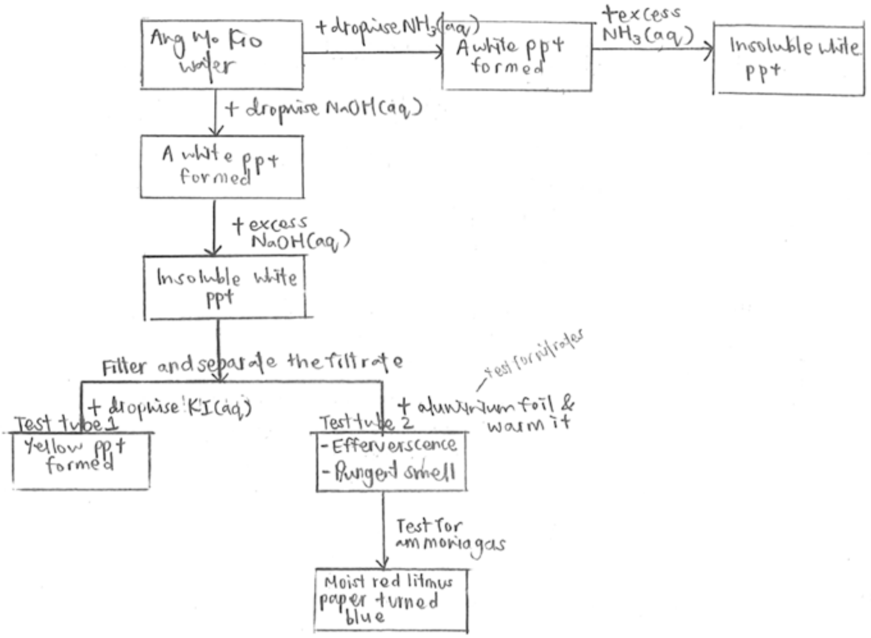


Fig. 6.3 A flowchart drawn by a student

this link was the material basis for statements of claim and evidence in the students' subsequent justification of their conclusion.

After the students had completed all the tests, in episode 4, they then drew a flowchart (see Fig. 6.3) with Kathryn's guidance to represent the steps and results of the tests. In episode 5, using this flowchart as a heuristic, each student wrote the conclusion and justification on a worksheet. In the next lesson in episode 6, Kathryn then got the students to present their conclusions and justifications to the class in order to foster an argumentative discourse among the students, particularly when the students obtained different conclusions from one another.

6.5.2 *The Actor-Network*

I will now discuss how the various literacy events I had described were connected through a literacy actor-network. Figure 6.4 is a simplified representation of the actor-network I had just described. As it is impossible to represent visually the sheer complexity of an entire network, it is important to note that Fig. 6.4 is only a heuristic to illustrate the key events (denoted as nodes), inscriptions (denoted as arrows), and the relationship between them. For this purpose, this figure serves as a useful inscription for me to highlight three key points.

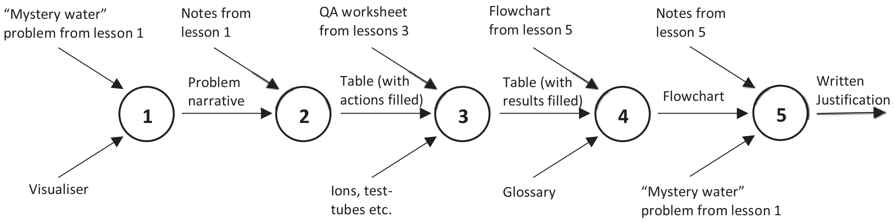


Fig. 6.4 A simplified representation of the actor-network in this illustration

The first point is that Fig. 6.4 shows the continuity of the literacy events across time. No literacy event can exist in isolation, and what is happening in a particular literacy event in real-time is always dependent on what came before and contingent on what would happen next. The second point is that Fig. 6.4 also shows the role of inscriptions in joining one key literacy event to another. The continuity from one literacy event to another is not simply following the passage of time in a linear and chronological manner. Instead, the continuity of a literacy event is multi-threaded and coordinated by the use of inscriptions. For instance, from the literacy event in episode 2 (lesson 6) to that in episode 3 (lesson 7), both lessons were separated by 1 day. However, through the table (i.e. Fig. 6.2), the activities on both days were coordinated and unfolded quite seamlessly. In addition, what circulated from one literacy event to another was not just a linear chain of inscriptions but a web of other non-human actors that came from other literacy events (not shown in the earlier illustration). For example, in episode 3, while the students were carrying out the QA tests by translating the written "actions" on the table into bodily actions and measurements and back into words, they also referred to a previously completed QA worksheet, which was the inscriptional product from a prior literacy event several days ago.

The third and perhaps most important point is that the continuity of the literacy events shown in Fig. 6.4 provides a more complete picture that allows us to compare to what extent the network resembles that of any scientific practice. We have earlier discussed that a scientific practice needs to be examined from the mutual interaction of its constituent performances within a system of performances, and not the individual performances in isolation (Ford, 2015). Thus, we cannot simply examine the performance within each literacy event to determine if it resembles any scientific practice, but rather we need to evaluate the scientific practice in light of the continuity of the literacy events as seen through an actor-network. In other words, scientific practice is a network of literacy events instead of a list of performances.

Returning to the example from the QA lessons, if we evaluate every literacy event against a set of criteria (e.g. NGSS list of practices) to determine whether the event mirrored scientific activities, we may say that the students were "carrying out investigations" and "constructing explanations". In carrying out investigations, the students followed laboratory and systematic procedures to handle the chemicals and record their observations. From their results, they also constructed an explanation of their conclusion. As for the NGSS practice of "engaging in argumentation", there was not much evidence from the literacy event that meets the criterion as defined in NGSS or resemble the research findings on scientific argumentation based on Toulmin's model (e.g. Erduran, Simon, & Osborne, 2004) or a dialogic perspective of argumentation (e.g. Kim & Roth, 2014; Kuhn & Crowell, 2011). For instance, there was no observable evidence that the students were using the language of claim, evidence, and warrant to support their justification, nor were they defending their conclusion against opposing results from their peers. However, when viewed as an actor-network in its totality, we saw the empirical basis of how raw materials were translated into inscriptions and later used as the justification to support the student's conclusion. We also saw how this translation of raw materials (in episode 3) was linked to the need to answer an unknown problem (in episode 1). This material aspect of how evidence is formed, collected, and represented in the context of a problem is an important part of scientific argumentation, which tends to be neglected by current frameworks that emphasise only the structural and dialogic aspect of argumentation (Ford & Forman, 2006). Furthermore, the actions involved in generating and representing empirical data is very much a literacy work as it is an argumentation practice, as we saw in the illustration.

6.6 Conclusion

How can this actor-network view be used to conceptualise and analyse research from disciplinary literacy and scientific practices? First, from an actor-network, we have a concrete way to describe the *enactment* of scientific practices as literacy events that are observable and interactionally constructed through the use of spoken words, written texts, graphic representations, bodily movements, apparatus, objects, substances, and specimen. Second, by tracing the connections of key literacy events through the inscriptions that are circulated in the actor-network, we can get an insight into the *characteristic* of the scientific practices in terms of the mutual interaction and interdependence of those literacy events. Third, by comparing actor-networks across different settings, we can better *evaluate* to what extent the network of literacy events in an instructional program reflects those in scientific practices.

An actor-network view has the potential to offer new research direction and methods to further connect the research between disciplinary literacy and scientific practices. One area is to generate more studies to illustrate actor-networks in different instructional and cultural contexts so that we can compare them to gain a number of insights. First, what makes a particular lesson enactment or intervention characteristic of a particular scientific practice? Second, what is the role of literacy in the lesson enactment or intervention that makes it characteristic of a scientific practice? For instance, the actor-network I have briefly illustrated can be compared to another actor-network of a lesson intervention focused on argumentation. By analysing the inscriptions and translation processes, we have a more grounded way of pinpointing what aspects of the literacy work make the lesson more or less like scientific argumentation. The comparison should also be made between the actor-networks in school science context and those in professional science, particularly when the literature in STS currently has many actor-network analyses of scientists (e.g. Callon, 1986; Latour, 1996; Latour & Woolgar, 1979). However, it is important to point out that the purpose of comparing with the practices of scientists does not imply that students must learn to mirror exactly what scientists are doing. Instead, the comparison must help us to identify the key differences by taking into consideration the larger networks that surround the actor-networks observed in the classrooms and laboratories (e.g. network of getting academic grades vs. network of getting publications).

Once we began to theorise and analyse scientific practices as an actor-network of literacy events comprising students, teachers, inscriptions, and materials, then the analysis of disciplinary literacy and scientific practices will be examining to some extent the same phenomenon. This thus provides a common frame of reference and meta-language that could mediate the cross-disciplinary work between literacy and science education. At a more specific level of analysis, the focus between both research communities might still be different in that literacy researchers would focus more on the language and linguistic aspects of various scientific practices, while science education researchers would examine the quality of the scientific discourse, explanation or argument, and its connection to scientific knowledge. However, at a more general level of analysis, both communities would share a common way of interpreting how language and representations are used to build scientific practices.

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Chapter 7
Immersive Approaches to Science Argumentation and Literacy: What Does It Mean to "Live" the Languages of Science?

Brian Hand, Andy Cavagnetto, and Lori Norton-Meier

While there has been much attention in science to the impacts of teaching on learning, the influence of socio-cultural orientations to classroom research, and the need to adopt and adapt curriculum to argument-based inquiry, the role of language writ large and its importance to learning have not received the same level of recognition. The groundbreaking article by Norris and Phillips (2003) was significant in that it clearly positioned language as indispensable to the learning of science, or any discipline. As they indicated there is no science without language. What does this really mean? A challenge we often give to science teachers is teach a science lesson removing all forms of language – text, graphs, picture, diagrams, graphs, equations (chemical and mathematical), and sign language. We are met with silence, as it becomes patently obvious to teachers that it is impossible for them to engage in anything resembling some form of learning. The teaching and learning of science cannot be done without these forms of language. This is critical because it immediately raises questions about how best to engage students with these languages, and how does such usage shape, or is shaped by, the learning environment that students are immersed in.

Understanding the role of languages in learning is important because they shape what type of learning experiences students will be engaged with. For example, while there have been many different lists made for what it means to be scientifically

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*, Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_7

literate, nearly all of these focus on replication in terms of language use and/or being able to read and interpret science languages. When this orientation is juxtaposed next to the epistemological criteria related to tentativeness, openness, critique, and skepticism, there appears to be a strong mismatch in orientation between language use and doing science – all of which are criteria for being scientifically literate. How does this manifest in science classrooms?

There has been a long history of science education research in the use of student-centered learning approaches (originally derived from theories on conceptual change and constructivism) within science classrooms. These approaches have strongly argued for the fact that students construct knowledge for themselves within science classrooms and that learning environments need to take into account students' prior knowledge and provide opportunities for conceptual resolution between everyday knowledge and disciplinary accepted versions of knowledge. However, such thinking has not focused on the languages of science, that is, while there has been a focus on students' constructing science knowledge, there has been very limited focus on construction of knowledge of the languages that underpins this construction process. Such a position has been strongly underpinned by a reliance on the work of Halliday and Martin (1993) who put forward a very strong genrist argument for doing science. They argued that students cannot learn science until they know the genres used by scientists. Thus, they have to know how to write laboratory reports before they can be let loose within the laboratory. This means that students have to be able to replicate the formats of reporting before they get to do science, because in knowing the formats they will be able to understand the science.

As the role of languages becomes more understood, then this raises questions about how should, or can, the concept of these languages as epistemic tools become aligned with the epistemic nature of science within science classrooms. What does it mean to have students understand that languages are tools that not only help them have a product from learning but are an essential component of their learning while they are learning the science? As new curricula focus on the practices of science, and suggest that learning environments need to focus more attention on involving students with these practices, what orientation to languages is needed to shift the community toward the concept of languages as epistemic tools? Norton-Meier (2008) has emphasized the need to go back to Halliday's original work where he put forward the concept that you learn about language through using language as you live the language. This orientation is much more about languages as epistemological tools, as compared to Halliday and Martin's genrist perspective which is much more about learning the languages of science.

In this chapter, we begin to explore how this living the language perspective can be linked to argument-based inquiry. There are a number of critical issues that need to be addressed: What type of argument needs to be implemented within classrooms? What knowledge bases are used by students within these classrooms? What are the cognitive resources that get developed through such environments? This shift in orientation is critical if we want to merge these different epistemological tools and discipline orientations to maximize learning for students.

7.1 Argument-Based Inquiry

In a review article by Cavagnetto (2010) on the use of argument-based inquiry approaches in science, he introduced the idea of immersive approaches to science inquiry. He introduced this term to differentiate between teaching and learning approaches to science argument that focused on a more traditional structured approach to the use of this type of inquiry and approaches to argument that were more oriented to socio-scientific issues. A critical difference between these different approaches is that the immersive approaches to argument-based inquiry place inquiry as the central focus of the learning experience for students – argument as an epistemic tool as opposed to argument itself as the learning goal. In a more recent effort, immersion into argument-based inquiry has been defined as:

> Argument-based inquiry is inquiry that is intended to build students' grasp of scientific practices while simultaneously generating an understanding of disciplinary big ideas. Construction and critique of knowledge, both publicly and privately, are centrally located through an emphasis on the epistemological frame of argument by engaging them in posing questions, gathering data, and generating claims supported by evidence. (Hand, Nam, Cavagnetto, & Norton-Meier, 2013)

The adoption and adaption of such a definition place the critical focus of developing understanding of the underlying scientific concepts of a topic as being achieved through immersing students in the epistemic practices of science as they learn the content knowledge of the discipline. Such a perspective is different from what has traditionally been the view of inquiry for students within school classrooms, where inquiry is used to confirm theory or as a precursor to content delivery. However, while there has been an emphasis in recent curricula put forward by different countries on engaging students in the epistemic practices of science, there still exists a lack of emphasis on immersing students in these practices as the central framework for learning.

This lack of implementation of immersive experiences is in part based around a lack of understanding of what these environments entail, how they are set up, what pedagogical skills and understandings need to be developed for success, and what are some measures of success that demonstrate immersion has occurred?

7.2 Emerging Studies

There have been a number of recent studies that have begun to show the value of placing students in positions where they are required to be an integral part of the learning experience. A recent publication by Resnick, Asterhan, and Clarke (2015) highlights a number of studies centered on the role of dialogical learning environments and the importance of these environments in promoting transfer. For example, Resnick and Schantz (2015) highlighted that transfer does occur within dialogical environments. Importantly, they highlight work by Adey and Shayer

(2015); O'Connor, Michaels, and Caphin (2015); and Topping and Trickey (2015) who showed in their respective studies that instruction in one discipline leads to significant gains by students in other nonrelated disciplines. For example, instruction in science leads to better performance in mathematics and reading (Adey and Shayer, 2015). Another study by Webb, Whitlow, and Venter (2016) that focused on examining the benefits of shifting learning environments to focus on the dialogical practices that underpin the argument-based inquiry approaches pushed by these new national curricula has resulted in transfer occurring. They highlighted that explanatory talk promoted success on the Raven's standard progressive matrices test compared with control studies. While these studies have provided evidence that transfer occurs, they do not address exactly what is transferred. Given that there is not a direct transfer of discipline content knowledge in these studies, it raises questions about what is transferred – if it is not content knowledge that gets transferred, then what is it?

The important points arising from these studies are that immersing students in situations where they are required to be active participants in the dialogical processes that frame the epistemic practices of a discipline does have benefit – not only in the learning of the discipline knowledge but also in promoting deeper reasoning and transfer of success into other disciplines. However, while these studies highlight the need to shift learning environments to incorporate richer dialogical engagement, they have not yet begun to explain why there is success.

7.3 Living the Language

In a recent publication Ardasheva, Norton-Meier, and Hand (2015) begin to provide a theoretical background to the role of languages in science classrooms, particularly in terms of immersive argument-based inquiry classrooms. Building off the original work of Michael Halliday, they posit that in order for students to be immersed in the languages of science, they have to "live" the languages of science. In much of the work by people working in the structured approaches to argument-based inquiry, students are required to learn about the languages of science prior to them using the languages of science. That is, much emphasis is placed on students having to learn the structure of argument separate from use – the argument being that one cannot argue in science if you do not use the words evidence, backings, warrants, etc. Interestingly when one reads science articles, one does not see scientists using these words as part of building their arguments.

Importantly Halliday suggested that students should learn about the languages of science through using them to live these languages. In their article Ardasheva, Norton-Meier, and Hand argue that it is at the intersection of these three positions that students become fully immersed in the languages of the discipline. They argue that within an argument-based environment, the language can be shifted to learning about argument through using argument as you live argument. One cannot have an argument without the languages of science – that is there is no argument without language. As Norris and Phillips (2003) have clearly pointed out, there is no science without language. Science as a discipline cannot advance without the languages of science. Scientists do not use these languages as tools for replicating the knowledge that has been constructed – languages are used as epistemological tools to advance the discipline. It cannot be advanced without these languages.

Scientists have to live the languages of their own discipline if they are to advance the discipline. Languages do not exist as separate entities to be replicated at critical junctures but exist as tools necessary for advancing a discipline. Understanding the nature of the tools begins to get us closer to understanding the nature of immersive environments. Do scientists have to pass vocabulary tests before they are allowed in the laboratory? Who tells scientists if they are allowed to use the languages of the discipline? Do scientists not use these languages as a vehicle for arguments within their own labs and through publications/conferences platforms? These languages (mathematical, textual, visual, etc.) are living tools that enable engagement within the discipline and the development of the discipline.

7.4 School Classrooms

If scientists immerse themselves in the languages of science as a function of doing science, should these practices not be what is done within school classrooms? Given the release of new national curricula like the Next Generation Science Standards where there is a much greater emphasis on the epistemic practices of the science, the question becomes how to engage students in these practices within the science classroom? Importantly, the further question becomes at what age can students engage in these types of practices both to understand science as a form of epistemic practice and to build understanding of the science content?

The excuses given most often are that students cannot be trusted to be engaged in these immersive environments, they lack the content knowledge to be able to be involved in these immersive argument-based inquiry classrooms, or they lack the sophistication to be able to argue in a scientific manner. However, this becomes a “Catch-22” effect for most educators – because they can’t do it, we can’t let them do it. This is a circular argument which gets away from the real question that needs to be addressed. These same students manage to build understanding of everyday language as they live their own lives. They learn language as they practice language because they use it as they live their lives. Yet we struggle as educators to take what is natural for learners and immerse them in these same types of experiences within science classrooms.

In imagining the use of immersive approaches, we also need to examine how these approaches may promote the transfer across disciplines that current studies are beginning to show. How does engagement in dialogical argument-based learning environments promote better results in other discipline areas?

7.5 Philosophical Perspective

The shift in the new national curricula in placing emphasis on the epistemological practices of each discipline raises issues related to what is learnt by students and what is able to be used by students as they move between different disciplines and into their future lives. This explicit emphasis on epistemic practices is a distinct difference from previous national curricula. In providing an explanation of the differences between science and mathematics, Moshman (2014) states that from an epistemological perspective science is framed around causal explanation which is "contingent and demonstrated through evidence" (p. 74), whereas mathematics is centered on "rule-based reasoning" and yields "objective truths" (p. 74). Thus, when considering the distinction between the two disciplines, there is a need to understand and distinguish between "the explanatory and causal nature of the empirical sciences from the formal necessities of logic and mathematics" (p. 80). Given that the content knowledge of each discipline is different, the question of what is available for each student to take into, and succeed in, learning environments centered on these practices becomes important.

In discussing this issue in relation to science, Bailin (2002) argues that scientists have intellectual resources which they apply across a range of inquiry activities, that is, a good thinker has a "constellation of resources" (p. 369) that he/she can bring to any inquiry activity. This shifts the conversation from knowing *that* (knowledge of ideas and cognitive skills) to knowing *how* (application of, and reasons for, using cognitive skills) (Mulnix, 2012). For Bailin (2002), this shift to knowing *how* moves the focus from "conceptualizing critical thinking in terms of skills or processes" to focus much more on "understand[ing] the criteria of good thinking … such understandings include criteria, concepts, and habits of mind as well as background knowledge" (p. 368). She argues for a "constellation of resources" that can be used across a range of situations in response to a "particular task, question, problematic situation or challenge, including solving problems, evaluating theories, conducting inquiries, interpreting works, and engaging in creative tasks" (p. 368). Thus, critical thinking can be viewed as "that mode of thinking that seeks to justify beliefs on the evidential relations that hold between statements" (Mulnix, 2012, p. 472), regardless of the context. Stromoand and Kammerer (2016, p. 231) have argued that the use of such resources aimed at "defining, verifying or justifying should be regarded as aspects of personal epistemology, and that the term epistemic cognition….maybe a more accurate term than epistemic beliefs." They refer to epistemic cognition as "cognitions related to knowledge and process of knowing."

7.6 Epistemic Cognition

Greene, Sandoval, and Braten (2016, p. 2) in their introduction to the recent *Handbook of Epistemic Cognition* also highlight that epistemic cognition is "cognition of or relating to knowledge." They argue that there is a difference between knowledge "that" (propositional knowledge) and knowledge "how" (procedural knowledge). In addressing the issue of "how," Elby, Macrander, and Hammer (2016, p.119) have argued for epistemic cognition being framed as "involving a rich variety of cognitive resources for understanding knowledge and how it arises." For Iordanou, Kendeou, and Beker (2016, p.48), epistemic cognition has to be viewed as a multifaceted construct including cognitive skills, meta-strategic understanding, and understanding of the epistemic norms of argumentation.

Sandoval, Greene, and Braten (2016), drawing on the work of Elby and Hammer, Chinn and colleagues, and Barzilia and Zohar, also put forward an argument that recognizes the idea that as part of epistemic cognition there are cognitive aspects that are fine-grained, activated in response to the context but are able to be used as epistemic resources. Building on this idea, Mason (2016), in highlighting the work of Hammer and Elby, suggests that while epistemic resources are used in a multiplicity of situations "cognitive structures activated in a given context" may "not necessarily [be used] in another, as different contexts trigger different resources" (p.380). While the concept of cognitive resources is argued for as an essential component of epistemic cognition, much of the current research in this field has focused on understanding epistemic practices and beliefs – that is, focusing on issues such as how learners generate and justify claims or the role of the individual versus the group.

7.7 Transfer of Learning

In thinking about the development of cognitive resources, one has to ask are there particular learning environments that promote such activity and development, and are these environments aligned with current thinking on transfer? We would argue that immersive environments where students are required to "live" the languages of science are environments which required active participation in the epistemic practices of science. As we have argued elsewhere, school classrooms are not science laboratories; however, the development of questions, claims, and evidence can occur in both if students undertake the same epistemic practices as the scientists.

