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REVIEW ARTICLE

Seeking a Comprehensive Theory About the Development of Scientific Thinking

Doug Lombardi[1] · Gale M. Sinatra[2] · Janelle M. Bailey[3] · Lucas P. Butler[1]

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Abstract
Our technological, information-rich society thrives because of scientific thinking. However, a comprehensive theory of the development of scientific thinking remains elusive. Building on previous theoretical and empirical work in conceptual change, the role of credibility and plausibility in evaluating scientific evidence and claims, science engagement, active learning in STEM education, and the development of empirical thinking, we chart a pathway toward a comprehensive theory of the development of scientific thinking as an example of theory building in action. We detail the structural similarity and progressive transformation of our models and perspectives, highlighting factors for incorporation into a novel theory. This theory will focus on beneficial outcomes of a more collaborative scientific community and increasing scientific literacy through deeper science understanding for all people.

Keywords Development of scientific thinking · Scientific literacy · Science expertise · Scientific evaluation

Scientific and technological advances have revolutionized our world, often in beneficial ways. Modern, western advancement began more than 300 years ago with the Enlightenment, centering on systematic and reasoned thought through which scientific and democratic discourse began to coalesce, grow, and spread. Such discourse led to pluralistic notions that sparked calls for increased justice, equality, and liberty. However, society has also continually grappled with the consequences of scientific