Engle, Lam, Meyer, and Nix (2012) have put forward a model for transfer centered around students actively participating within learner environments. We would argue that active participation is aligned to immersion within the learning environment. They argue that certain conditions within these environments promote transfer. Importantly, they highlight that prior knowledge and authorship are two critical components of the environment that promote transfer. Prior knowledge is necessarily activated within immersion environments because students are constantly referring to what they know as a means to explain the phenomena under study. Building on this component is the role of authorship. Engle et al. argue that it is in the authorship of their ideas that set up the conditions for the transfer of what the students are learning. This concept of authorship builds on extensive research on writing to learn research, where language is viewed as an epistemic tool (Prain and Hand, 2016). We believe there is a third factor associated with Engle's model and that is the role of prosocial environments – that is, how students build an understanding of the role of groups and how they actively participate in groups as a function of the learning environment. In building on these ideas of transfer, Day and Goldstone (2012) highlight the importance of getting learners to engage with more abstract concepts than with narrowly defined specific concepts. They argue that it is through understanding ideas more abstractly that learners are able to better transfer learning to new situations.

In using these ideas, we would argue that the science writing heuristic (SWH) approach, an example of an immersive argument-based inquiry approach, builds on the "lived" experience of constructing science arguments as the basis for success across a range of different measures.

7.8 Science Writing Heuristic (SWH) Approach

The SWH approach was developed by Hand and Keys (1999) as a means to recognize the role of languages in building science arguments. The SWH approach is framed around a question, claims, and evidence structure to argument that requires students to construct and critique scientific arguments as a central means of learning science concepts. In a more recent development, the approach has been framed as being about three critical phases – the development of the underpinning epistemic framework of science, an argument phase, and a summary writing phase (see Table 7.1). These phases are based around helping students develop knowledge and practices related to science and to apply these aspects to building their own arguments as well as writing to others about the phenomena being studied.

These three are distinct and are important in the way in which knowledge and associated practices are developed and used. The underpinning epistemic framework phase is based on development of scientific practices and understanding how learning is framed around the big ideas of a discipline. Importantly, this phase establishes the dialogical practices that are essential in using language as the means to achieve private and public negotiation of ideas. The argument phase is the inquiry phase – students need to engage with the question, claims, and evidence structure of inquiry. This phase is centered on the ideas of Walton, in that the overall purpose of argument is to persuade. While argument may have explanatory components, the

Table 7.1 The three distinct phases of the SWH approach

Development of underpinning epistemic framework	Argument phase	Summary writing phase
Unit framed around 3 "big ideas"	Generation of relationship between questions, claims and evidence	Canonical version of science "big idea" for the topic
1. Science concept		
2. Learning is about negotiation		
3. The role of language		
Determining what students know and build unit plan form there	Small group work generation of data moving to claims and evidence	Use ideas related to writing to learn theory to guide writing task
Development of rules for negotiation	Product for review by whole class	Authentic audience of peers or younger learners
1. Ideas not people		
2. Role of group		
Engagement with/discussion of epistemic practices	Informal writing in notebooks – audience is self	Purpose is to breakdown canonical version of big idea into audience language
Generation of questions	Movement from everyday to canonical versions of content	
Research design		
Question/claims/evidence structure	Development of construction and critique skills	
Development of prosocial environment	Alignment to disciplinary knowledge related to "big idea" of topic	

intent of argument is to move from unsettled knowledge toward a more settled position. Our argument here is that while the science content knowledge in terms of disciplinary is agreed upon, in terms of the students, they are moving from unsettled, fuzzy understanding (unsettled) to a more settled (disciplinary norm) version of that knowledge. This phase places much demand on the students' knowledge of the languages of science and their abilities to use these languages. By this we mean language writ large – students have to engage in multiple forms of representation both verbally and in written form to construct and critique their arguments (justification of claims) and to present their arguments to the public. The summary writing phase is in Waltonian terms, about settled knowledge where the intent is not to persuade but to inform. Students are required to explain to an audience other than the teacher the big idea of the unit they have been studying. The big ideas are the disciplinary norms for the topic, and thus this knowledge is settled. The types of language used in this phase is the same as the argument phase; however, the need to take into account the audience they are writing for places demands on the students to be aware of translating the science language into audience appropriate language.

In aligning with the model for transfer put forward by Engle et al. to the SWH approach, we would argue that there are four critical knowledge bases that students have to engage with that promote transfer:

Science Content Knowledge – students are required to engage prior knowledge to build knowledge of the phenomena under study (one can argue this is the only knowledge they have to build this understanding). This type of knowledge does not have particular practices associated with it. It is the consequence of other knowledge bases.

Argument Knowledge – by living the language of argument, students are able to build understanding of what is an argument, what are the components of argument, and what are the relationships between the different components of argument. Associated with knowledge of argument are the practices associated with argument. That is, having knowledge of argument is not sufficient for success with science argument. Construction and critique are practices required within argument – you require knowledge of these, but as a learner you have to be able to put these into practice.

Language Knowledge – in living the language of science, students have to engage with language writ large, that is, they have to engage in all the representational forms of the concepts (text, pictures, graphical, symbolic, etc.) not only as a means to generate a product but as a process of generating the product (argument, summary writing). Language is something students have to know about (the different forms of representation) and use as an epistemic tool (practice of language).

Knowledge of the Learning Environment – students are sensitive to the culture of a learning environment and understand how much power and agency they have in different environments. In an immersive environment, students need to develop knowledge of how to participate, what is the responsibility of the individual vs the group, and how negotiation proceeds in this environment.

It is through engaging in the practices of argument and language that students can construct understanding of the science concepts under study. These epistemic practices are based on construction of knowledge not on information transfer systems. By being immersed in these lived experiences, students are required to engage with the critical elements of Engle et al.'s framework. They have to build from prior knowledge experiences, and they are responsible for authorship both privately and publicly of their own knowledge. Importantly, emphasis is placed on each student constructing knowledge of the big idea of the topic and not on replication of language associated with the concept. That is, authorship is given to the students, rather than demands being placed on them to replicate the teacher's language.

While these may be theoretical arguments, the question is: does this approach lead to gains argued for in immersive environments?

7.9 Results for SWH Approach

As highlighted above, the work around dialogical environments has begun to highlight the benefits to students in terms of performance increases in other discipline areas and in reasoning tasks. As a research group, we have been using the SWH approach across a range of different settings that have enabled us to begin to better understand some of the benefits of an immersive environment. A couple of these results are:

Early Childhood Study – the study was focused on examining the role of summary writing with students in K-2, particularly in relation to written text and development of representation understanding. Deb Nichols and her group have analyzed student writing in relation to teachers' years of experience. Students were asked to write about the "big idea" of the topic using whatever form of writing they wanted to. The results show that for teachers with greater than 18 months of experience with the SWH approach, students were significantly better at the quality of their text, their ability to link text with other representations, even though the amount of text they wrote was less. That is, students in these young grades are building the foundation for multimodal representational competency at a faster rate than students not engaged with the SWH approach.

Random Control Trial – this was a funded project working with 48 grade 3–5 buildings in rural Iowa to test the value of the SWH approach. The study focused on requiring grade 3–5 teachers in each treatment building implementing the SWH approach for 2 years and examined student performance onto the Iowa Test of Basic Skills for science, mathematics, and language. Results show that SWH students scored significantly better in mathematics and language than control students. In addition to this transfer into mathematics and language performance, the grade 5 students were tested using the Cornell Critical Thinking Test to look at comparing the rate of critical thinking growth rates between SWH and control students. The SWH approach students had significantly greater rates of critical thinking growth. Not only did the students transfer performance to math and language, they were better at critical thinking.

Undergraduate Chemistry Laboratory – we have been doing a number of studies at the undergraduate freshman level. The original work with Tom Greenbow's group showed that the level of implementation of the TA and students' buy-in was critical in terms of the improved performance on ACS exams. Importantly, in using the SWH approach achievement gaps were closed, particularly the gender gap. Recent work with Fatma Yamen in Turkey has shown that SWH students are able to develop a greater understanding of the triplet relationship, a critical underpinning foundation for success in chemistry.

While there are other SWH studies, these are a representative sample of the benefits of being in an immersive environment. Students within these different settings are being required to engage with science content knowledge, as they engage with the argumentative practices underpinning the discipline of science, as they are required to utilize the languages of science to construct and critique knowledge.

While these studies represent success, they are the starting point for us to build richer understandings of how, why, and when students use epistemic practices that frame a discipline and what epistemic resources are developed as a function of being in these immersive environments.

7.10 Questions Going Forward

The ideas put forward in this chapter are the beginning points to the development of a much richer understanding of the concept of "living the languages" of science. While the emphasis in science is the justification of claims, given the causal explanation epistemology of science, there is a need to focus greater attention on understanding the role of languages and learning environments learners use and engage with in building understanding of science concepts. We believe that by putting forward the concept of multiple knowledge bases and practices, we can begin to unpack the complexity of the learning situation students are placed in when they are a part of an immersive environment. Critically, these knowledge bases are not engaged in isolated situations within a classroom, that is, doing science in a classroom does not mean we learn science content, now it is time to learn about argument, etc. It is at the intersection of these knowledge bases that students are being asked to "live."

Students bring cognitive, cultural, and linguistic resources with them into the classroom – it is up to us to recognize these and create environments where students are required to be aware of, and adapt, their resources to these learning opportunities. How do we help students build onto their resources? We know from our studies that we consistently close the gap between socioeconomically disadvantaged students and their fellow classmates, we consistently close the gap between special education students and nonspecial education students, and we consistently close the gender gap. However, we do not yet understand the critical role these resources play in building understanding of science concepts – let alone understand how and why they promote transfer, particularly far transfer. Critically, examination of such resources needs to draw upon cognitive, sociocultural, epistemological, and linguistic perspectives to begin to build understandings that have application to real classrooms.

Supporting students in building on their existing resources requires consideration of access to resources. In particular, building on existing resources assumes that students recognize the available resources as beneficial resources (relative to the cost of accessing them). That is, engagement with science, argument, and language knowledge bases is dependent upon how students choose to engage in the broader classroom environment. Therefore, the learning environment is a critical aspect of science learning that we must come to understand.

One classroom resource in particular that we believe to be underaccessed are other students. Simply increasing the amount of student-student interactions does not itself lead to productive interactions (Nokes-Malach, Richey, & Gadgil, 2015); rather it is dependent upon interpersonal relationships. Ultimately these interpersonal relationships influence one's epistemic vigilance (evaluating information based on the norms of scientific practice). Rigorously evaluating positions based on the norms of practice is cognitively taxing and therefore easily perceived as a short-term cost. We conceptualize an epistemic vigilance Goldilocks zone that is driven by environmental factors that ultimately influence perception of benefit to cost of engagement.

Bookending one end of the Goldilocks zone is passive sharing of ideas. Even when students are grouped and share ideas, information can and often does flow like two ships passing in a dense fog (Cavagnetto, Hand, & Norton-Meier, 2010). On the other end of the Goldilocks zone is premature rejection of ideas. Epistemic vigilance is heavily dependent on trust – without it, rejection of ideas becomes artificially inflated. In essence trust of classmates can become the devil on one's shoulder – a convenient excuse for not engaging in deep thinking.

Resources, including other students, need to be perceived as beneficial relative to the cost of engagement with said resource (Balliet, Mulder, & Van Lange, 2011). Negotiation of the merits of ideas becomes particularly important among larger group sizes as such settings can provide a more accurate picture of science. Science is exceptionally collaborative. The number of people involved in collaboration occurs across labs and, even within a single lab group, can be equivalent to the number of people interacting in a normal K-12 classroom. This raises the question of how does one create a broad classroom environment in which the benefit to cost ratio is great enough to support *living* the languages of science? There has been a good deal of work done examining and supporting small group interaction (Johnson & Johnson, 2009); yet little work in education has explored larger group sizes. So how does one support productive interactions at larger grouping levels? What are the key environmental factors that influence one's perception of benefit to cost? and What is the influence of whole-class collaborative environments on student reasoning, critical thinking, and measures of academic achievement?

In summary, the broader science classroom environment has largely been ignored. In the previous paragraphs, we speculate (based on the literature) of how environment can positively or negatively influence student learning. How much does the classroom environment matter? Is it possible that instructional activities and nuanced differences among science curricula account for a minor portion of the variance in performance when environmental factors such as cohesiveness among students are considered as a variable? At this point, no one knows. However, we would argue that finding answers to these types of questions does require recognition of the different knowledge bases and practices used within these environments, the cost/benefit ratio for participants, and how these impact on the development of the intellectual resources (including the cognitive resources) as a learner moves between the different environments within and outside of school.

Addressing such questions requires that multiple theoretical perspectives be utilized in constructing potential theoretical answers. Given the complexity of any learning environment, there is not going to be a single theoretical position that will adequately address this complexity. Thus cognitive, linguistic, representational, sociocultural, and epistemological frameworks are going to be required in order to address some of the questions raised. This immediately raises the question of what research methodologies should be employed in order to help address the development of such theory. As with the variation in theoretical positions, we need to be aware of the myriad of potential research methods that can be used. We believe that there is going to be a need to not only use the broad expanse of the current existing methods but also that we should take advantage of the changing technologies that are being created to support such research. Brain imaging technologies, computer modeling, and social media forms, for example, are all new areas that have the potential to be very useful in this work.

While we have located our current work within the context of using the science writing heuristic approach, we would argue that it is one approach reflective of an immersive learning environment. There are others that are emerging, and as a collective, we believe it is important to think not about a single approach but to focus on the broader view of immersion. For us, the SWH approach is a starting point to better understand the broad questions that relate to the idea of learning environments and the languages of science.

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Chapter 8
Writing as an Epistemological Tool: Perspectives from Personal, Disciplinary, and Sociocultural Landscapes

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There is a long history of psychological and educational research into using writing as a learning tool to develop students' disciplinary literacy (Klein & Boscolo, 2016), promote their conceptual understandings (Jang & Hand, 2016; Mason & Boscolo, 2000), motivate students to learn various subjects (Magnifico, 2010), and foster their self-regulated skills (Harris, Graham, & Adkins, 2015). However, how and why writing functions as an epistemological tool remain unclear and has not yet been explicated. We still do not know much about why and under what conditions writing can be considered an epistemological tool, what pedagogical competences are needed to engage students in epistemic writings, and what knowledge are critical to develop and measure.

Epistemology has been discussed and conceptualized in various ways based on researchers' beliefs, purposes, and agendas. In this chapter, epistemology is referred to as the nature, scope, sources, and theory of knowledge and knowing, especially with regard to normative matters of justification and truth (Moshman, 2014; Sandoval, Greene, & Bråten, 2016; Tsai, 2000). Thus, epistemology is concerned about how knowledge is constructed and developed. In this chapter, I focus in particular on three perspectives of epistemology to discuss how and why writing operates as an epistemological tool: (1) a psychological and cognitive perspective (*personal*), (2) a disciplinary perspective (*disciplinary*), and (3) a sociocultural and situated perspective (*sociocultural*). These three perspectives are not mutually exclusive. Rather, each perspective emphasizes particular rationales of the epistemology of writing and pays less attention to others.

Psychologists primarily conceptualize writing as cognitive processes to clarify, reorganize, and generate knowledge. While some researchers have defined writing as a problem-solving activity with a hierarchical view of top-down goals (Bereiter

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*,
Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_8

& Scardamalia, 1987; Hayes & Flower, 1980; Kellogg, 2008; Keys, 1999), other research has characterized writing as a cognitive loop making implicit schema into explicit texts that consequentially prompts further syntheses designed to reduce mismatches between individual syntheses and the writer's disposition (Galbraith & Torrance, 1999; Galbraith, Torrance, & Hallam, 2006). Although no universal definition or interpretation exists regarding how writing per se functions as an epistemological tool, this perspective treats knowledge as a personal representation through writing acts. The focus is on how and why the process of writing involves deliberate strategies to trigger knowledge development.

Educational researchers within the disciplines consider how writing contributes to students' knowledge development of subjects grounded in the philosophical nature of the disciplines themselves. For example, science educators consider issues such as how writing serves a role in students' logical reasoning, critical thinking, and understanding of what counts as knowledge. These researchers have expanded the definition of writing as single representation—texts—to multimodal representations, such as diagrams, tables, drawings, and mathematical equations, due to the nature and scope of scientific knowledge. Studies with this perspective examine how adapting a different approach to writing can make difficult and abstract concepts more plausible and intelligible for students.

Sociologists examining writing as an epistemological tool treat it as a resource to scaffold students' knowledge negotiation, evaluation, and justification within a community. This perspective views knowledge as accomplished across contexts through particular discourses, rather than just personal and disciplinary outcomes. Writing often has been analyzed through a combination of dialogic interaction, reading activities, and computer-supported collaborative learning. Pedagogically, writing has been claimed to play different roles than talk and reading. According to this perspective, it is only through the integration of writing with talk and reading that students can engage in productive knowledge development.

Each of the three perspectives describes potential conditions to define what and how writing can be considered as an epistemological tool. In this chapter, I briefly discuss how knowledge is constructed through writing and what approaches have been adopted and adapted through the three perspectives. Finally, future trends and implications that stem from those works will be discussed.

8.1 Writing as an Epistemological Tool from a Psychological and Cognitive Perspective

Janet Emig (1977) presents the first effort to make a case for writing as a personal tool to generate knowledge, describing an integrative model. Emig views writing as an integrated process involving three categories of cognitive activities: (a) enactive, learning by doing; (b) iconic, learning by depiction in an image; and (c) representational or symbolic, learning by restatement in words. The most efficacious knowledge generated by writing occurs when the three cognitive activities are simultaneously or nearly simultaneously deployed in an inherent reinforcing cycle.

Hence, writing can be viewed as a uniquely multi-representational or integrative model for knowledge generation. The integrative model is both process and product; that is, it allows for immediate feedback and reinforcement of the process while continuously displaying the written product. This constant back-and-forth of process and product, work and reward, is what makes writing so central to epistemology. Emig's notion that writing can be a tool of knowledge generation sparked a number of scholars to investigate the issue of writing as a language tool for learning (e.g., Galbraith, 1999; Hand, Hohenshell, & Prain, 2007; Hayes & Flower, 1980; Keys, 1999; Klein, 1999). However, how, why, when, and where the immediate feedback and reinforcement of process generation in the act of writing occurs are not clearly addressed in this model. How do writers actually choose diction, syntactic and organizational patterns, and content? Is there a difference between expert and novice writers in terms of their cognitive processes toward knowledge development?

Hayes and Flower proposed a problem-solving model to distinguish the difference between expert and novice writers in the act of writing as well as to address how experts and novice writers plan and make decisions about writing processes (1980, 1996). They argue that experts construct a more elaborate representation of their goals and continue to develop and modify those goals throughout the process of writing. Experts develop explicit rhetorical goals for the text as a whole and use these to guide retrieval of content, whereas novices rely on more concrete content goals and tend to generate content in response to the writing task. Consequently, experts develop more elaborate plans and modify them throughout the course of writing, rather than simply considering whether the text produced is appropriate. That is, the experts use the act of writing as a problem-solving activity, which can also be thought of as a goal-driven process. Unlike a traditional product-based view of writing as a linear process of plan-write-edit, Hayes and Flower argue that an important feature of writing is the recursive nature of the process. During the process, the writer finds the solution to a rhetorical problem and evaluates or revises goals that correspond to that solution. However, Hartley (1991, 1993) argues that the context in which this model has been developed is not sufficiently specified. Namely, it only concerns a single writer who works alone. Collaborative writing is thus not taken into account, although it is growing increasingly more frequent, most notably with the utilization of e-mail, Facebook, and Google Drive. Will all writing tasks lead to learning (Bereiter & Scardamalia, 1987; Hand, 2007; Langer & Applebee, 1987)? Langer and Applebee (1987) suggest that not all forms of writing promote the use of all the cognitive processes identified by Hayes and Flower. Their study indicates that writing activities such as note-taking are considered review activities, while essay writing engages more reformulation activities. Review activities require the writer to focus on specific content, while reformulation can promote higher-order thinking and new knowledge generation.

Bereiter and Scardamalia (1987) proposed knowledge-telling and knowledge-transforming models that can explain why not all writing leads to knowledge generation. Knowledge telling, typically employed by younger and less experienced writers, involves the associative retrieval of topic-related content from long-term memory and the direct translation of this content into text. The knowledge-telling model does not generate new knowledge because it relies on previously established connections between content elements and readily available discourse knowledge. In contrast, knowledge transformation, typically employed by expert writers, involves working out rhetorical goals and using them to guide the construction of content and evaluate the adequacy of text. The knowledge-transforming model may increase the writer's knowledge acquisition through content and discourse processing. That is, the writer can generate goals and sub-goals in the content space and transfer them to the rhetorical space in terms of ideas to be expressed, and the rhetorical space produces goals and sub-goals for the content space in the form of substantive problems to solve. Keys (2000) characterized specific content and rhetorical thinking engaged in by 16 Grade 8 students using think-aloud and qualitative analysis methodologies. The result showed that students needed to generate content for writing and did so through content problem-solving, as predicted in the knowledge-transforming model. On the other hand, students generated rhetorical goals and content sub-goals prior to beginning writing. Along the same lines, Klein (2004) examined the effects of using an informal journal style on 64 university students (non-science majors) who conducted a physics experiment on buoyancy and force on a balance scale. The results indicated that the knowledge-transforming model can foster student generation of new knowledge while using a problem-solving writing process.

Galbraith and Torrance (1999) address two major troublesome aspects of the problem-solving concept of writing (Bereiter & Scardamalia, 1987; Hayes & Flower, 1981; Hayes, 1996; Hayes & Flower, 1980). First, the problem-solving approach has remained a high-level, top-down account of writing, focusing on the explicit thinking process rather than on the more implicit process whereby thought transforms into text. Second, "Although we know quite a bit about the different kinds of thinking strategies involved in high-level components of writing, we know little about how thinking is linked, moment by moment, with the production of the text itself" (p. 4). From a text production perspective, Galbraith (1999) sketched a dual-process model of writing. The first process is the knowledge-transforming process as described by Bereiter and Scardamalia (1987) and involves the evaluation and modification of determinate ideas in working memory in order to create a mental model of the text that satisfies rhetorical goals. However, this process does not create new ideas. Instead, it either selects and organizes existing ideas "directly retrieved from episodic memory" or, when such content is not available in episodic memory, activates input to the second process (p. 146).

The second process is the knowledge-constituting process that assumes that, over and above the explicit representation of formulated ideas in episodic memory, the writer's knowledge is also represented by implicit relationships corresponding to the fixed connection between sub-propositional units in a constraint satisfaction network. These relationships constitute the writer's disposition toward the topic. Two implications follow from this assumption. First, the writer's ideas are not retrieved directly from episodic memory but are synthesized by constraint satisfaction within the network in the course of text production. Second, the writer's disposition is "represented by the set of utterances as a whole rather than by one particular utterance" (p. 147). Thus, it is assumed that each individual synthesis of content produces only a partial best fit to the writer's disposition and that feedback from this output prompts further syntheses designed to reduce mismatches between individual syntheses and the writer's disposition. A later study by Galbraith, Torrance, and Hallam (2006) suggests that the two processes are assumed to be complementary in their effects and that both are required for effective writing. Therefore, the knowledge-constituting process is "responsible for synthesizing conceptually coherent ideas, but needs the knowledge transforming process in order to ensure that content is presented in a rhetorically appropriate form" (p. 1341).

Historically, the cumulative theory-building pattern among different models is evident. For example, all three models are inspired by Emig's notion, Scardamalia and Bereiter's model (1987) is derived from Flower's and Hayes model (1980), and Galbraith's model includes Scardamalia and Bereiter's perspectives on explicit problem-solving. These models explain that not all writing has the potential to be an epistemological tool. Writing can be considered an epistemological tool when the act of writing is a complex cognitive activity. Importance is placed on how to engage novice writers in more complex writing models and how to effectively teach young students to use writing as an epistemological tool through the theoretical cognitive writing models.

8.2 Writing as an Epistemological Tool from a Disciplinary Perspective

A number of writing instructional approaches have been developed within different disciplines in recent years to provide students with more opportunities to use writing as a tool to organize and generate new knowledge. When writing is used within specific disciplines, writers have to consider the essence, philosophy, and nature of the discipline. That is, writers not only need to engage in rhetorical and linguistic networks but also with what constitutes the discipline. There are at least three perspectives on the writing approaches integrated in disciplinary-focused classrooms: (1) the approach of learning to write, (2) the approach of writing to learn, and (3) the hybrid approach of learning to write and writing to learn. To address these three perspectives, I draw on my professional background in science education research.

The first perspective clearly emphasizes the need for students to engage with the structure of the genres of writing as a precursor to doing science (Porter et al., 2010). The work of Halliday and Martin (1993) adopted the position that it is necessary to learn how to write prior to learning science; that is, students need to learn the genres of writing before they get to use them. An example of this "learning to write" approach is Self-Regulated Strategy Development (SRSD) instruction (Harris, Santangelo, & Graham, 2008). SRSD is a strategy to develop writing skills and self-regulation through incorporating guidance about the writing process that diminishes as internal guidance is developed. More than 40 studies adopting the SRSD in classrooms have consistently shown significant student gains in knowledge of writing, skills of writing, and self-efficacy, especially among students with significant learning difficulties. This approach is rooted in the assumption that writing is used as a tool to improve students' literacy more than as an epistemological tool to increase knowledge.

Researchers on reading employed the approach of learning to write to improve students' reading skills and comprehension (e.g., Fitzgerald & Shanahan, 2000). In a meta-analysis of true and quasi-experiments, Graham and Herbert (2011) concluded that writing about material read enhances students' comprehension of reading. That is, teaching students how to write advances their reading comprehension, word reading, and reading fluency that eventually lead to knowledge clarification and elaboration. The effect size they reported for extended writing activities, note-taking, asking or answering questions, and summary writing was all positive for reading comprehension, ranging from 0.28 to 0.68. The combination of learning to write and writing to read elevates the potential of writing as an epistemological tool to improve students' knowledge reconstruction after reading activities.

The second perspective is "writing to learn," in which students increase their conceptual understanding through a variety of writing tasks. Gee (2004) suggested that writing should be embedded within the learning experience that scaffolds students to reflect, argue, and explain the theories, laws, and concepts being taught. For instance, Dianovsky and Wink (2012) investigated the impact of the use of reflection journals in a chemistry course of elementary education majors on students' final course grade and grade point average (GPA). They found that student learning through writing had a positive impact on final grade and GPA.

However, not all writing to learn activities have an equal potential to promote knowledge development. A study by Gunel, Hand, and McDermott (2009) incorporated writing to learn activities in biology classrooms by asking students to write letters to different audiences, such as younger people, instructors, parents, and peers. They found that students performed significantly better when writing for a younger audience and peers than when writing for teachers or parents. Chen, Hand, and McDowell (2013) contend that writing to instructors and parents usually engages students in what Bereiter and Scardamalia (1987) called the knowledge-telling process, in which students just express preexisting conceptual structures. Students expect instructors and parents to be capable of understanding what they write and thus do not attempt to explain and persuade them. However, students writing to younger audiences and peers naturally engage in the knowledge-transforming process and Galbraith and Torrance's (1999) knowledge-constitutive processes due to translating demands. That is, in these cases, students consider that their audience may not understand the concepts, and thus they first translate their scientific knowledge to the language they typically use (home language) to aid comprehension of the concepts. Second, they need to translate everyday language to the language of their audience. Third, they may need to translate their audience's language back to scientific language to ensure the completion of the writing tasks. These translating processes particularly help students to re-evaluate, reflect, and seek the weaknesses of their ideas and further reconstruct their conceptual understanding (Kingir, 2013; Magnifico, 2010).

Obviously, only when students engage in highly cognitive-demanding writing modes, such as knowledge transformation or constitution, can writing contribute more to knowledge development and be considered an epistemological tool (Dianovsky & Wink, 2012). This probably explains why some writing tasks used by other researchers have had trivial effects on conceptual development (Klein & Boscolo, 2016).

Disciplines such as science are considered subjects that involve the combination, integration, and interconnection of mathematical expressions, abstract diagrams, quantitative graphs, informational tables, and a host of unique visual genres (Lemke, 1998). Klein (2006) suggests that writing in science becomes largely narrative and interacts with thoughts and fuzzy concepts that can only be represented by multiple representations. Building on this concept, McDermott and Hand (2013) investigated the impact of a writing to learn activity embedded within multiple modes of representation on students' performance in a unit about atomic structure. Their results show that students who engaged in this kind of writing to learn activity significantly outperformed students who did not. By examining students' writing samples, they further revealed that students who produce multimodal writing tasks with a high degree of embeddedness display greater conceptual understanding. That is, students involved in more demanding writing processes by embedding and tightly connecting different modes better improved their conceptual understanding. They further claim that writing tasks should be carefully designed to scaffold students to fruitfully develop competency through embeddedness techniques. That is, although writing can foster students to construct knowledge, students also need to learn a variety of the modes aimed at writing processes (Ainsworth, 2006). A study conducted by Klein (2000) shows that only a small portion of students benefit from writing to learn activities. He suspects that students probably do not perceive the purpose of the writing strategies they are taught. Nussbaum, Kardash, and Graham (2005) suggest that students not only need to use writing as a learning tool but also need to learn what they should accomplish when completing a writing task.

The third perspective is a hybrid of learning to write and writing to learn. This perspective claims that students not only need to learn the genre of writing but also need to use it as a tool to learn canonical concepts. This assumption rests on students' ability to transfer writing skills to the development of disciplinary knowledge (Prain & Hand, 2016). The research conducted by McNeill and colleagues (McNeill, Lizotte, Krajcik, & Marx, 2006) applied this perspective to foster students to understand core concepts in chemistry. They adapted Toulmin's argument patterns to a school-friendly argument structure: claim, evidence, and reasoning. Students were explicitly taught the argument structure and applied the structure to their journal writing when they conducted experiments by following prompts that diminished in frequency as they gained experience in developing meaning through argument structure. The analyses showed significant gains in students' conceptual understanding. Similarly, an instructional writing model called Argument-Driven Inquiry (ADI) creates an environment mediated heavily by writing (Sampson, Grooms, & Walker, 2011; Sampson, Enderle, Grooms, & Witte, 2013). Unlike traditional science labs that culminate in writing a summary report, ADI engages students in argumentative writing tasks as part of the inquiry process to promote their understanding of concepts and the advancement of scientific writing skills at the same time. ADI turns the nature of science—interpreting data into evidence, coordinating theory and evidence, and providing appropriate evidence to support claims—into individual and collaborative writing activities. Students not only learn how to craft scientific writing but also learn core concepts through writing.

Nevertheless, researchers have continuously reported that there are limitations to using writing alone and to focusing on writing as an individual-product perspective to support knowledge construction. For example, McNeill (2009) investigated the effect of using a written argument structure in science classrooms and found that although performance on posttests had improved, students still had difficulty reasoning in their written arguments. She conjectured that students' thinking and writing to justify claims were strongly influenced by social dialogue, which "offer[s] a way to externalize internal thinking strategies embedded in argumentation" (Jimenez-Aleixandre & Erduran, 2008, p. 12). This view is supported by van Amelsvoort, Andriessen, and Kanselaar (2007), who contend that dialogue with peers about their written explanations helps students become immersed in the process of using argument to develop their conceptual understanding of reasoning skills. In this regard, written language is not only more complete but also socially distinct because of the opportunities it allows a writer to revise and make individual products more publicly accepted.

8.3 Writing as an Epistemological Tool from a Sociocultural and Situated Perspective

Studying writing as a sociocultural practice entails viewing it as part of the process and product of knowledge development through social activities (Mason, 2001; Syh-Jong, 2007). For Wickman, "epistemologies are not entities of isolated individuals but of individuals participating in socially shared practices" (2004, p. 327). Based on the sociocultural perspective of epistemology, knowledge evolves through a process of negotiation and consensus building (Goldman, 1999; Green, 2016; Strømsø & Kammerer, 2016). Van Aalst and Truong (2011) contends that knowledge development requires talk, writing, and representational evaluation to investigate questions, generate arguments, and justify the extent of advancing knowledge within a peer community. According to Vygotsky's perspective (1978), increased cognitive challenges and justifications as well as useful negotiations can therefore be scaffolded using a variety of writing forms. That is, knowledge construction occurs through a series of active negotiations of meaning in or between private and public aspects while utilizing a variety of writing forms and modes to clarify those meanings.

Writing, from this perspective, is not a matter of internal cognitive process but rather an interpretative commingling of the writer's actions and disposition as well as values in the community (Gee, 1996; Magnifico, 2010). Bakhtin (1994) explains this situation:

> Together with the verbal factors, they also take in the extraverbal situation of the utterance. These judgments and evaluations refer to a certain whole wherein the verbal discourse directly engages an event in life and merges with that event, forming an indissoluble unity. (p. 3)

Writing, talking, and social experience become unseparated and complementary resources in the process of knowledge development. This is especially true for current reformed science classrooms that emphasize constructing explanations validated by a community, arguing from evidence, and communicating through information (NGSS Lead States, 2013). By reviewing 54 articles, Cavagnetto (2010) introduces a concept of immersive approaches to distinguish this more socio-orientated use of writing to more traditional structured approach. One of an extensively research approach is the Science Writing Heuristic (SWH; Ardasheva, Norton-Meier, & Hand, 2015; Keys, Hand, Prain, & Collins, 1999). The SWH approach is rooted on conception of learning science as a community of inquiry mediated largely by writing. The function of writing is portrayed in explanatory context as an embedded component weaving varied activities such as small group discussions, whole class discussions, investigations, and reading occurring cylindrically. A study conducted by Cavagnetto, Hand, and Norton-Meier (2009) within an SWH classroom found that students were engaged, on average, in talk associated with generating an argument for 25% of the time but talk associated with representing an argument in a final written form accounted for 71% of the time (students were on task 98% of the time). Specifically, students oftentimes utilized writing and talk simultaneously to represent or defend their knowledge claims and interpretation of evidence. The researchers further suggest that the kind of writing associated with talk occurring within the group context may have encouraged students to higher levels of argument than would have been achieved if the task had not required representation of the argument in written form.

To elucidate the empirical impact of the use of talk and writing together on students' conceptual understanding, studies by Rivard and colleagues (Rivard, 2004; Rivard & Straw, 2000) have found that writing and talk used together were more effective than either talk alone, writing alone, or a control condition in contributing to aggregate knowledge on a posttest and delayed posttest, especially of more complex concepts. They suggest that "writing only seems to work if talk works with it" (Rivard & Straw, 2000, p. 586). From a social-linguistic perspective, talk and writing have been recognized as critical learning tools for productive knowledge development.

Extending from Rivard's studies, Chen, Park, and Hand (2016) investigated how students used writing for knowledge development through constructing and critiquing arguments within an argumentative environment while learning two science units (i.e., ecosystem and human body systems), during a 16-week period. They identified that the synergistic use of talk and writing (i.e., *talk and writing in sequence*; *talk and writing simultaneously*) has greater potential to support argumentation in terms of cognitive, social, and epistemic engagement than the use of talk and writing separately (i.e., *talk only*; *writing only*). They suggested that talk only and writing only engaged students in the practice of construction but not critique. Knowledge development in these two conditions is more about clarifying and confirming well-defended concepts rather than justifying claims with evidence. In contrast, the synergistic use of talk and writing engaged students in critical argumentative practices, especially the use of evidence to justify, negotiate, and make sense of alternative arguments. Students are also scaffolded during synergistic use to epistemically engage in causal reasoning and scientific thinking processes through integrating their everyday knowledge with scientific knowledge (Laman, 2011). Chen et al. (2016) further suggested that writing is not only a process and product for knowledge development but also a critical resource for students to make sense of each other's ideas when used for collective discussion. This sort of writing freezes students' ideas on paper, which consequently creates a negotiation space to discuss, debate, and debunk arguments.

In the condition of *talk and writing simultaneously*, writing is not a static artifact but is instead a dynamic representation of spontaneously interacting with an audience. Thus, writing is a social resource adapted to communicate, negotiate, persuade, and co-construct knowledge validated by a community. Tang and colleagues (Tang, 2016; Tang, Delgado, & Moje, 2014) have found that written language plays a significant role in mediating the dialogic move from interactive-dialogic to interactive-authoritative and eventually builds canonical knowledge among students. In a similar vein, Waldrip, Prain, and Sellings (2013) found that written representations were used as reasoning and negotiation tools to develop students' conceptual understanding of motion through the scaffolding of teachers' prompts. Nichols and colleagues (2016; Gillies, Nichols, & Khan, 2015) found that writing as social representation not only fosters students to advance difficult concepts but also improves their argumentative and interpreting competencies. In this situation, writing serves several purposes: it externalizes and visualizes presenters' internal ideas to an audience for discussion, evaluation, and critique; it is used to clarify and identify the deficiencies of presenters' ideas; it creates a serious reasoning process, engaging students in making their knowledge more coherent; and it is explicated and annotated in drawings, diagrams, and tables to make causal conceptual arguments within the different modes fostered by talk.

When writing serves as a social epistemological tool, Yoon (2012) claimed that students engage in dual processes: cognitive process for crafting writing responsible for audience and social process for evaluating and critiquing writing in order to improve the writing and be acceptable by the community. Students' knowledge begins from fuzzy understanding about a phenomenon and move toward developing consolidating knowledge through social negotiation (Hand, Villanueva, & Yoon, 2014).

Recently, Graham (2019), drawing from on activity theory (Greeno & Engestrom, 2014) and the concept of genre as epitomized ways of engaging in tasks for social purposes (Bazerman, 2016), proposed a model to consider two perspectives from a cognitive and sociocultural perspective: writing community and writer(s). In this model, the cognitive capabilities of writers and their collaborators within the community shape the value and function of what is written and what is represented.

Cognitive resources not only include individual's dispositions, beliefs, and knowledge for rhetoric, linguist, and composition for the writing task but also include acquired social knowledge for speaking, listening, reading, representing, interpretation, justification, presumed audience, and the purposes, norms, and practices of the writing community in questions (Graham, Harris, & Santangelo, 2015). Five optional components are included in this model: purpose (how writing is used within a community), members (who serve as an audience and the power structure for the community), tools (means to accomplish writing tasks), actions (practices that a writing community uses to achieve writing objectives), written product (complete texts and tangible artifacts writers use while composing such as past drafts of text, notes, drawings, films, or recordings of ideas), physical and social environments (physical place involves where people congregate and digital locals; social environment involves the relationships between members of the community), and collective history (identities, roles, responsibilities, norms, and values developed through the community). This model is promising but still requires more targeted research to substantiate in different disciplines and contexts.

8.4 Trends and Future Directions

Table 8.1 recaps the features of writing as an epistemological tool through the lens of the three perspectives. Each perspective offers a unique but complementary philosophical view and practical approach to how knowledge is constructed and generated. For instance, disciplinary, sociocultural, and situated perspectives are rooted in and apply models from psychological and cognitive perspectives to disciplinary-focused learning environments. Across the three different perspectives, some common themes emerge and future directions are suggested.

First, writing as an epistemological tool from personal perspective more likely only happens under higher and demanding cognitive conditions. A trend becomes clear in the research from all three perspectives that not all writing activities have the potential to serve as a tool for knowledge construction, development, and generation. From a personal perspective, it seems only when students engage in knowledge transformation or knowledge constitution processes that writing can obtain maximum capacity as an epistemological tool. Does this mean that as long as we create writing tasks and environments that are matched to knowledge transformation and constitution, students will engage in higher cognitive processes to produce knowledge? The answer is probably, disappointingly, no. For example, a study conducted by Chen, Hand and Park (2016) created an argumentative writing task for

Table 8.1 The features of writing as an epistemological tool across three perspectives

	Epistemology	Writing approach
Psychological and cognitive perspectives	Knowledge is considered to be mental possession, idiosyncratic beliefs, and personal theories of individuals influenced by how they conceptualize the way of knowing	Hierarchical and explicit problem-solving
		Process across three major elements (task environment, long-term memory, and writing process) to deal with the goals
		Dual-drafting strategy (explicit problem- solving process and implicit knowledge- constituting process) to stabilize conflicting inputs
Disciplinary perspective	Knowledge is constructed based on the nature and philosophy of disciplines themselves. Taking science as an example, knowledge is constructed through solid evidence with multiple and appropriate reasoning	Learning to write: students need to learn linguistic, rhetorical, and disciplinary knowledge to craft writing
		Writing to learn: students learn concepts through completing writing tasks
		Hybrid of learning to write and writing to learn: writing is embedded in the learning process. Students use writing as a tool to produce knowledge through learning to complete writing tasks
Sociocultural and situated perspective	Knowledge is accomplished through particular social events, including debates, negotiation, and communication among members of a group	Immersion-based intervention: writing as an embedded component weaving inquiry process
		Writing is an activity occurring before/after/during social events depending on its function and purpose for knowledge development. Writing is a dynamic mode and serves as a resource to negotiate, communicate, and represent

fifth graders to explain and persuade their peers about their group arguments using claims and evidence. They found that students did not engage in high cognitive writing processes such as synthesizing and comparing in the beginning of the unit even though they were situated in high-cognitive writing tasks. Students treated writing as a tool for expressing and presenting, which is how they had used it in past learning experiences. Writing can work as an epistemological tool only when students perceive that it has the potential and function to clarify, reconstruct, and generate knowledge. However, how can we scaffold students to effectively perceive and understand the purpose of writing tasks teachers have designed for them? How can students develop their understanding of how to use specific writing tasks to foster their knowledge development? Future studies should focus on two layers: First, what and how are students' perception of the function of writing influenced by and related to the writing strategies they implement for tasks? Second, how can we nurture and elevate students' engagement with higher writing processes?

Second, based on disciplinary perspective, it becomes clearer that students need to learn the purpose, genre, function, and "hidden" rules of writing in order to engage in the writing to learn condition. That is, writing to learn by learning to write provides more opportunities for students to understand the nature of different writing tasks and transform that understanding to drive them to develop knowledge through the writing tasks teachers' design. This raises a question: How can we effectively and efficiently support students to engage in this approach? In science education, scholars such as Cavagnetto (2010) and Klein and Boscolo (2016) have suggested that writing tasks should be embedded in inquiry to require that students practice writing through interpreting data to create evidence, crafting claims and support for evidence with reasoning, and revising written arguments according to peers' evaluations. Cavagnetto and Hand (2012) call this "immersion-based intervention," wherein students simultaneously learn how to write through the experience of writing to learn. However, it is still not clear how "immersion" happens in classrooms. We also need substantial research to explore how immersion-based intervention benefits different students, especially second language learners, special students, and early childhood learners (Huerta, Lara-Alecio, Tong, & Irby, 2014). What scaffolding do we need to consider and provide for those groups when they engage in this intervention?

Third, researchers are increasingly viewing writing as a social epistemological tool with a disciplinary focus, adapted by interacting with others via discourse such as semiotic signs, multimodal representations, and social norms. Epistemology as social practice assumes that knowledge is framed through social discourse and interpreted among peers within a particular community (Lidar, Lundqvist, & Östman, 2006; McDonald & Kelly, 2007; Sandoval et al., 2016). Therefore, "writing is inherently social and shaped by cultural influences" (Prain & Hand, 2016, p. 433). My early work suggests that writing as a social epistemological tool involves students in an iterative process of negotiating meaning between social interaction in small group and whole class settings, which is the public landscape, and a cognitive dynamic within individuals, which is the private landscape (Chen, 2011). When students move quickly and effectively between the two landscapes, their knowledge construction and critique can best be facilitated. The synergistic use of writing and talk plays a critical role in moving students between the two landscapes. However, more empirical evidence and a coherent theoretical framework must be developed and articulated about how writing acts a mediated role between private and public landscapes. It is also definitely the case that such efforts at synthesis across these three perspectives of epistemology are much needed, especially as they may be related to what social and disciplinary rhetorical constraints influence students to construct writings, what particular social feedback impacts students' writing revision in order to eventually develop new knowledge, and the dynamic relationship between writing and talk in different disciplinary and social contexts.

8.5 Closing Remarks

Results from review of research from the three perspectives suggest that the future research directions draw from and influenced across perspectives. However, the concept of viewing writing as an epistemological tool from the sociocultural perspective is relatively new and innovative to research in science education. As discussed above, writing from this sociocultural perspective plays a role to weave talk and reading activities to develop knowledge coherently. This means that both teachers and students are required to possess different bases of knowledge to have successful and productive engagement that is much beyond the psychological and cognitive perspective (personal). For example, students need to understand how to negotiate their ideas to others in order to reach consensus that may result in knowledge development. Students need to have sophisticated understanding about what counts as good claims and evidence and apply the understanding to writing and talking activities. Students also need to understand how to engage in all the representational forms of the concepts (text, pictures, graphical, symbolic, etc.) and to generate a product after negotiation. Therefore, more research is needed to be explored about what knowledge bases and resources can be developed, used, and measured in order to have productive engagement.

Ardasheva et al. (2015) have suggested that immersive approaches have potential to engage diverse students in learning science concepts "as a balancing act between simultaneously focusing on language and content development," especially for English language learners (ELLs) (p. 201). They claimed that students can simultaneously learn academic language and social language through immersive approach. However, it is still not crystal clear about how students learn the two different systems of language through immersing in this kind of writing environment. We also lack understanding of the trajectories of ELLs that construct their knowledge and language within immersive approach. Both quantitative and qualitative studies across culture are needed to reveal and unpack the effectiveness of immersive approach.

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Chapter 9
Scientific Literacy Practices from a Concept of Discourse Space: Focusing on Resources and Demands for Learning

Sae Yeol Yoon

In 2016, there was a very interesting match between human and artificial intelligence (AI). In this match called Google DeepMind Challenge Match, a human professional player, Lee Sedol, and a computer Go program, *AlphaGo*, had a five-game Go match. Differing from many experts' predictions in regard to this historic match, AlphaGo won all but the fourth game. Go has long been considered a difficult challenge in the field of AI and is considerably more difficult to solve than chess since this complex board game requires intuition, creative deliberation, and strategic thought (Bouzy & Cazenave, 2001). However, this advanced program or AI exceeded human capacities to seek and utilize *resources* as well as the strategies to manage *demands* of the task. In other words, AlphaGo was literally better than the human champion, not only at reading the opponent's external strategies but also at considering his potential strategies by seeking the patterns retrieved from multiple previous matches and by comparing those with the patterns that emerged in the match. During this process, AlphaGo also ran countless simulations for reviewing and evaluating the observed and potential opponent's strategies and finally selected its own strategy. Of course, it might be just one of a few areas AI could surpass human thought (Remember, AlphaGo was built to do one thing only using 1920 CPUs and 280 GPUs!), but the results of this event were shocking to me. It was not because AI defeated a human professional player but because I witnessed that AI had been advanced to successfully employ humanlike intuitive processes, as well as reflective or evaluative processes in order to make a decision. Additionally, it was quite stunning to observe its self-learning processes (or called deep learning on big data analytics) by utilizing available resources and interpreting and managing demands. In this chapter, drawing from several cognitive science perspectives, I discuss human cognitive processes that AI continuously tries to learn, and then I

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*,
Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_9

explore two elements, “resource” and “demand.” These elements play a key role in any complex process, task, or practice and are essential in rethinking the goal of science education to incorporate the concept of scientific literacy.

For over two decades, the term scientific literacy has been exclusively discussed in science education. In this time, there have been many attempts to answer two critical questions regarding what scientific literacy means. The first question relates to applications of scientific literacy in classroom practice and student learning. The second question asks what teachers must do to support scientific literacy with their students (Cavagnetto, 2010; Yore & Treagust, 2006). Although the meaning of science literacy does not have a universally agreed upon definition, Norris and Phillips (2003) indicate that these dual interacting senses of science literacy are broadly accepted in the field: the fundamental sense of general literacy skills of speaking, listening, reading, and writing in science and the derived sense that is comprehension of a body of knowledge in the discipline of science. This dual emphasis in defining science literacy has contributed to a search for pedagogical interventions that are most likely to encourage the development of science literacy for students (McDermott & Hand, 2010). One way to address the investigation for effective pedagogy in science, then, is to view the traits of a scientifically literate person. The National Research Council offers this description:

> Scientific literacy means that a person can ask, find, or determine answers to questions derived from curiosity about everyday experiences. It means that a person has the ability to describe, explain, and predict natural phenomena. Scientific literacy entails being able to read with understanding articles about science in the popular press and to engage in social conversations about the validity of the conclusions. Scientific literacy implies that a person can identify scientific issues underlying national and local decisions and express positions that are scientifically and technologically informed. A literate citizen should be able to evaluate the quality of scientific information based on its source and the methods used to generate it. Scientific literacy also implies the capacity to pose and evaluate arguments based on evidence and to apply conclusions from such arguments appropriately. (National Science Education Standards [NSES], 1996, p. 22)

According to a definition and description in the National Science Education Standards that is similar to Norris’ and Phillips’ (2003) definition, scientific literacy has been seen as the ability or capacity achieved by individual learners (see Table 9.1). Although the general ideas and definition of scientific literacy proposed by multiple sources, including NSES, seem broadly accepted in the field, recent understanding indicates that this view might be problematic if scientific literacy was solely limited to an individual’s ability or capacity. A growing number of scholars have proposed that complex human activities integrally include internal processes of thought, as well as external representations and interactions among individuals (Hutchins, 1995; Zhang & Patel, 2006). Therefore, scientific literacy cannot be limited to individual cognitive processes alone. For this reason, this chapter discusses possible ways to extend the definition of scientific literacy from the perspective of science education. As students achieve core practices and outcomes in science classrooms, pedagogical practice should include collaborative engagement. Particularly, this chapter discusses potential theoretical approaches to “scientific literacy practices” through both collaborative and individual learning processes,

Table 9.1 A scientifically literate person by NESE (1996, p.22)

A person	can	ask	answers to questions derived from curiosity about everyday experiences.
		find	
		determine	
	has the ability to	describe	natural phenomena.
		explain	
		predict	
	is able to	read	with understanding articles about science in the popular press
		engage in	social conversation about the validity of the conclusions.
	can	identify	scientific issues underlying national and local decisions
		express	positions that are scientifically and technologically informed
	is able to	evaluate	the quality of scientific information on the basis of its source and the methods used to generate it
	has the capacity to	pose	arguments based on evidence and to apply conclusions from such arguments appropriately
		evaluate	

leading learners to be literate in the discourse of sciences in both the fundamental and derived senses.

9.1 Klein's Three Shifts and Scientific Literacy Practices

First, Klein's (2006) theoretical suggestions on scientific literacy provided valuable insights into possible scientific literacy practices in science classrooms. Drawing from contemporary cognitive scientists' perspectives, he argues that in science education, there have been two distinct but interconnected perspectives for explaining students' cognitive processes of reasoning, language use, and knowledge construction. In terms of these so-called *first-* and *second-generation* perspectives, Klein suggested that learning is traditionally described according to a *first-generation* perspective, wherein reasoning or thinking is seen as a process of physical symbol manipulation, and is explained in terms of meaning-neutral formal rules, such as deductive logic for manipulating propositions. In this perspective, knowledge is constructed as a system of propositions, comprised of strings of classical concepts with necessary and sufficient features and well-bounded sets of referents. Language viewed from a first-generation perspective is a by-product of thought where cognition operates on textual representations of science content in the same way it operates on the science knowledge the text represents. Meanwhile, the second-generation perspective recognizes that students' initial understandings in science are perceptually-based, fuzzy, and contextual. With respect to reasoning or thinking, Klein suggested that the mind is modeled as a connectionist network engaged in perceptual simulation or pattern completion and analogy, wherein language is primarily metaphorical and narrative.

Although Klein (2006) highlighted the second generation of cognition, he also argued against the dualistic notion that either of the "generational" cognitive perspectives is "right" or "wrong" in science classrooms. Instead, he argued that there was a difference between the two approaches and that each was beneficial to the learning and teaching of science. Therefore, the main argument in his work was to highlight the benefits that each perspective brings. He stated that science education should attempt to bridge first- and second-generation perspectives by providing students with opportunities to shift from second- to first-generation cognition. He focused on three shifts in terms of reasoning, the use of language, and knowledge construction: (a) a shift that emerges as a student develops written argumentation as a form of scientific text based upon their everyday oral language; (b) a shift that emerges as a student develops formal reasoning, which requires understanding scientific concepts based upon their perceptually driven reasoning; and (c) a shift that emerges as a student develops personal understanding of classical concepts as scientific ideas based upon his or her fuzzy, contextual concepts of the world.

Klein's (2006) theoretical suggestions were well supported by this author's previous studies (Hand, Villanueva, & Yoon, 2014; Yoon, 2012). From empirical data, a *five-phase model* was proposed. This model exhibited five different phases of fifth-grade students' learning processes throughout a unit of study (see Fig. 9.1). This five-phase model gave a snapshot of the shifts that participants went through as they learned about science, focusing particularly on how fifth-grade students' use of language (written texts and diagrammatic representation) had been changed depending upon their reasoning as it appeared in their writing. In the studies, participating students brought many interesting ideas on the topic at the beginning of the unit but those looked like more personal experience-oriented (*contextual, perception-based,*

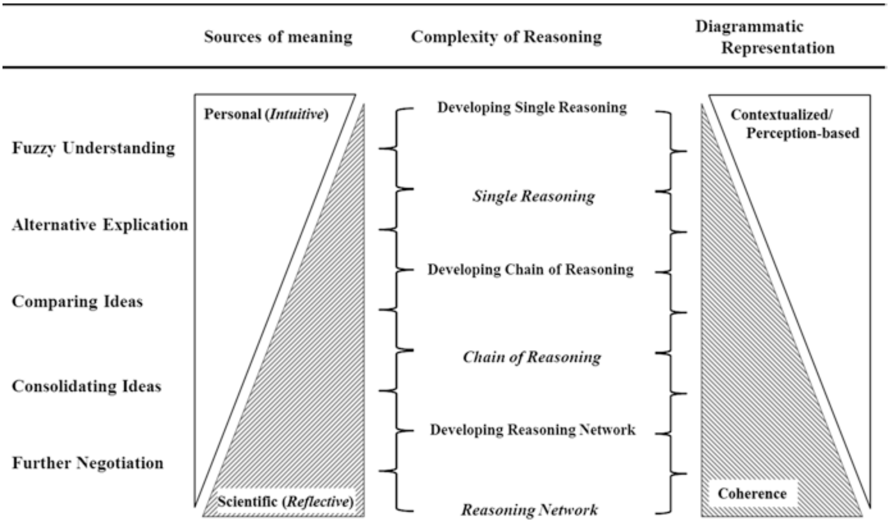


Fig. 9.1 Five-phase model by Yoon (2012)

and fuzzy). The ideas were expressed and shared through their own personal language, and not yet fully elaborated. For example, student diagrams offered limited cues for observers to understand what their ideas were, how their ideas were related to the written text, and why those ideas were presented. It did not mean that the students as producers did not know what they were doing, what they produced, and why. Rather, it seemed that they probably did not feel any need or face any demand that required them to explicitly describe all of the information for their potential readers or audiences. In addition, although a lot of information was provided through reading so that students could use that material at the early phase, most of them did not simply borrow the text information. Instead, researchers observed more frequent use of students' own words and ideas, both in writing and talking.

However, student reasoning was more sophisticated through student engagement in learning activities that required them to share, compare, evaluate, and argue ideas with one another, leading to new patterns in student scientific literacy. That is, the use of language, reasoning, and knowledge development, appearing in both written and verbal language, began to be more sophisticated and complicated, and multiple cues emerged to indicate that students in the role of producers were aware of potential readers or audiences. The changes observed in five phases (see Fig. 9.1),were closely associated with the shifts proposed by Klein (2006). Findings indicated that observed changes in the use of language, reasoning, and knowledge development were interconnected and interdependent, giving an insight that scientific literacy pedagogical practices should embrace all three changes or shifts together, rather than any one practice in isolation. That is, literacy learning may be limited in the discourses of sciences when teaching practices in science classrooms emphasize solely either general language practices, individual reasoning skills, or knowledge construction. Klein (2006) did not explicitly explain scientific literacy practices that would occur in terms of shifts that emerge when both the first and second generations of cognition interact with one another. Yet, it could be assumed that such shifts are always accompanied by and observed in scientific literacy practices.

This chapter, however, did not intend to define scientific literacy practices or to introduce practical classroom interventions. Instead, the author focused this chapter on theoretical scientific literacy practices that always lead to three shifts. In order to further understand the shifts, the following sections provide information about two core elements, resources and demands, that play a key role in scientific literacy practices. A particular learning environment where students interact with two elements is explored in light of dual processing theories and situative approaches.

9.2 Resources and Demands for Scientific Literacy Practices

Resources and *demands* are two core elements for understanding scientific literacy practices that lead to Klein's (2006) three shifts. Resources for scientific literacy practices refer to items and activities that are available and accessible to students in their individual cognitive processes, as well as in shared social practices (i.e., talking, discussion, group lab activities, group presentation, etc.). However, resources are not simply limited to physical resources such as blocks for counting numbers, computers for searching information, thermometers for measuring temperature, and other materials that students use for their classroom empirical activities. Cognitive and representational resources are also considered to be essential resources for scientific literacy practices. These three types of resources have complementary relationships that have a condition such that the use of multiple types of resources can supplement limitations that the use of only one resource inherently has.

For example, the appropriate use of thermometer (physical resource) requires a student's previous understanding of what it is, as well as their prior experience of how and why it is used (*internal* cognitive resource regarding a concept of temperature and the instrument of thermometer). If the student has been instructed about the thermometer (*external* cognitive resource), there might be higher likelihood for the student to use it more appropriately. Written text instruction (representational resource, which might also work as additional cognitive resource) might be fine, but if there are some pictorial descriptions (additional multimodal representational resource) on how to use it, the student is more likely to use the thermometer even more appropriately. Of course, the instruction itself cannot be seen only as cognitive resources for users since cognitive resources are always represented by *texts* (here, a word of *texts* is used in a broad meaning of sign systems that include any forms of representations of meanings). In other words, cognitive resources cannot be simply separated from representational resources. Interestingly, physical resources also contain implicit *affordances*, which might lead users to use and think in an intended or designed way, so it could be argued that all three types of resources are interconnected.

According to the situative approach, the use, nature, and purpose of resources may be negotiated and actively constructed by students (or participants in the practices) through representation as a part of scientific literacy practices. Although some resources can be seen as external representations of internal, individual cognition, the resources often changed, transformed, or evolved depending upon learning tasks (or activities), environment (as a collective culture of activity systems), and participants (as core agents) (Hand et al. 2014; Yoon, 2012). The changes, transformation, and evolution of students' uses of the resources are closely associated with Klein's three shifts as discussed previously. For example, Yoon (2012) revealed the changes of the use of language and multimodal representations throughout the unit in an elementary classroom setting. The representational resources in speaking and writing were examined. Data analysis showed the changes in those resources based upon learning activities or tasks. Also, dynamics in the use of resources were observed when external resources were imported both in written and spoken discourses (i.e., teacher's instruction, reading, talking with peers, presenting, watching videos, etc.). Students' own internal resources also emerged and continuously interacted with the newly appeared or shared resources. These interactions were optimized in "joint action" such as talking, resulting in the construction of shared information (Clark & Schaefer, 1989). This shared information was found in students' individual writing journals and encouraged them to review, refine, and reframe the previous and current resources that resulted in the changes, transformation, and even evolution of resources over time. Of course, such conversions definitely depended upon students' understanding and interpretation of demands of the activity, as well as the established culture of the learning environment that might be seen as an activity system.

For instance, in a traditional science lesson, most resources were given by the instructor (a major voice in the established activity system) or through curricular materials. Under this condition, the ways to read, interpret, and utilize resources were mostly predetermined or guided by the instructor, with the major demand seen as completion of the given task or finding the predetermined correct answer, so that students were provided to limitedly explore alternative ways. Consequently, the degree in students' interaction with and utilizing resources would be small. These methods, as a whole, characterize a common culture of learning settings, often referred to as a traditional science classroom. Once this type of culture was established, similar patterns might be repeatedly observed. Therefore, understanding how to utilize, develop, and interact with resources would play a key role in meaningful scientific literacy practices.

From this perspective, Lamb, Hand, and Yoon (2016) examined the relationship between students' use of resources and cognitive dynamics. In the study, 15 college students were asked to respond to two different writing prompts. As students produced the requested written texts, their brain activities were examined through the use of functional near-infrared spectroscopy (fNIRS) technology. College students' use of resources and reasoning complexity were analyzed in two different writing samples, and the relationships between their writing and brain activities were also examined. The major demand for two writing tasks was to generate a letter for a target audience to explain the topic. In the first writing prompt, 20 vocabulary words related to the topic were given as external resources without additional information such as definition and explanation, and students could select some of given words for their writing. In the second writing prompt, information on the topic with different representational modes including written text description, tables, and a graph were given as resources. Although students were identically asked to generate a letter for a target audience to explain the topic, data analysis on student writings and cognitive dynamics indicated that students' responses to the second writing prompt possessed more sophisticated reasoning structures and more brain activity was detected (see Fig. 9.2).

With 20 vocabulary words provided as external representational resources, students generated an explanation of the topic by primarily utilizing their own internal resources from prior knowledge. According to cognitive load theory, people represent knowledge as networks of connected facts and concepts that provide a structure for making sense of new information. The construction of schemas and the automation of schemas require learning (Sweller, 2010). This theory indicates that students would have difficulties representing well-structured knowledge unless they had previous learning opportunities on the topic and rich understanding of it. In the first writing prompt, due to limited external resources, students rely on their own

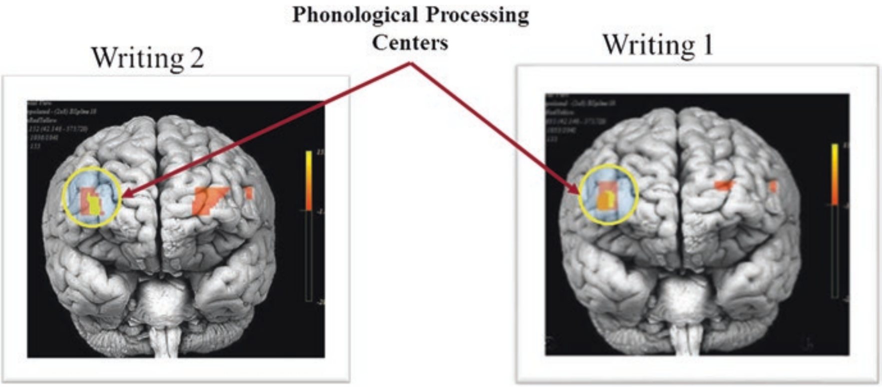


Fig. 9.2 Visual comparison of two writing tasks by Lamb et al. (2016)

limited internal resources. For this reason, less structured knowledge or less sophisticated reasoning was found. On the other hand, the second writing prompt offered a lot of information with which students could interact. Students were asked to interpret the external resources, and the newly interpreted external resources interacted with their internal resources (existing knowledge). As a result, the transformation of the external resources was observed in their written texts. This transformation process in utilizing resources led them to more actively engage in cognitive processes that might encourage or require them to reorganize and further develop their own internal resources. Consequently, students were more likely to engage in additional cognitive processes such as reviewing, rearranging, evaluating, and transforming resources to meet the demand of the task, resulting in more sophisticated reasoning in written texts and more cognitive dynamics as seen through the functional near-infrared spectroscopy.

In sum, Lamb et al. (2016) stated that limited opportunities for college students to interact with external resources led to their reliance on prior knowledge as internal resources when they were asked to generate an explanation. This recalling/generating and limited transforming process resulted in relatively less developed reasoning complexity, as well as in a lower activated cognitive dynamic. On the other hand, diverse opportunities to interact with both external (new) and internal resources led students to engage in cognitive processes, enabling them to change, transform, and evolve through the use of the resources to meet the demand for the task. In this case, students as producers were more considerate of the general quality of their own outcomes. Student participants engaged beyond completion of the task that required them to apply cognitive processes such as reviewing and evaluating the flow of ideas or reasoning structures as well as the need for reorganizing and restructuring both external and internal resources. Findings of this study implied that the resources available and accessible to students play a critical role in their cognitive processes that possibly impact students' engagement in scientific literacy practices to a higher degree.

In this section, resources as a core element in scientific literacy practices were discussed. However, the changes, transformation, and evolution of resources always depend upon the demands of learning activities, environment, and participants. In the following section, the author discusses how to encourage students' more active engagement in the changes, transformation, and evolution of resources, particularly focusing on demands in scientific literacy practices.

9.3 Dual Processing Theory and Demands for Scientific Literacy Practices

In exploring demands in scientific literacy practices, this chapter adopted the theory of dual processing. In this theory, any observed cognition such as the use of language, reasoning, and knowledge construction is imagined to result in part from two types of cognitive processes working in concert – one each aligned in some way with the two aforementioned generational perspective "types." There have been multiple attempts to model dual processing according to a wide range of characterizations of its paired processes: "implicit" versus "explicit," "heuristic" versus "analytic," "automatic" versus "controlled," "domain-specific" versus "domain-general," and "associative" versus "rule-based" (Reber, 1993; Sloman, 1996; Smith & DeCoster, 2000). In this chapter, the two processing types based upon the heuristic-analytic theory (Evans, 2006; 2011; Evans, Over, & Handley, 2003) have been adopted.

According to the heuristic-analytic theory, type 1 processing is called *heuristic/intuitive* processing with the major goal of generating selective representations of knowledge. Cognitive processes that occur because of type 1 processing are fast, automatic, and belief-based and selectively focus attention on task features that appear relevant. Prior knowledge is introduced in this process (Evans, 2011). On the other hand, type 2 processing is called *analytic/reflective*, indicated when learners make inferences or judgments from representations generated by type 1 processing. Analyses and reflection include evaluation that is often slow, explicit, and understood as abstract and decontextualized (Stanovich, 2009). The heuristic/intuitive and analytic/reflective processes do not simply work separately, but as a set of systems, and, as such, continuously and iteratively share representations. Heuristic processing generally supplies hypotheses within contextualized reasoning, while analytic processing critically evaluates the representations generated by heuristics and, if need be, modifies or replaces them. Although analytic processing is used to evaluate all possible representations generated by analytic processing and gathered by other sources, this slow, explicit, and sequential evaluation process may have bias, depending on individuals' cognitive capacity, resources, and context. The two types of processing are interdependent and do not occur in a simple sequential way. In fact, heuristic processing sometimes even competes with analytic processing (Verschueren, Schaeken, & d'Ydewalle, 2005).

The descriptions of these two processes may have merit in describing students' engagement in analytical and reflective processing as they transition between Klein's (2006) *first-* and *second-generation* ideas. Similar to students' fuzzy ideas, heuristic processing constructs default or initial inferences are based upon the individual's background knowledge, perceptions, and contexts. This processing is linked to implicit reasoning, since this type of reasoning requires a learner to retrieve the most plausible or relevant knowledge claim, and is thus a relatively fast process influenced by contexts. In this sense, the inferences that students generate initially are not always scientifically acceptable. Rather, it shows students' perceptually driven reasoning and fuzzy contextual understandings of a topic. Meanwhile, valid scientific reasoning, texts, and knowledge goals can be aligned with the major features of analytic processing, requiring a characteristically reflective level of cognition. Therefore, for successful mediation or negotiation between Klein's three shifts (2006) that is a necessary condition for scientific literacy practices, students need a particular challenge that requires them to practice and engage in analytic and reflective processing in their use of language, reasoning, and knowledge construction, as well as heuristic and intuitive processing.

For example, Yoon, Aguirre-Mendez, Nurcan, and Hand (2014) explored the effects of audience awareness on students' understanding of sciences. Thirty-one ninth-grade students were asked to write a letter to summarize and explain a scientific topic for fourth graders. Sixty-four fourth-grade students in teams of two reviewed the letter with guiding questions and offered feedback including questions, critique, and comments. Applying fourth graders' feedback, ninth-grade students rewrote their letters. This study examined both writing samples and feedback. In data analysis, a one-way repeated measures MANOVA was conducted to compare the scores of ninth-grade students' pre- and post-writing, focusing on four different types of knowledge: knowledge of argument, knowledge of rhetoric, knowledge of scientific content, and knowledge of multimodal representation. The results showed that students' overall composite writing scores of knowledge in all categories significantly improved from pre-writings to post-writings. There was a significant effect for pre- and post-writing scores, Wilks' lambda = 0.677, $F_{(2, 30)} = 4.452$, $p < 0.011$, multivariate partial eta squared (η^2) = 0.11. Given that the differences between pre-writings and post-writings were obtained, the paired sample T-test was conducted to evaluate categorical differences on ninth-grade students' pre- and post-writing scores. Results indicated that there were statistically significant mean differences between pretest and posttest scores on knowledge of argument (MD = 0.581, SD = 0.172, $t = -3.374$, $p < 0.002$, $d = 0.30$) and knowledge of rhetoric (MD = 0.613, SD = 1.086, $t = -3.143$, $p < 0.002$, $d = 0.27$) and significant mean differences between the pretest and posttest scores of ninth graders' knowledge of content (MD = 0.419, SD = 1.177, $t = -0.1984$, $p < 0.056$, $d = 0.19$). However, there were not statistically significant mean differences in knowledge of multimodal representation (MD = 0.097, $p = 374$) (see Fig. 9.3).

The results of this study indicated that younger audiences' feedback seemed to impact the observed mean differences in terms of multiple types of knowledge as they appeared in ninth graders' pre- and the post-writing. Importantly, in this study,

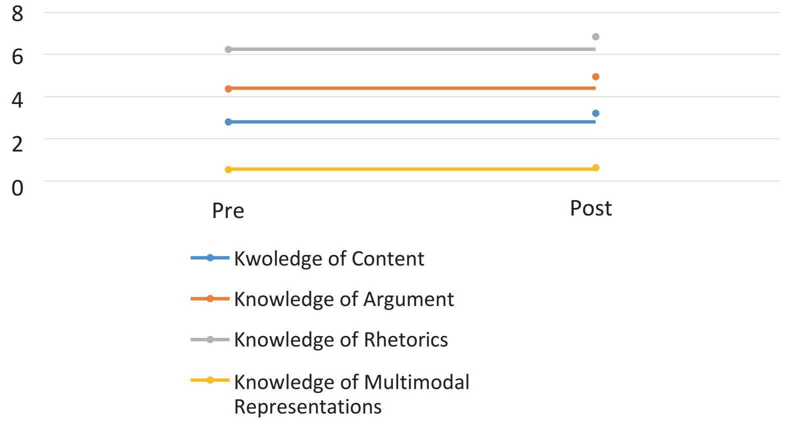


Fig. 9.3 The comparison of knowledge variable means by Yoon et al. (2014)

the feedback served as external resources that created both explicit and implicit demands for ninth graders to engage further in type 2 processing. First, the rewriting activity based upon the feedback helped students to improve the quality of writing (knowledge of rhetoric) since it required them to review and reorganize ideas, as well as to check mechanical writing components such as grammar and spelling. Second, the guiding questions fourth graders used were based upon core epistemic elements of argumentation, so the feedback enabled student writers to reconsider and evaluate the coherence among questions, claims, and evidence in their original writing (knowledge of argument). Interestingly, statistical significances were not found in knowledge of content and multiple representations. Younger audiences' feedback differed from that of a content expert, implying that ninth graders received very limited attention to the scientific contents from younger reviewers, so that it might be unnecessary for them to elaborate the content in their original writing (knowledge of content). The same interpretation is possible for understanding students' use of multiple representations (knowledge of multimodal representation) in writing because there were no explicit demands either in ninth graders' writing prompt or in guiding questions and instruction of fourth graders.

In sum, scientific literacy practices should provide diverse opportunities for students to build, transform, and develop their own capacity based upon both internal and external resources. Additionally, scientific literacy practices should embrace the demands for students to engage in both type 1 and type 2 processing. Yet, the discussion on resources and demands should not be limited to individuals' cognitive processes. These two core elements could be dramatically changed based upon the ways in which students interact with others, as well as a learning environment where they engage in the shared social practices. Therefore, in the following section, the resources and demands for scientific literacy practices are further discussed, focusing on students' interactions and a learning environment through the concept of discourse space.

9.4 Discourse Space: Interactions Among Resources, Demands, Participants, and Cultures

Drawing from cognitive linguistics' perspectives (Chilton, 2005; Moulin, 1995), Yoon (2012) proposed a concept of discourse space that is comprised of a set of external representations of meanings that participants in discourse accessed, changed, and developed while engaging in a particular practice. It is seen as the theoretical space where the embodiment of individual's and multiple agents' experiences of discourse, knowledge, and practice can be observed. The externally represented resources and demands in discourse space serve as potential materials that improve participants' current and future experiences. The concept is particularly useful to generate a systematic presentation of dynamic changes of resources (physical, cognitive, and representational) and demands, while students engage in diverse science classroom discourses, knowledge development, and practices over time. The critical point in understanding of this concept is that discourse space does not simply refer to a system of activities nor to a learning environment. Instead, it offers the critical cues enabling teachers to restructure and recontextualize a system of activities and a learning environment where learners interact with each other and with physical, cognitive, and representational resources in their environment.

Discourse space changes, transforms, and evolves depending upon participants, activities, and classroom cultures. Drawing from Bernstein's (1999) concept of vertical and horizontal discourses, Yoon (2012) stated that the process of developing discourse space in science learning was understood via the movement from the horizontal to the vertical discourse stage (see Fig. 9.4). Bernstein defines the differences between vertical and horizontal discourse as follows:

> …a vertical discourse takes the form of a coherent, explicit, and systematically principled structure, hierarchically organized, as in the sciences, or it takes the form of a series of specialized modes of interrogation and specialized criteria for the production and circulation of texts, as in the social sciences and humanities… [In contrast], a horizontal discourse entails a set of strategies which are local, segmentally organized, context specific and dependent, for maximizing encounters with persons and habits. (Bernstein, 1999, p.159)

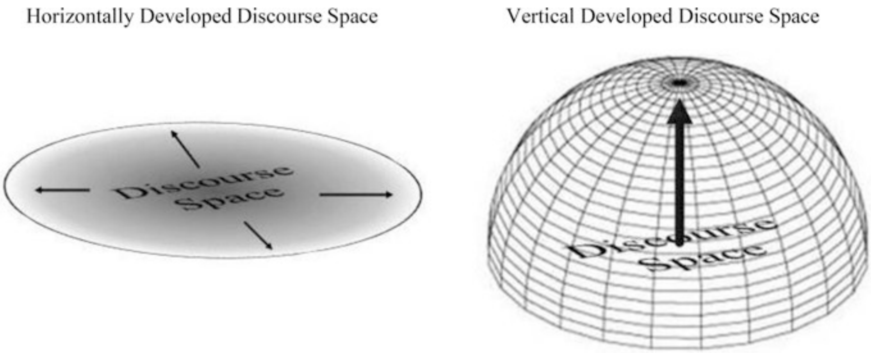


Fig. 9.4 Two different developments of discourse space

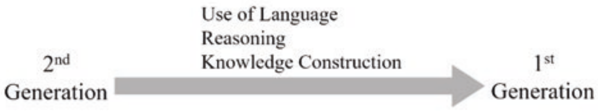
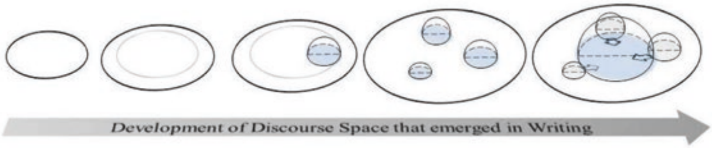
That is, when students engaged in the vertical discourse stage by analyzing, evaluating, elaborating, and advancing the ideas that were generated and shared at the horizontal discourse stage, the discourse of science might take place. This movement from the horizontal to the vertical discourse occurred while students had engaged in multiple scientific literacy practices, and it would be closely linked to Klein's (2006) three shifts. Students' active engagement with both type 1 and type 2 processing might function as the vehicle bridging this movement and three shifts.

The changes of discourse spaces could be observed both in an individual's cognitive artifacts (i.e., writing) and in shared social practices (i.e., group discussion). These changes could be linked to the Hutchins' (1995) argument that cognition does not occur solely within an individual mind but rather is distributed across people, artifacts, and environments. That is, such changes were largely influenced by the ways in which participants shared, utilized, and developed resources; the ways in which they communicated the appeared demands and interpreted the hidden demands; the ways in which students as participants interacted with others with and without a teacher's scaffolding; and the ways in which a series of activities were introduced and structured as a system. It is important to note that in a system, ideas and knowledge possessed by participants are both highly variable and redundant. Individuals working together on a collaborative task are likely to possess different kinds of knowledge and so will engage in interactions that allow them to pool their various resources to accomplish their tasks (Rogers, 1997). Therefore, discourse space is uniquely developed depending upon interactions among the resources, demands, participants, and the system of activities (or culture).

For example, Yoon and Hand (2016) compared two different classrooms in an elementary school setting and reported the varying patterns of interactions among participants, of interconnection among representations, and of interpretation of demands. They argued that those differences influenced individuals' reasoning complexity and their use of language. Data analysis indicated that, in both classrooms, the similar shared social practices and the similar level of accessibility to resources for learning were observed. In terms of discourse space, it could be argued that a horizontal discourse space (the extension of accessible external representations) was developed in both classrooms. However, significant differences were found particularly in demands of activities and interactions among participants. In classroom A, the primary focus in the activities and interactions was seen to share and generate ideas or knowledge to complete the given task, while in classroom B, students were additionally asked to engage in reviewing, elaborating, and evaluating the ideas not only to complete the given task but also to practice sciences framed by argumentation. As a result, the level of reasoning complexity emerged differently in individually written texts and in the use of language between two classrooms. It indicated that students' writing in classroom B exhibited more coherent description and explanation with higher complexity level of reasoning, as well as more use of reflective sources rather than personal and contextualized sources. From the perspective of the development of discourse space, it seemed closely associated with the development of vertical discourse space, which could be aligned with Bernstein's vertical discourse stage.

In summary, we should consider students' interactions and a learning environment where scientific literacy practices were established as activity systems. In other words, scientific literacy practices should be related not only to an individual's cognitive processes but also to "joint action" that constructs shared information and experiences. Participants' shared social practices can be systematically represented through a concept of discourse space and allow us to explore how participants interacted with external representations of collective knowledge, how they understood the process of knowledge construction and development, and how they experienced learning as transformations over time in the nature of interactions among and between learners and their constructed artifacts. Table 9.2 shows a brief summary, visualizing the interrelationship among multiple theoretical perspectives on the processes of being literate in the discourse of sciences.

Table 9.2 A brief summary of interrelationship among multiple theoretical aspects on scientific literacy practices

	A process of being literate in Discourses of Sciences
Klein	*Three Shifts* 
Dual Processing	*Interactions between Type 1 and 2 processing* 
Five Phase Model	*Five Phase Continuum* 
Discourse Space	*Changes/Transformation/Evolution of Discourse Space* 

9.5 Challenges and Future Perspectives

In this chapter, the author discussed possible ways to differentiate the definition of scientific literacy from the goal of science education that a student needs to achieve, toward core practices and outcomes in science classrooms where learners collaboratively engage and realize scientific processes over time. Instilling scientific literacy in a person is not the same as coaching that person to efficiently imitate what scientists have already built in terms of language use, reasoning, and knowledge, but rather scientific literacy is fostered by providing experiences that encourage the language of science. For example, we learned that scientific language had unique characteristics such as abstraction and technicality (Halliday & Martin, 1993). To be literate in the discourse of sciences does not mean that our students simply learn the specialized language of science as the key goal of science learning. Instead, students must build their awareness of the unique grammar of scientific language through multiple scientific literacy practices that encourage them to experience and practice the movement, shifts, and development as discussed throughout this chapter. Importantly, it is hard to argue that students' developed understanding of scientific language in an isolated manner automatically leads to an improvement in their reasoning ability or knowledge construction.

In this chapter, I discussed two major areas drawing from some perspectives in a field of cognitive sciences. First, Klein's theoretical suggestions on scientific literacy and dual processing theory were discussed to explain how cognitive processes function as students are engaged in scientific literacy practices. Second, a new concept of discourse space was introduced and discussed, focusing particularly on resources and demands to understand environments that promote students' scientific literacy practices. Based on findings of previous studies and theoretical assumptions discussed here, I conclude this chapter with some future goals for research on scientific literacy practices.

One area for further research is the examination of the relationship between a relatively microlevel of cognitive processes as discussed in this chapter and a fairly macro- level of epistemic practices. Methods in previous studies that have been discussed in this chapter were based largely on psychological approaches, including detailed analysis of words, clauses, and other small units of representational clues recorded in participants' verbal and written texts or observed changes in the human brain. This thorough analysis helped to trace kinds of cognitive processes that might occur when humans participate in a certain scientific literacy practice, the ways that different types of resources and demands are represented, and by what means representational practices became established within particular learning environments or systems. However, there remains a need to further explore how complicated processes impact the ways that students build knowledge in general and how their engagements in the epistemic practices are transferred to other settings. That is, philosophical exploration of students' engagement in local and global epistemic practices is needed, with emphasis on the socially organized and interactionally accomplished ways that members of a group propose, communicate, assess, and legitimize knowledge claims (Kelly, 2016) that might be influenced by different characteristics of diverse cognitive processes and by the changes, transformation, and evolution of discourse space and vice versa.

The second goal is to closely examine interactions between students and environments where cognitive processes occur. Particularly, it is vital to understand the roles and influences of the external representations, a crucial element for discourse space. Complex human activities integrally include internal processes, as well as external representations and interactions among individuals (Hutchins, 1995; Zhang & Patel, 2006). In this venture, it is more appropriate to consider cognition as a property of the whole system within which the individual functions rather than as something limited by an individual's brain (Karasavvidis, 2002). Therefore, it becomes important to consider external representations as well as participant abilities as contributing to the distribution of cognition within the system (Kim & Reeves, 2007). Therefore, the idea of distributed (and extended) cognition helps us to expand our understandings of the roles of external, and distributed, representations in scientific literacy practices. Although external representations seem to have limited resources, ways to utilize the representation varied based upon multiple influences by the ways that participants shared, utilized, and developed resources; the ways that they communicated the evident demands and interpreted the hidden (or emerging) demands; the ways that student participants interacted with others with and without a teacher's scaffolding; and the ways that a series of activities were introduced and structured as a system. Therefore, it is critical to further examine the nature and roles of distributed representations that might include cognitive, representation, and physical resources for scientific literacy practices, particularly in current educational circumstances that encounter rapid changes of educational mediums and the increasing demands to integrate technologies in teaching and learning due to the continuing revolution of information technology.

The third goal is to construct pedagogical approaches to manage demands for scientific literacy practices. According to an argumentative theory, humans are natural-born arguers and reasoning has evolved chiefly to serve argumentation that inherently requires both of the cognitive processes we learned from dual processing theory. However, human reasoning frequently falls into unsatisfying or even disappointing outcomes. It is because when people reason on their own, they typically find reasons that support their preexisiting beliefs (*myside bias*), and they are not critical toward these reasons (*laziness*) (Mercier, Boudry, Paglieri, & Trouche, 2017). Similarly, previous studies have reported that students do not automatically engage in all types of cognitive processes, particularly evaluative/reflective processes (type 2 processes). Therefore, educators need to construct instructional strategies and pedagogical approaches to design appropriate demands that support students in avoiding myside bias, as well as laziness. In designing these processes, educators must consider three areas. First, it is important to study ways to reduce extraneous cognitive processing, to manage essential cognitive processing, and to foster generative cognitive processing. Second, it is important to study ways that optimize external representations for reducing, managing, and fostering cognitive processes. Third, it is important to consider demands from theoretically different perspectives (see Leach and Scott's (2002) concept of learning demands). Future research that focuses on this goal will support educators in their quest to increase scientific literacy.

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Chapter 10
Future Research in Learning with, Through and from Scientific Representations

Vaughan Prain

10.1 Making and Using Signs in Science

An intensive research focus over the last 20 years on how representations relate to learning in science has generated fresh insights and new complexities. Rather than being viewed simply as pedagogical conveniences to summarize or explicate models, representations are now seen as key building blocks of scientific literacy. Their many forms serve diverse heuristic purposes, with divergent theories proposed to explain what and how students learn with or from them. In this chapter I briefly review the current state of play on how representations are conceptualized, and how their epistemological work is explained, before indicating complexities to be addressed by future research, as well as theoretical frameworks to guide this research.

These complexities include (1) the relationships between representations and concepts and models, (2) the value of creativity in student-generated representations, and (3) the relationships between reasoning and student representation construction. These interlocking issues are significant in pointing to future generative uses of representational work as disciplinary creativity in student science learning. There is also the question of the extent to which current theories of how students learn through this claim-making address these issues adequately. To make discussion manageable, I particularly focus on student construction of representations, but note the reciprocal relationship between making and interpreting representations. Students are constructing new representations when they interpret others' signs and also when they make sense of their own scientific sign-making.

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*,
Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_10

10.2 What Are Scientific Representations?

The nature and purposes of representations or signs in science are now understood from many perspectives (Frigg & Nguyen, 2019). These include socio-semiotic, cultural materialist, historicist, pragmatist, embodied cognitivist, phenomenological and pedagogical accounts. While entailing distinctive takes on this topic, these diverse perspectives fall generally into two traditions or camps. The first broadly cognitivist perspective tends to see representations as externalized meaning organizers where users' minds insert or extract semantic content. Representations are therefore understood as illustrations or accompanying pictures of pre-existing concepts, processes or theories. Representations are seen as products of cognitive schemas, exemplifications of prior knowledge, psychological props to support or organize new learning and/or simplifications of complex referents or other, more complex representations (Ainsworth, 2006; Gilbert & Treagust, 2009). They can be static, as in a hand-drawn sketch, or dynamic, as in computer-generated images of processes or in successive writing drafts, but they are all viewed as outcomes of prior thought or reasoning. From this perspective, students as sign-makers and sign-interpreters put meaning into (and take meaning from) these signs through prior or emergent cognitive constructs or schemas in their heads. They draw on mental pictures of past first-hand experiences and past interpreted representations. Representations in science are therefore seen as demonstrations of how minds organize and explain phenomena and communicate these explanations.

The second sociocultural perspective argues that representations become meaningful signs for learners through learner immersion in the material practices of doing science (Roth & Jornet, 2013). Minds, bodies and these practices are not seen as separable but interact to provide the basis for student meaning-making with and from signs. This meaning-making depends on students connecting the signifying conventions of these signs with their immediate and ongoing experiences of scientific inquiry purposes and practices. The meanings of these signs are not derived from, or dependent on, internal resolved representations in heads but from direct sensory, situated engagement with the purposes and practices to which they refer. Meaning-making entails knowing how to proceed in using these symbolic tools as part of these practices.

Advocates of this second perspective claim that sensory perceptions and guided interactions with teachers, peers and inquiry processes and resources provide the grounds for multiple abstraction processes and symbolic meaning-making (Latour, 2014; Roth & Jornet, 2013; Sennett, 2008). For example, concepts such as "inside", "outside" and "reduction" are first learnt from first-hand material experiences with everyday language before they can become tools for abstraction and explanation construction in science. Sub-signs within scientific representations that signify time measurement, space and degree of change in representations (such as arrows in flow charts, line direction in graphs, mathematical formulae) are abstracted from first-hand experience before they can function as signifying signs. In this materialist "turn", these signs (linguistic in talking and writing, visual, mathematical, material, gestural and embodied) are more than accompanying pictures of existing or prior knowledge. Rather, they are material acts (de Freitas & Sinclair, 2012, pp. 138–139) that also create new understandings, where gestures can entail "pre-linguistic apprehension", and where diagrams are "capturing devices" and "sampling mechanisms" to imagine and create new understandings. In this view, collective embodied minds generate, recognize and share knowledge.

These two broad takes on representations have generated many insights into science learning. Here I note briefly some of their differing strengths and shortcomings to set up discussion on how we might conceptualize student creativity, inventiveness and reasoning with and through representation construction. Cognitivist accounts are strong on strategies to coordinate texts and other forms of representation and explain differences in individual student performances in meaning-making. However, this perspective often defaults to a linguistic shorthand to explain the referential function of scientific signs. Representations are seen as "translations" or "redescriptions" rather than as "transduction" (Bezemer & Kress, 2008, p. 169), where meanings change or are reshaped as learners cross or integrate different modal accounts of topics and where the use of visual-spatial and other nonlinguistic modes enable new ways to imagine and reason about claims. Early cognitivist perspectives also struggled to recognize or explain how learners integrated experiential practices and strategies into abstract knowledge (see Klein, 2006). However, more recent accounts of embodied cognition (Barsalou, 2008) and "manipulative abduction" (Magnani, 2015) have provided persuasive extensions to the case for the centrality of both tacit and deliberative cognitive processes in student learning. From this perspective, embodied understandings and contextual influences affect what is learnt and how. Playing with both material and symbolic tools in speculative option-testing can produce new insights, enabling reviewable outcomes.

Sociocultural accounts of science learning are strong on explaining how intentions and first-hand experiences are crucial for setting up meaningful sign-making, but these accounts also face theoretical and practical challenges. Why do some learners, but not all, move from first-hand experiences to recognizing and using abstracted signifiers effectively? Cultural materialists, such as Roth and Jornet (2013), have noted the challenge of how to explain (and theorize) student capacity to make links across experiences, stabilize understandings and achieve long-term learning gains. They acknowledge that cognitivist accounts of representational refinement are on stronger theoretical footing here. Growth in representational adequacy and complexity can be tracked and supported closely by guided student analyses of their own representations. As a counter to this cognitivist account, Roth and Jornet (2013) argue that representational visual and narrative capacities are built up by students over time, but this leaves open the question of what exactly is built up and how to enable abstraction from experience as well as future use of abstracted models.

Both perspectives agree that scientific signs are signifying tools within larger systems of meaning-making and meaning-sharing. They disagree about the nature of the organising systems and how they are accessed. There is broad agreement, following Peirce (1931–1958) and other semioticians, that representations in science are signs that enable users to explore, imagine, create, contest, critique, clarify and communicate meanings generated by practices in this domain. Despite their differences, advocates of both perspectives agree that successful induction into these systems is achieved largely through guided ritualized practices and immersion in the multiple purposes for this sign-making. They therefore both struggle to theorize the value, scope and practical opportunities for worthwhile student creativity within these induction processes. This is the question of what scope is there for student creativity when they are expected to learn and use accepted conventions in scientific representations. In the next section, I consider more closely how these two broad theoretical perspectives explain what enables student learning from representation construction and, by implication, the potential to theorize worthwhile student disciplinary creativity within or beyond these accounts.

10.3 Researching What and How Students Learn with and Through Representations

In analysing these processes of scientific semiosis, researchers have mainly addressed two questions. What are students potentially or actually learning from this activity, and what precisely enables (or could enable) this learning? Studies have focused on micro-, meso- and macro-dimensions to this learning or their combination. Micro-genetic studies seek to identify the interplay of individual and group intentions, actions, attitudes and understandings, drawing on various theoretical lenses. These studies include neuroscientific accounts of brain activity when students make and interpret scientific signs (see Lamb & Hand, Chap. 7, this volume) and phenomenological accounts of students responding to material stimuli (Roth & Jornet, 2013). Micro-genetic studies have also shown how new meanings are prompted and stabilized for individuals and groups by representational construction and repurposing. Meso-dimensional studies analyse the processes and outcomes of student co-representational activities in classroom-based tasks and artefact analyses. These studies have drawn on socio-semiotic, cognitivist, pragmatist and pedagogical perspectives (Gillies & Baffour, 2017; Hand, Mc Dermott, & Prain, 2016; Hoban, Loughran, & Neilsen, 2011; Prain & Waldrip, 2006; Tang, Delgrado, & Moje, 2014). In these accounts student meaning-making is both individuated and achieved through co-representational collective inquiry. Macro perspectives embed student meaning-making using broader cultural signifying resources over time (Prain & Tytler, 2012; Roth & Jornet, 2013).

Multiple persuasive claims are made for what scientists have learnt, and what students need to learn, and are learning, when they construct representations. These include (a) use of their referential function to make or confirm new scientific knowledge claims, (b) the requirement for internal coherence in representations as model-based claims, (c) procedural knowledge of how to use the signifying conventions and possibilities of individual and combined representations, or meta-representational competence (diSessa, 2004) to achieve the above and (d) the broader epistemic understandings of how their usage contributes to students developing and enacting science literacy and science-literate identities.

Researchers generally agree that students fundamentally need to learn about the referential and coherence requirements for scientific representations. This is the epistemic imperative of scientific signs as claims. In other words, the abstracted claims made in these signs must be warranted by (a) the internal coherence of their parts, (b) their defensible extensions of past signs and their underpinning models, (c) their explanatory logic in that they also meet the criterion of plausible correspondence to key features of their referent and (d) their predictive strength in relation to their referents. Degrees and kinds of abstracted signification have ben codified by Peirce (1931–1958) in his account of icons, indexes and symbols, but these categories are only a starting point for understanding signification systems in science and their histories of change over time.

In science, a representation reputedly is a sign that stands for something else (such as an object in an experiment, the property of a material, a concept, process, model, theory or law). However, that “something else”, if it is to be interpreted and communicated, always entails more or new signs. Rather than leading to defeatist infinite regress, this semiotic insight provides the basis for understanding that signs are necessary resources that need to be constructed and interpreted continually to generate, share, contest and perpetuate scientific knowledge. This insight confounds claims that concepts can exist purely in the abstract, separable from any representation of their meaning or application. This insight also points to the possible value of students engaging in claim-making through representation construction. Such claim-making can:

1. Encourage students to participate first-hand in the creative, imaginative problem-solving and visualizing dimensions of science inquiry and thus enhance engagement
2. Signify for teachers their students’ current understandings and areas of confusion
3. Generate student resources that can be used subsequently to enhance understandings for both the sign-makers and their peers
4. Provide leads for effective teacher feedback and timely introduction of relevant signifying conventions
5. Lead to student understanding the epistemic imperative signs in science serve and the value and necessity of shared signifying systems in this community
6. Provide the basis for guided teacher mediation between creative signification processes by students and scientists.

Beyond the complex process of learning how to link representations and their many possible referents, students also need to learn the potential and actual signifying functions of different types of scientific representations. What and how does each feature/convention in a scientific representation signify, whether it is direction in a line in a graph, layout of a flow chart, the use of a material instrument in an inquiry or components of a mathematical equation? When, how and why should different representations be constructed and combined to develop coherent integrated visuo-spatial, mathematical and linguistic scientific claims? What are the practice-tested and potential affordances of different sign systems for speculative and systematic inquiry, data sorting and ordering and warranted claim-making? Detailed accounts of the ordering functions of semiotic features of standard types of representations have been specified from socio-semiotic perspectives in considerable detail (Kress, Jewitt, Ogborn, & Tsatsarelis, 2001). From cognitivist perspectives, when students engage in these micro-connecting signifying processes, they are also learning the epistemic ingrained habits, skills, methods and dispositions (habitus) of scientists (Greene, Sandoval, & Braten, 2016). They are learning to enact epistemic virtues of vigilance in designing inquiry, seeking and providing explanations, systematic testing, evidence and claim weighing, judging logical plausibility in represented findings and assessing representational adequacy in their claim-making. From a pragmatist pedagogical perspective, they are practicing first-hand how to construct, understand and apply representations of science concepts, models, processes, and explanations to a range of contexts (Tytler, Prain, Hubber, & Waldrip, 2013). From these processes, students are also learning how to enact literate identities in this domain (Prain & Hand, 2016).

In summary, we have learnt over the last 20 years that representations in science education are multi-functional epistemological tools with complex relations to varied referents. They can serve many purposes and enable quite different kinds of learning (Cox, 1999; Greeno & Hall, 1997). Through extended first-hand experience with these signifying systems, students can learn how, when and why to use them to speculate, reason and justify domain-specific claims known to their teachers (but new to the students). Students can learn **with** representations, as exploratory tools to understand new aspects of topics, **through** representations as resources that mediate emerging understandings of scientific concepts and processes and **from** representations, as inspectable, revisable tools to apply to new concepts and contexts.

10.4 What or Who Mainly Enables Learning from Constructing Representations?

Researchers tend to align strongly with either cognitivist or sociocultural theorists on this question. For cognitivists of various persuasions, student learning is mainly enabled by their own mental processes. These are supported by guided teacher induction and peer input into experiences and frameworks and resources that prompt successful student visualization, reasoning and representation in this domain. These guidelines include teacher and student enactment and review of inquiries, schemas for purposes and procedures, retrievable propositional knowledge stored in memory and procedural know-how derived from past experiences and now applied in new contexts. Students learn by forming conscious intentions, drawing on embodied individual and group perceptions, pattern spotting and guided reflection. Cognitive organizers, such as teacher questions, rubrics, prompts, guidelines and reflections on inquiry, provide frameworks to guide student induction into and organization of scientific meanings. Representation construction consolidates this learning through combining automated and deliberative cognitive processing (Hughes, 1997; Kellogg, 2008; Klein, 2006).

Early cognitivist accounts of learners as adaptive information processors have been augmented by more nuanced cognitivist perspectives on the interplay of mind, body, affect and environment in learning. Thus, researchers have focused on the embodied nature of cognition (Barsalou, 2008) and the role of practical experimentation or "manipulative abduction" in explaining scientific breakthroughs in an ecological model of cognition (Magnani, 2015). Aesthetic preferences also shape what individuals find meaningful and affecting (Johansson & Wickman, 2011). As noted by Barsalou (2008), cognition and learning are enabled by perceptual simulations, bodily states, feelings, introspection and situated action. Individuals know and learn not just through manipulating stored symbols in memory or cognitive schemas but through the interplay of mind, body, feelings and environment, supported through reenactment of these experiences in offline perceptual simulation. Creating external representations is more efficient than purely mental work because external mechanisms distribute cognition. Learners bootstrap and manipulate new ideas, coordinate and encode more complex structures and simulate more complex processes as they specify, develop and archive claims (Kirsh, 2010).

By contrast, researchers from socio-semiotic and sociocultural perspectives foreground collective cultural influences on learning rather than individual cognitive capabilities. Guided first-hand experiences with scientific practices, their purposes and their signifying tools (both material and symbolic) are seen as enabling learning. Students here need to make strong experiential connections between scientific activities and how they are signified generally through inquiry processes, hypotheses, experimentation and claim-making and then through specific represented multimodal claims (Bezemer & Kress, 2016; Roth & Jornet, 2013). From these broad sociocultural perspectives, students are characterized as immersed "players", learning through teacher and peer guidance on how and why to proceed with effective practical inquiry and all of the signifying options in representations for claim-making. Learning processes are understood as both explicit and tacit, phenomenological and formal and often context-bound. Learners map perceptions, simulate experiences, visualize, rehearse, improvise, speculate and seek coherence in their accounts as they construct, share and review their own symbolic accounts of these practices.

Both these broad theoretical orientations on how learners make scientific meanings with and from signs assume either explicitly or tacitly the role of multiple affordances in this semiosis. These affordances are variously conceptualized as material, symbolic, cognitive, perceptual, affective, experiential, collective or individuated, pedagogical, conventionally stable or emergent, contextualized or abstracted, explicit or tacit. Cognitivists foreground affordances taken up through individual mental and external organizers; sociocultural prioritize affordances arising from collective purposeful participation with enculturated material and symbolic practices and tools. The current state of play in research in this area suggests that both orientations have made persuasive claims for multiple identifiable affordances that trigger, consolidate and extend individual and collective student learning.

However, there is scope for more research on which affordances enable gains for different topics, or stages in topics, and different student cohorts and the relationships between different affordances and student reasoning. Affordances have been noted to include design features of representational modes (such as graphs, tables and flow charts) that act as productive constraints on meaning-making; material objects in an experiment that can be manipulated to yield new questions and new insights; and the capacity for scientific signs and their significations to be recycled, redesigned and reinvested with new meanings (Prain & Tytler, 2012). However, there is considerable scope to research teacher and student perceptions and use of different affordances across the school science curriculum. The enabling resources and processes for student semiosis in science are now generally understood within a much larger frame of influences, prompting some cognitivists to favour ecological metaphors to explain influences on learning (Magnani, 2015). From this perspective, students learn when they and other signifying systems or networks interact productively to shape, share and judge individual and collective reasoning and claim-making.

In researching an extended program where students constructed, shared and justified their own representations, we have drawn on elements from these theoretical perspectives in an eclectic manner (Carolan, Prain, & Waldrip, 2008; Prain & Tytler, 2012; Prain & Waldrip, 2006; Tytler et al., 2013). Our approach was guided by (a) the sociocultural insight that learning science entailed students learning a new literacy, and one best learnt through extensive guided immersion with scientific inquiry practices; (b) the need for students to understand and apply signifying conventions in science in general and for particular topics; (c) scope for students to extend or apply partial knowledge of topics to address representational challenges, with scope for imaginative invention of signs for claim-making; and (d) the need for collaborative teacher-guided reflection about the accuracy and adequacy of successively refined representations in terms of the epistemic imperatives of science discourse. In this program, we conceptualized representations as heuristic devices, in combination with practical inquiry, to imagine, visualize, trial, reason about, refine, justify and share scientific claims. Where possible, students were encouraged to draw on perceptual and other clues about phenomena, collaborative inquiry, debate and teacher-guided input, to formulate and signify multi-modal claims. Where appropriate, students were introduced in a timely manner to key sign conventions to elicit and focus their creativity (Carolan et al., 2008).

Our understanding of creative reasoning in science education was guided by Csikszentmihalyi's (1999) generic sociological perspective. Here creativity is understood as the interplay between a set of domain practices with recognized symbolic rules and procedures, participants who brings new approaches, processes or insights and solutions to this domain and experts (teachers) who appreciate and endorse these domain contributions. By implication, there are strong epistemic criteria for gauging the value of student's creative contributions, with creativity understood as culturally bound within collective practices and endorsement. The extent to which students can be creative in learning science is therefore bounded by disciplinary norms around symbolic expression and abstracted claim-making, curricular demands and teacher expectations that students demonstrate authorized representations that teachers can guide and endorse. As noted by Rowlands (2011), Paavola and Hakkarainen (2005) and others, this disciplinary constraint entails students coming to understand what counts as disciplinary explanatory adequacy in terms of represented meanings.

By implication, for students to be productively creative in learning science, they need to have some relevant background knowledge of the problem or topic to be addressed. They also need to understand or experiment with (and have the ability to make use of) potential and actual affordances of representational resources at hand to explore possible explanations. This is not to argue that sign system affordances do all the work, but rather that students need to know and use these affordances effectively to signify their intended or emergent claims. In characterizing creative activity, Csikszentmihalyi (1999) noted that creative processes entail various steps, including preparation, incubation, gaining insights, evaluation and elaborating ideas. This suggests that there is potential (and necessity) in these processes for teacher-guided problem-solving, feedback and negotiated reasoning as students engage in creative improvisation and reflection on their emerging understandings and claims.

While our representation construction approach led to strong student learning and dispositional gains, it raised further questions and new complexities. To instantiate some of these complexities and scope for future research, I here revisit an early example of a student-constructed representation from our studies (Tytler et al., 2013). This example is not intended to exemplify instructional excellence or highly successful learning, or justify focusing on student-generated representations, or demonstrate advantages over other possible pedagogical approaches. Also, my intention is not to show systematically how theoretical accounts of the many learning enablers covered above can be plausibly identified as influential in this particular case. Rather, I use this example to flag challenges and opportunities around future conceptualizing of the relationships between student-generated representations and concepts and models, the place of guided creativity in this representation work and student reasoning.

10.5 Identifying Theoretical Complexities in Student Representation Construction

The example (Fig. 10.1) is a representation produced by a 12-year-old student in a unit where the teacher aimed for the class to understand key concepts around the particulate nature of matter in relation to real-world phenomena. The unit began with a formative assessment of student understanding of the basis of different states.

The teacher posed the question of what the bubbles in boiling water contain. He provided the class with a worksheet prompting them to “show the smallest parts of water” and “show the smallest parts of the bubbles in boiling water”. The students then explored the properties and nature of each state of matter. Student groups were provided with a phenomenon such as expansion or a change of state to enact by showing changes to particles. Some groups had to explain the phenomenon that they were enacting and provide reasons for their choice. Students were asked, for example, to predict whether water or cooking oil would have a greater temperature gain when heated concurrently on the same hotplate. Finally, students completed the task of building 3-D explanations of the three states of matter. These models were photographed, annotated and presented to peers.

These representations aimed to show the degree of attraction, spacing and movement of particles in each of the three states of matter. The students were also asked to show one change of state with the same resources. In Fig. 10.1, the student has attempted to show particle movement by blurring the photograph in the image at the bottom left of the account. While revealing some lack of conceptual clarity around structures of matter, the representation visualizes particle vibration in a creative way broadly aligned to scientific accounts. This representation is creative in the sense that the student has imagined a novel way to integrate his prior knowledge into a visual explanation.

This example indicates the complex relationships between representations and referents and student creativity and reasoning in representational construction. This example also raises the question of how such constructions should be assessed and on what bases. To take the representation/referent relationship first, this example seems to show the student’s attempt to instantiate his emergent model of the particulate nature of matter. The student’s construction is not creative simply because it represents the movement of particles (a feat now easily copied from animated accounts on the internet). Rather, his improvised adaption of the potential for blur-

Fig. 10.1 Student example of representing spacing, movement and attraction of particles

ring effects in photographs enables him to make sense of and communicate in an imaginative way (both to himself and more broadly) a scientific claim.

However, to confirm this interpretation would require further verbal or other representations by the student of his intentions, as well as his interpretation of his degree of success in relation to his understanding of particle movement.

As noted by Frigg and Hartmann (2019), models in science serve many different explanatory and heuristic purposes and are generated through applying varied, even contradictory, principles. They noted that models can entail idealizations, simplifications and distortions of their target system of referents, foregrounding or omitting known features in the target system. Some models combine these principles to generate and justify scientific claims. By implication, representations (including this one) idealize, simplify and distort the models they are meant to signify. Pedagogical "authorized" representations of models of molecular motion on the Internet indicate diverse conventions around animation, varying degrees of abstraction, including models of internal motion of molecules, with explanations customized for younger or older students. This raises the question of what representations of this model do teachers consider adequate to show student understanding at Year 8 within a trajectory of increasing developmental representational competence and conceptual complexity about this topic. More broadly, what should teachers view as generative variations from, or potential transitions to, canonical representations? What should count as a threshold of adequacy? In our research, these questions were addressed pragmatically in terms of teachers' understanding of (a) key concepts in this topic, (b) the epistemic imperative of communicative adequacy in claim-making about these concepts and (c) internal coherence in student representations. In this example, the class's agreement about the value of using balls or circles to represent molecules was achieved through visual experimentation and guided teacher discussion, but the signification of movement was left for students to explore, visualize and then assess the explanatory effectiveness of their signs.

In terms of future research on how representations relate to models in school science curricula and learning, there is a need to identify which models and their purposes now underpin, or are advocated to underpin, science curricular prescriptions about student learning. What should teachers see as explanatory signs that students have a working understanding of the semantic content, origins and functions of representations of particular models, as well as their strengths and limitations? What is lost or gained by narrow or broad teacher prescriptions and expectations around "adequate" student constructions? If students are constructing their own representations, to what extent should modes and signifying practices be scripted by teachers to design and guide intended student learning outcomes?

An intensive research agenda has been undertaken on these questions (Lehrer & Schauble, 2017; Lehrer, Schauble, & Sawyer, 2006). This entailed researching elementary students' learning of particular topics in science and mathematics through a sequence of representational challenges as the bases for model-based reasoning, with evidence of strong student learning gains. In this research, students with teacher guidance were encouraged to invent and assess their own representations, including construction of data, as an induction into scientific and mathematical reasoning. However, a broader account of this representational competence/adequacy in relation to models for all topics covered throughout the years of school science (and student understanding of these relationships) is yet to be identified. Such an account could provide evidence-based guidance for teacher and student representational practices and their assessment. This research agenda could identify what promotes generative interplays between student-generated representations as model-building and model-confirming practices in learning sequences within and across topics. Such a research agenda could be guided by tracking teacher and student perceptions of affordances as students are guided to make, interpret, judge and share their own representations. Our research indicated that students who have created their own representations of models show some capacity for informed critique of the well-intentioned, but often misguided simplifications and limitations in hybrid accounts of models in textbooks and other sources (Tytler et al., 2013).

On the question of disciplinary creativity in student-generated representations, this student representation highlights a potential tension for teachers. Genrist prescriptions that students should be inducted into authorized uses of semiotic conventions in scientific representations are at odds with some sociocultural injunctions that students should have first-hand experiences where they creatively imagine, test and share scientific claims. There are problems with both principles in that genres are changing continually because of changes to technology-mediated resources, with consequent effects on how scientific research is conducted and reported. At the same time, scientific claims still need to be framed in recognizable scientific discourse to count as learning in this subject. In seeking to resolve this tension, in our research program, we encouraged teachers to guide students in a timely manner to understand useful authorized signs and sign systems. However, students were left space to recognize, explore and justify a (new to them) scientific claim or claims about phenomena. These visualizations were therefore guided by teachers' understandings of epistemic imperatives in scientific signs: signification should be unambiguous, internally coherent and communicable and make persuasive multi-modal claims about their referents.

Creative improvisation has a recognized history in many scientific breakthroughs, as noted by Gooding (2006) and Watson (1968). Nevertheless, the role and value of improvisation in scientific work, and in student-generated representations, remains under-theorized and under-researched. In this regard, Weick (1998) from a cognitivist perspective, but recognizing the influence of embodied, learnt and practiced responses, offers some useful leads. He claimed that improvisation in many fields entails forgoing recipes and scripted action. By contrast, improvisers make deliberative use of resources at hand to solve problems, where action with these resources shapes thinking, and where user perceptions of affordances in tools influence processes and products. Weick further claimed that improvisation, while having a degree of serendipitous spontaneity, is also necessarily structured by past knowledge and procedural know-how and often entails transformations of original models. These may be embellished, reinterpreted or reshaped in the process, depending on the degree of creativity, leading to anticipated and unanticipated outcomes and solutions. In this example of a blurred photograph, it is not possible to know from one sign the extent to which the student has a "resolved" model of the particulate nature of matter, but further representational work (verbal or material) would clarify this question. Clearly, some forms of material improvisation are necessarily constrained by safety concerns in the science classroom, but Weick's (1998) general account of its character, purposes and means, like representation construction in general, reprises the explanatory power of theorizing this activity partly in terms of agentic take up of cognitive, material and symbolic tool affordances. In this way, the proposed processes of improvisation also align with sociocultural and cultural materialist phenomenological accounts of how learners learn from participating in guided inquiry and testing of claims. Guided induction into the particular affordances of different tools is claimed to encourage imaginative speculation, trialling of possible methods and practical testing as students notice, manipulate and interpret these resources (Roth & Jornet, 2013). These processes of sign-making, sign-judging and sign-sharing also entail both creative and critical reasoning by students which I consider briefly in the next section.

10.6 Student Reasoning in Constructing and Judging Representations

Cognitivist and sociocultural lenses again frame research orientations here. Cognitivist approaches focus on both formal reasoning processes (Furtak, Hardy, & Beinbrech, 2010; Hodges, 2005) and informal ones (Cox, 1999; diSessa, 2004; Greeno & Hall, 1997; Lehrer & Schauble, 2017). If decision-making in representation construction is understood as broadly a two-step process (Mercier & Sperber, 2011), then the first stage of imagining and representing solutions is seen as automated, intuitive and based on past knowledge and personal preferences. The second phase of assessment/judgement is then viewed as analytical, linguistic and evidence-based and thus aligned with formal logical processes. However, this version of a two-step process tends to oversimplify how students reason when they create, judge and share claims (Lehrer et al., 2006). More recent cognitivist accounts of reasoning from creating and using representations as heuristic tools have identified subtle informal learning processes, where reasoning is individualized by first-hand practical experiences and "manipulative abduction" (Magnani, 2015). However, how learners generate models from this reasoning across all science topics and subdisciplines remains to be investigated systematically.

Sociocultural accounts of student reasoning with and from representation construction have identified complex interplays between contextual, embodied, cognitive, pedagogical and task design influences. Reasoning strategies include informal, contextual practical reasoning based on observations and data collection, perceptual pattern-spotting, approximations, enactment and re-representation of experiments. Other reasoning processes include dialogic classroom conversations and elaboration of contested perspectives to clarify claims, inductive reasoning from examples, deductive reasoning from principles to new cases and abductive reasoning or "guessing" from logical inferences. Students analyse adequacy and coherence in their own and others' representational and re-representational claims, drawing on visual/linguistic/embodied shared experiences, understandings and signs (Pande & Chandrasekharan, 2017; Tytler, Murcia, Hsiung, & Ramseger, 2017; Waldrip, Prain, & Sellings, 2013). While these studies provide leads on what influences student reasoning, there is more to learn about what enables these individual and co-representation learning processes.

10.7 Future Research Agendas and Methods

This brief review points to both generative complementarities between current theories for understanding enablers and outcomes of student representation construction but also limitations. Drawing on both cognitivist and sociocultural insights, student learning from sign-making and sign-sharing in science is enabled by multiple influences. These include student individual and collective embodied cognitive contributions, teacher-guided induction into sign purposes and usage, contextual affordances (including task design and requirements, guidelines, and student and teacher roles), practical experiential insights from inquiry processes and sustained opportunities to use material and symbolic tool affordances for scientific sign-making and analyses. This implies that the search for a theoretically justified singular or major affordance to enable learning (rather than a patchwork of influences) may be misplaced. Both broad theory families assume reasonably that learning can be partly "designed" by guided immersion and meaningful take up of these enablers, and the theories provide leads on how to achieve this. However, these theories do not prescribe precisely how student improvisation and creative engagement can be incorporated into these learning processes. Additional challenges to this focus are also readily identifiable. These include teacher concern about unanticipated and "mistaken" signs and significations that do not sit easily within assumptions of curricular orderly design. Also, ongoing changes to how scientific claims are represented in different media, and how ongoing techno-mediated changes to communicative resources increase the scope for how students express claims, add to the complexities. However, at stake is the very large issue of what conditions and invited creative roles for students are likely to enhance their motivation and long-term engagement in science learning.

In looking to future theory refinement to support opportunities for student creativity in learning science, I noted that both current theory orientations often refer to "affordances" as a catch-all to explain how students achieve scientific meaning-making or semiosis. However, cognitivist and sociocultural perspectives offer different takes on how this construct gets instantiated in their accounts of student learning. Are they collective or individuated resources? In the interplay between embodied affective agents, tools, purposes, experiences and cultural/individual histories, are affordances relatively predetermined or more open in how they influence individual and collective meaning-making? This is a critical issue for understanding and working with student variations in their scientific sign-making. If “affordances” are to explain and support student learning from this sign-making, and clarify the role of teachers in this process, then there is the need for research-justified accounts of their explanatory scope and usefulness. This applies not just to “old” technologies like pen and paper, gesture and embodiment but to all new and future techno-mediated sign systems that enable users to generate new signs to share represented claims.

While a generic case has been made for the value of students learning through making and analysing their own drawings (Ainsworth, Prain, & Tytler, 2011), the affordances of different tasks, purposes, instructional processes, technologies for drawing across different subjects, time-spans, and for different cohorts of learners, remain to be identified and enacted beyond many current valuable preliminary studies. More broadly, studies need to focus on how students move from perceptual first-hand practical experiences in science classes (or their virtualized equivalents in computer-based programs) to model-based reasoning and imaginative abstraction with and from representations. What are conditions for generative visualizations by students across different tasks and topics? Studies are also needed that connect micro-genetic and longitudinal studies of representational/conceptual learning in science. What insights does a representational focus offer on interdisciplinary learning, where science is connected with other subjects, such as mathematics, and in STEM programs? Such studies have the potential to identify sequences of new representations and critique that can enhance learning within and across these subjects.

Our current theories do not tightly predict learning outcomes in science but rather point to enabling conditions and challenges for this learning. Just as this learning through making signs in science seems to proceed through elaborate abductive processes, it also seems plausible, as a pragmatist, to suggest that future research in this area should also proceed through researchers’ abductive reasoning. As noted by Starbuck (2016), this reasoning through analysing data to draw inferences about systematic patterns and implications seems preferable to claiming we know in advance precise explanatory frameworks that justify practices and predict which improvisation tasks in student sign-making work well for particular topics and specific student cohorts. As with all learning from research, we should be willing to expect surprises.

This is not to rule out the value of design-based research, with systematic cycles of planning, trialling, data generation and evaluation of learning in case studies but rather to be open to unanticipated and confounding insights. Research studies need to track multiple re-representational data sources to identify teacher and student intentions, reasoning processes, use of embodied/material/symbolic resources and perceived significant/useful aspects of representations and their manipulation as well as patterns in supportive teacher discourse. We need to track student assessment of the adequacy of their representations to their own understanding as well as their perceived communicative adequacy and contextual effects of whole-class and subgroup negotiations of intended and realized meanings. How is co-representation enabled and refined? We also need further studies of the interplay of different modes of representation, including how written texts serve other modes (Prain & Hand, 2016). From such studies, we can develop ways to assess not just learning gains but their interconnection with the development of representational competence within and across science subjects and sequences of representations.

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Chapter 11
"I'm Not a Writer": Shaping the Literacy-Related Attitudes and Beliefs of Students and Teachers in STEM Disciplines

Lisa Emerson

> *I tell my students that you may think you're a scientist – you're not – you're a writer who writes about science*
> Senior Scientist, Genetics

11.1 Introduction

For many years, I have taught a large 1st year writing/communication course as part our BSc program. This course is compulsory in the BSc for most majors – a decision made by the degree management committee over 15 years ago, when surveys of science employers made clear that transferable skills (e.g. writing, oral communication, and group work) are both essential and commonly lacking in the graduates they employ (Gray, Emerson, & MacKay, 2005, 2006). Our course is specifically designed to equip students with employment-related science-specific literacy skills. "This is not a school English course", I tell them, "there is no analysis of Shakespeare or poetry – everything we teach you has been researched and shown to be essential to a future in a science-related career". Yet, year after year, we encounter resistance. Many of our students are taking science specifically because they disliked or performed poorly in writing-rich subjects at school; most of them cannot see a relationship between writing and science or its relevance to their futures. The STEM students in my class have come out of school convinced that they can't write and they won't have to and shouldn't have to write.

Why does this matter? It matters because writing – and literacy more broadly – is fundamental to the work of science (Norris & Phillips, 2002). All scientists, or individuals working in science-related industries, are writers: whether science students pursue careers in research science, extension science, the applied sciences, or

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*,
Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_11

science-related industry, their success will depend to a great extent on their ability to write (Feliu-Mojer, 2015; Gray et al., 2006; Poe, Lerner, & Craig, 2010). Scientific knowledge is progressed and communicated through writing, whether that be writing scientific papers, engineering reports, business cases, health science blogs, or grower blueprints. Further, recent research (Emerson, 2017) suggests scientists in any discipline or applied industry must be highly sophisticated and flexible writers, able to communicate in a wide range of genres and contexts for a variety of audiences.

Student resistance to writing also matters because we know that writing is an essential learning tool in multiple sites of learning (Bangert-Drowns, Hurley, & Wilkinson, 2004; Graham & Perin, 2007; Prain & Hand, 2016). For example, research indicates (Bazerman, 1988; Emerson, 2017; Lerner, 2007) that writing is a means by which scientists create and refine scientific narratives, and students consequently need to engage with, and have experience of, the centrality of writing to meaning-making in STEM in their classrooms. Further, the writing to learn movement (Emig, 1977; Fulwiler & Young, 1990; McLeod & Soven, 2000) has shown more broadly that writing is a powerful pedagogical tool; student resistance to writing therefore potentially deprives them of opportunities for deep learning.

Dissatisfaction with student literacy in any discipline is, of course, nothing new (Connors & Lunsford, 1988; Lunsford & Lunsford, 2008; Pinker, 2015) but has perhaps come more into focus in many countries in recent years as governments work to realign universities with a neoliberal agenda of employability (Gerrard, 2017; TEC, 2014). For example, in New Zealand, both an independent taskforce (New Zealand Productivity Commission, 2016) and a government review of University Entrance in New Zealand (NZQA, 2017) have recently identified literacy as a problem in terms of the preparedness of students in the transition to higher education:

> all TEOs [Tertiary Education Organisations] expressed concerns about some students' literacy skills, particularly extended writing skills…. Concerns with literacy were identified across a wide range of degree programmes, from humanities to science disciplines. (NZQA, 2017)

And New Zealand is not alone in these concerns (e.g. see ETINI, 2015; Northern Ireland Assembly, 2013; Ofsted, 2013, in Northern Ireland).

In the past, such concerns have inspired a range of initiatives in both the secondary sector and higher education. In New Zealand schools, for example, we can point to the *draft statement of aims* in the 1970s (Department of Education, 1972, pp. 5–15 cited in Fowler, 2005) which positioned language learning as a key factor for effective student engagement and academic success in all subjects across the curriculum (Aitken, 1976; Catherwood, Rathgen, & Aitken, 1990; Openshaw & Walshaw, 2010) and *English in the New Zealand Curriculum* in the 1990s (Ministry of Education, 1994), which functioned as both a national subject and literacy curriculum for all primary and secondary years. More recently, *the Secondary Literacy Project* (2006) saw professional development which positioned literacy as central to learning in all discipline areas rolled out across the country. Nevertheless, student resistance to writing has persisted (Kilpin, Emerson, & Feekery, 2014). Turning to the international context of higher education, we can see that concerns with student writing led, over a series of decades, to the development of freshman composition and writing centres in the USA, the WAC movement globally and the development of (variously named) learning support units in the UK, Australia and New Zealand.

Yet despite apparent gains (e.g. see McNaughton, Wilson, Jesson, & Lai, 2012, for an assessment of the impact of the Secondary Literacy Project in New Zealand), concern with student writing – particularly in STEM disciplines – persists, as does STEM student resistance to writing. Poe et al.'s (2010, p. 1) experience of teaching STEM undergraduates at MIT mirrors my own:

> MIT students, by and large, do not love to write….the science and engineering orientation of MIT undergraduates can often lead them to believe that in their professional careers, the search for engineering solutions or scientific phenomena, not the seemingly tedious process of communicating those findings, will dominate.

In this chapter, which I have developed as a thought-piece to promote further research, I want to shift the focus of discussion about STEM student writing away from product and process ("my students can't write") to a focus on the literacy-related attitudes and beliefs of students and those of their teachers. While literacy in the STEM disciplines is multimodal, this chapter focuses in particular on writing, as a primary way in which knowledge is made and communicated in science (Bazerman, 1988). Drawing on my own research into both scientists as writers (Emerson, 2017) and academic literacy in the transition to higher education (Emerson, Kilpin, & Feekery, 2014, 2015; Kilpin et al., 2014) as well as literature in a wide range of fields including science writing and science literacy, theoretical studies related to attitudes and beliefs, expertise, literacy expertise, and international literacy-related policy documents, I suggest that, in STEM disciplines, students may emerge from K- 12 with established literacy-related attitudes and beliefs that are problematic to their development as scientists or as science-literate citizens. Further, I will argue that these attitudes and beliefs may be, at least in part, attributable to the attitudes and beliefs of their teachers and core definitions of STEM disciplines in schools. Finally, I will suggest that concerns about student writing and resistance persist because the curricula, pedagogy, student support systems and professional development opportunities for teachers that we have put in place to address STEM student literacy conflict with national and international definitions of science and science education, and have consequently failed to address the literacy-related attitudes and beliefs of STEM teachers.

11.2 Literacy-Related Beliefs and Attitudes Impact on STEM Students

In any investigation of attitudes and beliefs, we are first faced with the challenge of definitions. Research into attitudes and beliefs is a large and highly contested field which straddles a range of disciplines, and a full discussion is beyond the scope of this chapter. Jones and Leagon's (2014) review of teacher attitudes and beliefs, while silent on the subject of literacy-related beliefs and attitudes, nevertheless provides a useful framework within which to examine the relationship between literacy-related attitudes and literacy practices in the STEM disciplines. Observing that the terms attitudes and beliefs are often used loosely and interchangeably in the literature, they nevertheless provide the distinction that beliefs incorporate both cognitive and affective factors that include notions of self-efficacy and views of how knowledge is made while attitudes are largely affective, including an inclination to respond positively or negatively to a situation or concept. In simple terms that suffice for the purposes of this discussion, beliefs relate to cognitive factors and the emotions related to those factors (e.g. "I think that writing is irrelevant to learning science, and I feel annoyed with people who suggest otherwise"), while attitudes relate to affect, including enjoyment, motivation, and interest (e.g. "I love to write and am highly motivated to write every day").

One of the long-term goals of science education is to produce individuals who will go on to contribute to the STEM research communities and science-related industries or become science-literate citizens (Bybee, McCrae, & Laurie, 2009; OECD, 2006). If we first consider the needs of students to develop appropriate STEM literacies, then a range of literature has demonstrated that literacy-related attitudes and beliefs are foundational to developing professional identity within STEM disciplines (Beaufort, 2008; Dall'Alba & Sandberg, 2006; Gee, 2000; Harding & Hare, 2000; Lea & Street, 1998; Poe et al., 2010). Scholars from a wide range of theoretical fields (e.g. discourse theory, writing in the disciplines, academic literacies, and theories of expertise) have shown that learning to adopt or engage with appropriate processes and behaviours is tightly tied to the acquisition of disciplinary attitudes and beliefs (Bereiter & Scardamalia, 1993; Blakeslee, 1997; Geisler, 1994; Poe et al., 2010). In this context it has been argued that beliefs (about writing, about the aims of science, and about the relationship between writing and science) and attitudes may be more influential on a novice's capacity to gain disciplinary fluency than learned behaviours.

Both the academic literacies' perspective on writing (Lea & Street, 1998) and theories of discourse acquisition, particularly Gee's concept of discourse (2004, 2014), suggest that acquiring the "ways of being" (including language use and attitudes and beliefs) and identity of a STEM disciplinary community is essential to engaging with that community. Lea and Street and Gee both argue that language use and literacies are situated practices (amongst other practices) within a specific discourse community, a community whose behaviours are determined by specific beliefs, attitudes, and ways of looking at the world. Within disciplinary communities, literacy (and the literacy attitudes and beliefs that inform that literacy) is positioned as one of the central practices which defines an individual's identity as a member of that community (Bartlett, 2007).

The literature on writing in the disciplines, with its focus on using writing to learn and use authentic genres and practices, similarly highlights the relationship between attitudes and beliefs and effective practice (McLeod & Soven, 2000). Writing scholars in the cognitive tradition (Bereiter & Scardamalia, 1987; Blakeslee, 1997; Geisler, 1994) have long recognised that, while learning to write science must involve learning specific literacy-related skills and practices, emerging scientific writers must also learn to adopt the beliefs (about writing, about the aims of science, and about the relationship between writing and science) and attitudes of their disciplinary community if they are to engage with that community.

Likewise, theories of expertise stress the expert's "intuitive" behaviours, practices, and ways of being (Dreyfus, 2004; Ericsson, 2004; Holyoak, 1991) and the significance of attitudes and beliefs to the acquisition of expertise (Dall'Alba & Sandberg, 2006). In her model of domain learning, which focuses specifically on academic expertise, Alexander (2011a, 2011b) focuses on three key elements of expertise: knowledge, strategies (processes and practices), and affect, and suggests that it is essential that all three elements are included in any disciplinary curriculum, observing that "If the educational experience is too narrowly focused on the acquisition of domain-specific knowledge…[without regard to affect factors] we may be stressing one aspect of expertise to the detriment of others". If we consider this model within the context of STEM literacy, we might relate this to knowledge about how scientific knowledge is made, engagement with discipline-specific writing strategies, and positive affect factors such as interest in, motivation for, and enjoyment of writing. Clearly, then, it is important that any STEM curriculum must address student literacy, but equally importantly, it must address students' literacy-related attitudes and beliefs. Whatever way we hope our students will engage with STEM communities – whether that be as professionals within STEM-related industry, or as research leaders, or simply as science-literate citizens – literacy, and the attitudes and beliefs that support STEM-based literacy, is a critical aspect of that engagement. This is all the more important in the school curriculum because we know that attitudes and beliefs, once they have been established, are very hard to change (Breslyn & McGinnis, 2012; Dall'Alba & Sandberg, 2006; Fletcher & Luft, 2011; Jones & Leagon, 2014; Martinez, Sauleda, & Huber, 2001; Peters-Burton, Merz, Ramirez, & Saroughi, 2015; Tobin & Tippens, 1996).

11.3 What Attitudes and Beliefs Do We Want Our Students to Acquire?

If we accept that learning the literacy-related attitudes and beliefs of a disciplinary community will strongly influence students' acquisition of STEM literacy, we need to know what we're aiming for; we need to align the literacy-related attitudes and beliefs in the classroom with the literacy-related attitudes and beliefs of the STEM community. While the literature on the attitudes and beliefs of STEM writers is relatively sparse (Harding & Hare, 2000; Yore, Hand, & Florence, 2004; Yore, Hand, & Prain, 2002; Yore, Florence, Pearson, & Weaver, 2006), we can identify key broad themes.

In terms of beliefs, while anecdotally scientists are often portrayed as having poor self-efficacy in relation to literacy, research (Daley, 1999; Emerson, 2017; Florence & Yore, 2004; Hartley & Branthwaite, 1989) indicates that successful

STEM writers are likely to have strong, positive self- efficacy in relation to writing and that, while they are unlikely to describe themselves as writers, they nevertheless have a confident identity as a writer of science. Findings from the literature concerning beliefs about the purpose of science writing are more contested, but Florence and Yore (2004), Bereiter and Scardamalia (1993), Bazerman (1988), and Keys (1999) suggest that successful science writers are likely to see writing as fundamental to science and being part of knowledge generation. In a more in-depth analysis of scientists' beliefs relating to writing, Emerson (2017) indicates that adaptive STEM writers (i.e. those who write for a wide range of audiences and hold beliefs about the social responsibilities of science) are likely to see writing as knowledge building.

In terms of attitudes, positive attitudes towards writing are generally correlated with adaptive scientific writers (Emerson, 2017). Research suggests that, while enjoyment is not essential to successful science writing, there is evidence that motivation (Fox & Faver, 1985; Jones & Preusz, 1993; Rodgers & Rodgers, 1999), resilience (Boice, 1994), and confidence (Morss & Murray, 2001; Shah, Shah, & Pietrobon, 2009) are key characteristics of successful disciplinary writers.

These are the broadest brushstrokes of the key literacy-related attitudes and beliefs that we need to promote in the STEM classroom, if we are to impact positively on student writing. Attitudes and beliefs are likely to be more nuanced within different STEM-related discourse communities; nevertheless, in a science curriculum that is designed to be both introductory and broad (PISA, 2006), the central themes may be all that is required.

11.4 The Literacy-Related Attitudes and Beliefs of STEM Students

I began this chapter with a story from my professional life that suggested all was not well with STEM student attitudes to and beliefs about writing, supported by evidence from Poe et al. (2010) that I was not alone with this experience. This is an opportunity for further research, but in the absence of recent data about student literacy-related attitudes and beliefs, a recent study on scientists as writers (Emerson, 2017) may throw some light on where these negative literacy-related attitudes and beliefs come from and what has happened in STEM students' schooling that has developed and reinforced such literacy-based perceptions.

11.5 The Problem Starts Early

At the beginning of my 2017 study, I observed that there is little, if any, research into scientists' or STEM-oriented students' early experiences of writing in school. What evidence we have is largely anecdotal. Martin (2012, para 9), for example, identifies an informal stratification that begins in elementary school where, she argues, we identify students as having a maths or writing orientation:

> *We begin differentiating scientists and writers in elementary school. One "likes math" or "likes English". Our academic system from pre-K through graduate school, contrasts science and literature – objectivism and subjectivism, reductionism and holism.*

My 2017 study of scientists' experience of learning to write in their 1st years of school appears to confirm this observation, showing that, for many scientists, the early years of schooling not only failed to lay the groundwork for their future identities and practices as scientific writers but also impacted negatively on their self-efficacy as writers, actively forming or confirming their notions of themselves as poor writers.

Many participants in this 2017 study could recount – 30 or 40 years not lessening the bite to their confidence – painful responses from teachers to their writing. They described consistent criticism that they didn't understand and a sense of failure, even when they started school with positive experiences of writing. The following quote is illustrative of such experiences; this particular scientist described himself as a child who loved writing and wrote constantly at home, until this experience:

> *I was 8 years old in school in Singapore; I took a cruise with my parents to Hong Kong from Singapore and I wrote a card every day to my class. They were …bubbling over with stuff, right, and very messy and, I remember now, the teacher stuck them on the board and said 'this is exactly how not to write' because my handwriting was terribly sloppy so I was obviously creative but I was messy and he made it – he embar- I must have come home and my mother said 'you've stopped writing, what's going on?* – Senior Scientist, Physics.

Beyond the influence of specific teachers, however, we can identify one aspect of the early English curriculum that recurred as having a significant impact on students' self-efficacy as writers: the focus in elementary school on creative writing, which posed significant problems for many of these students:

> *I was top in maths but I was desperate in English. …The title was 'Your House'. Now as a mathematician … I've got to write about my house. What is my house? And I went to numbers straight away. It's got five windows, it's got one door…. I knew it was a disaster when I wrote it. But I was incapable of doing anything better… I had imagination in maths but no imagination in writing….I thought I'd got to write the truth, I'd got to write the facts, strive for accuracy. Because accuracy is what mathematics is about* – Senior Mathematician.

This focus on creative writing produced a sense of inadequacy in many of the scientists in this study, who needed something (facts, data) on which to hang their writing. This response, from a senior scientist in human health, sums up the concern:

> I felt that what I wrote wasn't the way that I'd intended it….. But I've never really enjoyed it. Never. Up until later. And I guess partially because [writing at school] is creative writing, and that's quite different from the sort of writing that I do now, which I enjoy. I can certainly see a creative component in [scientific writing], but it's still centred around something tangible: I don't have to make it up. There's still data or dogmas or other sort of theories that I can use to develop my story.

For many of the participants in this study (from senior scientists to doctoral students), elementary school was the place where their view of themselves as poor or inadequate writers was established – a view that, for some, still troubled them, even after a successful career based on writing in a range of STEM genre. If we go back to Martin's comment, about the early and enduring differentiation of students as "liking maths" or "liking English", we can see that "liking English" most likely equates to "likes creative writing" and writing from the imagination. Students with a science-orientation, it seems, may be thus deprived, at a very early age, of an opportunity to see the connections between writing and data, to develop the writing skills for which they may have more capacity, and, more importantly, to view themselves as successful writers.

11.6 Middle and High School

While problems of self-efficacy in relation to writing appeared to be negatively established in elementary school, the issue in middle and high school clearly shifts to other beliefs: beliefs about the relationship between writing and science and the nature of scientific writing.

Over half the participants in this study felt they left school with an adequate grasp of the basics of grammar, punctuation and spelling, and some of the higher-level skills of paragraphing and constructing an argument. However, the critical point to note about post-primary schooling is that these skills were developed, not in science classes but through compulsory English courses or other writing-rich subjects, thus helping to construct student beliefs that writing and science are separate. No interviewees could recall any specific instruction on scientific writing in high school. The only genre of scientific writing they could recall was lab reports, which positioned writing as knowledge reporting and completely failed to model the complex, creative process of writing to make meaning:

> *You don't sit down and say the experimenter did this, and then this. We had this awful thing at school, you know, 'Observation, Results, Experiment'... I mean, whoa! …You know, the things we do to kids, we teach them this garbage! No, no, you are telling a story …And we've got to somehow sift out of all this complexity, what we've learned, and throw the extraneous stuff away, and tell a story* – Senior Scientist, Physics.

The major concern was that lab reports, as they are currently presented, do not resemble the creative, narrative-focused process of advanced scientific writing while at the same time perpetuating the myth that scientific writing is a formulaic reporting of findings:

> *You were taught what a lab report structure was and aims and methods and stuff [at school] but when I got to doing my PhD I quickly realised that this was just fantasy – like, there was this myth that lab reports were important, like teaching you for the future! No, it's not! It's not like a scientific paper at all: that's outrageously stupid! I don't even know why we persist with this artifice that lab reports are somehow important….I'd much rather have people fill in boxes with their thoughts that gives them some structure…and then later, when it comes to writing papers, they won't have this idea that your paper will be like just a really long lab report. That's just stupid* – Emerging Scientist, Chemistry

Criticism of laboratory work in school science is not new. Hart, Mulhall, Berry, Loughran, and Gunstone (2000), for example, discuss the fundamental discrepancies between what happens in a school lab and the activities and processes of a research scientist, concluding that "school science leaves out many crucial aspects of scientific activity, including the fallibility, the passion, the commitment, and the creativity involved". However, the significant point to take away here confirms Lerner's (2007) view of the basic disconnect between lab writing and the aims and processes of science, as well of the tendency of this practice to promote erroneous beliefs about the relationship between writing and science and the ways knowledge is made in science.

Perhaps, then, it is hardly surprising that students in my 1st-year science writing class are both puzzled by and anxious about a writing class in their science degree. Years of schooling have provided them with negative self-efficacy as writers and used models of writing that promote beliefs of writing and science as, at best, disconnected and of knowledge making in science as divorced from the process of writing, leading to a consequent belief that there's no reason to expect them to learn to write science.

11.7 The Literacy-Related Attitudes and Beliefs of STEM Teachers

If we accept that writing is integral to how science is made, that most (if not all) science writing careers depend on writing and communication, that literacy-related attitudes and beliefs are an essential part of becoming part of a STEM community, and that our current approach to teaching writing in science is producing students with poor self-efficacy as writers and negative literacy-related attitudes and beliefs, then the solution seems obvious: we must revise our elementary and high school science curricula to include authentic opportunities to develop writing skills and to embed positive writing-related attitudes and beliefs in our K-12 students. Unfortunately, it is not that simple. As we have already observed, years of initiatives to embed literacy in STEM disciplines have failed to have a significant impact on STEM student attitudes to writing. Why is that?

It is here that we must begin to speculate – and turn to the teachers and to STEM education policy makers. I want to suggest, perhaps controversially, that these aims to embed literacy in the STEM curricula have failed for two reasons: first, because years of professional development have failed to shift STEM teachers' own entrenched negative literacy-related attitudes and beliefs and these have been transmitted (perhaps unwittingly) to students and, second, because literacy remains tangential to definitions of science in schools. This section of this chapter is perforce speculative: I am aware of no study that has directly focused on the literacy-related attitudes and beliefs of STEM teachers. However, the literature on beliefs and attitudes in relation to professional development initiatives provides us with a way to speculate about our failures to integrate literacy into the STEM curriculum in a way that transforms student attitudes and beliefs.

Michelle Gregoire, in a significant review of how teacher beliefs relate to the implementation of educational reforms, argues that “understanding how teachers’ beliefs relate to their practice as well as to student outcomes may be the missing link between calls for school reform and teachers’ implantation of that reform” (2003, p. 149). Both Jones and Leagon (2014) and Gregoire site multiple studies that confirm that beliefs, including self-efficacy beliefs, impact on teacher practice and their adoption of curricula and pedagogical reforms. Amato (2004), for example, shows that teachers with negative attitudes to a topic are likely to avoid teaching that topic, while Eagly and Chaiken’s (1995) research suggests people tend to ignore or discount information which does not support their own attitudes and beliefs. In a recent article in the *Times Higher Education*, David Matthews (2017) reports on work by anthropologist Lauren Herckis which shows that, even when presented with evidence of more effective teaching methods, teachers will persist in old beliefs and attitudes about the nature of teaching. “When our gut tells us to do one thing and an article tells us another”, Herckis comments, “it is very difficult to change behaviour”. Our “gut”, we might suggest, comprises the beliefs and attitudes that we have accumulated, often without conscious awareness, throughout our education. As Dewey (2002, p. 224) comments: “Man is not logical and his intellectual history is a record of mental reserves and compromises. He hangs on to what he can in his old beliefs even when he is compelled to surrender their logical basis”.

But what do we actually know about teacher beliefs and attitudes to literacy in STEM? This is another promising field for further research, and here we must again extrapolate because we simply don’t have sufficient data to draw strong conclusions. Nevertheless, there are indications that STEM teachers may exhibit the same negative literacy-related attitudes and beliefs as their students.

In our 2014 study of using academic literacy to effect a successful student transition into higher education (Emerson et al., 2014, 2015), the most reluctant teachers to engage with our work were science teachers. The most common arguments against integrating writing into the curriculum were that it was unnecessary, they didn’t have the time, and there was too much material in the curriculum already. Many suggested that the English department were the right people to teach writing. In other words, *these teachers presented with similar literacy-related attitudes and beliefs as their science-focused students.*

In many ways this should not be surprising: after all, we might expect that these teachers would have experienced the same negative self-efficacy factors and acquired the same negative attitudes and beliefs as the science-oriented students described earlier in this chapter. Nevertheless, we might have expected a corrective to have occurred during their experience as undergraduates in a STEM discipline.

However, it is unlikely that these expectations are being realised. Beyond school, most participants in my 2017 study of scientists as writers reported that the undergraduate years were equally devoid of opportunities to develop as writers. Outside of mathematics, only three participants were able to identify intentional support for authentic writing opportunities. Instead, engagement with scientific writing did not begin in earnest until the postgraduate years. What this means, then, is that most secondary school teachers who have completed only undergraduate studies in a science-related discipline will not have been exposed to any teaching that would enable them to adjust the writing-related beliefs and attitudes they themselves acquired in school and will not have experienced effective pedagogical approaches to developing their own science literacy. Far from being masters of a science-related discourse, science teachers may have completed their undergraduate science before they could be fully engaged with science-related literacies. And they may not have experienced any teaching or assessment that would have challenged the negative literacy-related beliefs and attitudes that were instilled in them through their own schooling.

Without direct data on STEM teacher's literacy attitudes and beliefs, we can do no more than conjecture. But if further research did confirm the suggestion here that STEM teachers also embody negative literacy-related attitudes and beliefs, then the literature on beliefs and attitudes which demonstrates the persistence of such beliefs and attitudes provides us with an answer to why literacy initiatives are failing to bring about change. This literature also provides ample evidence that teacher attitudes and beliefs are likely to impact on their practice in the classroom, the way they approach a curriculum, and their pedagogical preferences (Amato, 2004; Gregoire, 2003; Jones & Leagon, 2014; Wong, 2016). STEM teachers may continue to avoid or minimise teaching writing, in the face of professional development opportunities to centre literacy in the curriculum, because of beliefs about their own capacity as writers and teachers of writing, beliefs about the nature of science and the relationship between science and writing, and their overall negative attitudes towards writing. The following model, adapted from Jones and Leagon (2014), illustrates what this might look like (Fig. 11.1).

11.8 The Impact of the Science Curriculum's Founding Documents

I want to suggest that there is one last piece of the jigsaw. Another explanation for science teachers' resistance to integrating writing into the STEM curriculum may relate to the locus of writing initiatives: they come from a literacy perspective, not a science perspective. And definitions of science which underpin school science curricula commonly do not include writing as a key competency.

Let us start with a local, New Zealand example. The science curriculum is underpinned by five key capabilities: gather and interpret data, use evidence, critique evidence, interpret representations, and engage with science (Hipkins, 2014; MoE, n.d.). While information literacy (the ability to engage with and critique information) is clearly part of these capabilities, writing is absent. Integrating writing into the curriculum or using writing pedagogy as a learning tool are absent in a key policy document that describes the aims of the curriculum.

Fig. 11.1 A model of possible STEM teacher attitudes and beliefs in relation to practice

Another example from a larger context: the *Science for All Americans* initiative (1990) which focuses on effective pedagogy with an emphasis on authentic practices includes a single comment in relation to writing in science, under the heading "Insist on Clear Expression":

> …science teachers should emphasize clear expression, because the role of evidence and the unambiguous replication of evidence cannot be understood without some struggle to express one's own procedures, findings, and ideas rigorously, and to decode the accounts of others.

In focusing on *clarity*, this document reinforces the belief that the purpose of writing in science is communicating not forming knowledge.

Broadening the discussion yet further, neither Vision I nor Vision II definitions of science literacy and scientific literacy proposed by Douglas Roberts in his 2007 landmark study (Roberts & Bybee, 2014) incorporates writing as a fundamental aspect of science (Vision II does incorporate aspects of information literacy). In the PISA assessment, science and literacy are separated, with no mention of writing as fundamental to science in the definition of science literacy:

For the purposes of PISA 2006, scientific literacy refers to an individual's:

- Scientific knowledge and use of that knowledge to identify questions, acquire new knowledge, explain scientific phenomena, and draw evidence-based conclusions about science-related issues

- Understanding of the characteristic features of science as a form of human knowledge and enquiry
- Awareness of how science and technology shape our material, intellectual, and cultural environments
- Willingness to engage in science-related issues and with the ideas of science, as a reflective citizen

Once again, information literacy is an element of PISA's approach (indeed, the PISA documents are highly specific about the importance of information literacy). But broader issues, of using writing to engage in knowledge creation and development, are entirely missing.

An interesting aspect of the PISA framework is that it does directly address the importance of attitudes to engagement with science: "the PISA 2006 definition of scientific literacy has been expanded by explicitly including attitudinal aspects of students' responses to issues of scientific and technological relevance" (OECD, p. 25). However, attitudes to writing in science are not included. In the key competencies listed in the PISA framework, there are several areas where writing could be privileged, for example, in *recognising the key features of a scientific investigation* or *interpreting scientific evidence and making and communicating conclusions.* However, writing is not integrated into the discussion of these competencies, and while some writing (a brief paragraph or text accompanying a diagram) is required in the test, there is no suggestion that the writing process or writing to learn is expected to be a significant part of this aspect of the test.

Neal Lerner (2007), writing about how writing is placed in the school science curriculum, argues that while writing may be a part of the STEM curriculum in schools, it is *not* presented in such a way "for students to learn the relationship between *doing* science and communicating what they are doing… And not in a way, in Russell's (1991) words, 'to engage students in the discovery of knowledge, to involve them in the intellectual life of the disciplines'" (p. 100). This may well be because, as we have seen here, key policy documents, and an international testing system, do not integrate writing or literacy (beyond information literacy) into their definitions of science or science literacy – with subsequent consequences for the STEM classroom (Norris & Phillips, 2002).

When STEM teachers are confronted with literacy initiatives that both conflict with their own prior beliefs and attitudes and with national and international definitions of science and science education, it seems hardly surprising that their beliefs and attitudes prove resistant and their motivation to change their practice by integrating literacy in a meaningful and discipline-appropriate fashion remains low.

11.9 Where to from Here?

This chapter began with an exploration of student resistance to literacy in the STEM curriculum despite multiple efforts over many years to integrate literacy into the school STEM curriculum. And we have ended with the teachers, suggesting that

STEM teachers themselves may be impacted by negative literacy-related attitudes and beliefs. We have further suggested that these attitudes and beliefs, combined with national and international policy documents defining science and science education, may make these teachers resistant to literacy initiatives which originate outside of the STEM curriculum, with the consequence that they continue to minimise writing in the curriculum and as an effective pedagogical tool – leading to negative literacy-related attitudes and beliefs in students. There are many steps in that argument, some of which are based on extrapolating from the literature rather than from direct empirical data. We have already indicated areas that would benefit from empirical enquiry: research into student and teachers' literacy-related beliefs and attitudes would be a good place to start. But on the basis of the argument I have made here, what are the implications for the school STEM curriculum and for literacy-related professional development initiatives?

Our challenge is to adjust the attitudes and beliefs of both teachers and students. If we start with our students and we accept that attitudes and beliefs are hardwired against change, then we must begin in elementary school to ensure negative literacy-related attitudes and beliefs never take root. Part of this includes adjusting the focus on elementary school writing instruction from creative writing to at least some focus on writing from data, to enable science-focused students to experience success with writing at an early age.

But the most significant idea to emerge from this chapter, I believe, is that if we want to make changes to STEM student literacy-related attitudes and beliefs, then change needs to emerge from *within* the STEM educational community in terms of the way it defines science and characterises science education. Literacy initiatives and curricula that originate outside of STEM will always be challenged (overtly or covertly) because they are unlikely to shift STEM teacher attitudes and beliefs, with subsequent failure to fully engage with literacy in their classroom. Professional development related to literacy in STEM then needs to start with a challenge to the way STEM teachers define science and the scientific process, and from there it needs to work on the literacy-related beliefs and attitudes that our teachers may have acquired in their childhood.

This is no small task. And we know that changing beliefs and attitudes is hard. Gregoire comments: "if teacher educators…are to get teachers' attention and increase their motivation to process reform messages, then they should acknowledge that their teacher identities are at stake and that their resistance to change may come from their reluctance to confront that which is threatening" (p. 171). In the case of both STEM teachers and students, who have learnt from an early age that you can either "like science" or "like writing" (Martin, 2012), messages about the fundamental connection between literacy and science may be deeply confronting.

But scientists are writers, and if we are serious about our students' futures as science-literate citizens or as contributors to science industry or science research, this is a challenge we must address. As the quote at the beginning of this chapter says, "*I tell my students that you may think you're a scientist – you're not – you're a writer who writes about science*" (Senior Scientist, Genetics, quoted in Emerson, 2017). There are recent, positive signs of change in the way the school science community in some parts of the western world defines science and science education: in the USA, for example, the New Generation Science Standards do provide an integrated approach to literacy in science by positioning both argumentation using evidence and the communication of findings as integral to the work for science (National Research Council, 2012) – and this is important precisely because the initiative is emerging from within the scientific community itself. However, as Binns and Popp observe (2013), teacher resistance remains a challenge. Nevertheless, I would argue that this is a start in the right direction, because only when change comes from within the science community will STEM teachers have the motivation to change their own beliefs and attitudes – even if it takes time – and, thus, to reform student resistance to writing.

Postscript: I began with a description of student resistance in an undergraduate STEM writing course. This is the solution we are currently developing: we are working with college of science staff to centre the course and all relevant assessment, around a series of experiments in specific disciplines. We are using writing to learn pedagogy in our classes and ensuring that all assessments integrate information literacy and audience-focused writing. Finally, we are bringing professionals working in STEM industries and STEM researchers into the classroom to talk about writing in their daily lives to demonstrate the centrality of writing – and literacy more generally – to science.

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Part III
Review

Chapter 12
Critical Dialogues for Emerging Research Agendas in Science Education

Gregory J. Kelly

The chapters in this book focus on the intersections of science, knowledge, literacy, and writing in educational contexts. These authors apply multiple perspectives to propose a research agenda for science education. While the topics, analytic domains, and approaches to research vary, there are some common understandings and a variety of assumptions that can be examined through reflection and dialogue. A common theme is that scientific literacy involves language use, in its many forms, and that engaging in discourse processes entails participation in a community with the associated norms, expectations, genre conventions, and ways of being as defined by the actions of its members. Thus, learning to describe, argue, or write involves reading the given situation to make decisions about how to slot into a set of cultural practices of some epistemic community. The cultural practices of science are interpreted, translated, reformulated, and manifested in schools and other educational settings. To the extent that writing and literacy involve knowledge, the role of epistemic practices becomes central to such activities (Kelly, 2008).

Considerations of the epistemic practices of science entail examining how a community of inquirers engage with each other and the world to establish legitimized knowledge claims. Although differences in interpretation of science exist across the chapters, a common feature of the collective views of science is that knowledge claims require an evidentiary basis. In this way, science may be different than other fields (such as art or music) where breaks from tradition and new metaphors arise from creative inspiration. Science requires a statement of evidence to support new claims, theories, and metaphors. As educational researchers constructing an agenda for research on science literacy and writing, we can pose reflexive questions: What counts as educational research? What are the empirical bases for knowledge claims? How do different theoretical traditions define and represent a

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V. Prain, B. Hand (eds.), *Theorizing the Future of Science Education Research*,
Contemporary Trends and Issues in Science Education 49,
https://doi.org/10.1007/978-3-030-24013-4_12

conceptual world? How is the ontology of educational research defined through the actions, practices, and products of educational researchers?

Questions posed about the research agenda for science education and, in particular, the relationship of spoken, written, and symbolic language in science make visible differences in assumptions about science, knowledge, language, and learning. Across the perspectives offered in this collection, there are also assumptions about the nature and purpose of educational research. In an introductory chapter in the *Handbook of Complementary Methods in Education Research*, I (Kelly, 2006) built on the work of Habermas (1990), Longino (2002), and Strike (1995) to identify three types of critical dialogue for advancing educational research. These critical dialogues provide a framework for discussing and articulating the different theoretical and associated epistemological and ontological assumptions of the perspectives informing a science education research agenda. I labeled these conversations *critical discourse within group*, *critical discourse regarding public reason*, and *hermeneutical conversations across groups*. Next, I apply this frame of critical dialogues to consider contributions of the chapters of this book to the ongoing conversations about science education reform.

12.1 Critical Dialogues About Science Education Research Agenda

The purpose of this book is multifold but includes setting some directions for future research in education about science, literacy, and writing. The critical dialogues I am proposing help sort the type of ontological category in the debates and setting of the agendas. The complexities identified by the editors and authors cut across theoretical, methodological, and epistemological categories. Research is conducted within groups of scholars that share common ways of conceptualizing, describing, and interpreting phenomena of interest (Strike, 1989). Murray (1998) referred to such loosely affiliated groups of researchers as theory groups. Members of these theory groups typically share high degrees of communication, participation in common professional organizations, a number of mentor-student relationships, and long-term commitments to particular research topics. In this book, the authors participate in number of common theory groups, some of which are represented in the chapters. These groups bring different ways of doing research through choices about foci, employed theories, research methods, and purposes of education research. Some sorting of the ideas and proposed agenda items may be helpful. For this, I turn to the critical types of conversations.

Critical Discourse Within Group *Critical discourse with groups* conversations concern the developmental and definitional work regarding the creation, specification, and extension of a research group's central theories, assumptions, key constructs, and empirical scope (Kelly, 2006). Within-group critical discourse provides a forum for development of a research area's core theories and commitments.

Rhetorically, contributions to critical discourse within group build on current knowledge by proposing new theoretical constructs, new avenues for research, or branching into new empirical domains. For example, Graham (Chap. 4, this volume) provides explication of the Writers in Community Model. His chapter articulates the central premises, identifies areas for growth, and proposes 15 specific recommendations for research. This is an example of a progressive research program advancing an agenda within the basic assumptions of the tradition. Lamb, Hand, and Yoon (Chap. 5, this volume), on the other hand, propose a new paradigm for research on science writing. Their chapter examines argumentative and summative writing from a new methodological approach, namely, localized hemodynamic responses by writers. This is the beginning of a research program and seeks to tie human behavior (e.g., types of writing, critical thinking) to neurological activity. As this research program continues to develop, it will need to further articulate how neuroimaging provides insightful contributions to teaching and learning practices. In both cases, the nature of the contributions is an extension of the research groups' current work.

The chapter by Tang (Chap. 6, this volume) proposes actor-network theory as a way to bring together theoretically converging views of science and literacy. This is an example of how theoretical considerations entail advances in research methodologies (see also chapter by Yoon (Chap. 9, this volume)). In this case, Tang interprets both literacy and science events as distributed in space and time, focused on performative aspects of social practices, and interactionally constructed through spoken, written, graphical, gestural, and physical movement. The complexity of the interactional accomplishment of scientific practices thus suggests the use of actor-network theory to recognize the myriad of ways that what counts as science, argument, literacy, and so forth are constructed in a nexus of human and textual actors. Yoon (Chap. 9, this volume) similarly makes a theoretical contribution to the ongoing conversation about scientific literacy practices. His chapter makes the case for a consideration of the activity system within which students' interactions constructing literacy practices occur. Yoon proposes the idea of Discourse Space as a "set of external representations of meanings that participants in discourse accessed, changed, and developed while engaging in a particular practice". These two chapters advance the theory by offered ways to conceptualize the cognitive and representational artifacts created by the collective knowledge of an epistemic community.

Understanding the multiple factors relevant to research in argumentation and literacy is proposed by Hand, Cavagnetto, and Norton-Meier (Chap. 7, this volume). This chapter builds from previous research (thus extending the critical discourse within group) to specify some of the relevant factors that might contribute to an actor-network view of the immersive ecology of "living the languages of science." The authors identify key topics such as closer attention to the cognitive, cultural, and linguistic resources students bring to the classroom, relevance of student-student discourse to support science learning, and underutilized potential of the broader science classroom environment. The chapter calls for greater use of new "cognitive, linguistic, representational, socio-cultural, and epistemological frameworks" (p. #) to address such emerging topics.

Critical Discourse Regarding Public Reason *Critical discourse regarding public reason* focuses on the development of epistemological commitments to assess the value of educational research within and across different research traditions (Kelly, 2006). These conversations concern the criteria used to judge the value of research. Likely candidates for criteria would be insightfulness, empirical warrant, theoretical salience, consistency with other knowledge, transparency, and usefulness for practitioners. These conversations get at the questions about the nature and purposes of educational research.

The chapter by Webb and Whitlow (Chap. 2, this volume) investigates the assumptions and value of how cognitive and sociocultural approaches can be brought together given recent advances in theories of knowledge and learning. The chapter traces some of the historical roots of the perspectives and compares how the two theories contrast in treatment of knowledge, transferability, ways of researching, and metaphor for learning. The chapter goes further to pose the criterion of far transfer as a way to judge the value of educational interventions. The authors seek to bring cognitive and sociocultural scholars together for mutual learning. In this respect, Webb and Whitlow are considering the criteria for quality research on argumentation, literacy, and science writing. They proposed the value of recognizing far transfer. There may be other examples and questions that can be raised about the epistemological commitments of the field of education regarding research methods. This would thus be a dialogue about public reason—the development of common criteria used to place value of different approaches to research.

Hermeneutic Conversations Across Groups *Hermeneutic conversations across groups* are designed to learn from differences across traditions. In educational research, like many fields, the foci of empirical work can be examined from different theoretical or methodological perspectives. There is potential for different research groups to learn from the perspectives of others regarding research literacy, writing, and science learning. Chen (Chap. 8, this volume) considers writing as an epistemological tool from three points of view: personal, disciplinary, and sociocultural. This chapter thus compares and develops perspectives through contrastive analysis of writing in these three landscapes. The work builds on studies of epistemology and learning by considering how personal theories of knowing, disciplinary knowledge, and social practices views of knowledge and learning (Kelly, McDonald, & Wickman, 2012) offer different perspectives for approaches to writing. The chapter evinces how views of knowledge have consequences for understanding different dimensions of writing. Chen offers specific details about how each of the perspectives (personal, disciplinary, and sociocultural) contributes to important questions about the teaching and learning of writing.

Emerson provides an example of how such conversations across groups may address persistent problems in the field of science writing research. This chapter takes on the important problem of students' (particularly in STEM disciplines) attitudes and beliefs about the importance (or perceived lack thereof) of writing in science and these students' self-efficacy regarding their own abilities to write. While drawing from research on literacy, students' attitudes, and science writing, Emerson identifies how both situated definitions of science in the disciplines and among teachers and students, as well as assumptions about the writing in knowledge construction and communication, serve as a countervailing ideology to purposes of developing effective writers in science. Emerson points to the need to bring scientists, teacher educators, and students into the conversations about the role and importance of writing in science.

Hermeneutic conversations across groups also manifests in the chapter by Prain (Chap. 10, this volume). His chapter considers ways that scientific representations have been considered across research traditions in education. Echoing a tension found in earlier chapters of this volume, Prain notes that the "two camps" are broadly a cognitivist perspective and a sociocultural perspective. The perspectives have different views about the nature of uses of representations in science and education. Prain points out that despite some differences, the perspectives agree on the importance of representations for meaning making and meaning sharing. The chapter notes areas of complementarity and poses a set of questions for further scholarship related to how individual and collective actions can support representational competence.

12.2 Reflexive Turns

Gee (Chap. 3, this volume) asks us to develop "committed testers" among our students that are willing to examine their own and others' claims about the world. Claims are constructed and reliant on a set of other claims and assumptions, and thus such claims come in clusters that cannot be examined one at a time. Rather, these claims form a constellation of ideas that create a bigger framework. In philosophy of science, these related claims are referred to as auxiliary hypotheses, any one of which can be challenged so that a hypothesis under question would not necessarily be refuted by evidence—as either the tested hypothesis or one of the auxiliary hypotheses can be blamed for empirical failure. In this way, claims can be (seemingly) immune from empirical refutation, leading to stubborn recalcitrance of frameworks.

As educational researchers, we can pose reflexive questions and ask ourselves, and hold ourselves accountable, to be the sought-after committed testers. The field of education adheres to frameworks that need to be examined. Gee points out many ways that the goals for science education have not been achieved, particularly as the focus on "science as content" has not lead to "science as a form of life," where the epistemic practices for proposing, testing, and legitimizing ideas are valued.

The authors of the chapters in this volume clearly seek to develop science as a form of life through education. The proposed research topics that comprise an emerging agenda need to be examined from the point of view proposed by Gee.

Indeed, the three types of critical dialogues outlined in this chapter seek to clarify the ways that educational researchers can become committed testers of our own constructs, theories, methods, and approaches to research. Gee notes that what is at stake as humans face an existential crisis of our own making. Committed testers need to develop ways of examining ideas, but also a set of dispositions and commitments, as challenging ideas also entails challenging the identity of those proposing ideas. From a sociocultural perspective, the norms and expectations of the epistemic community are just as important as the detailed ways that claims are examined through practices, as norms and practices co-construct and mutually inform each other. Gee's call for an honest look at the value of education asks us as educators to examine our learning goals for teaching and how we too can examine our beliefs about schools, learning, literacy, and science.

The chapters in this book pose challenges for setting a research agenda for studies of science literacy and writing. I have proposed that we consider how each of the chapters has made a contribution to conversations within a tradition, to conversations about the nature of research, or to conversations about how multiple perspectives can be complementary.

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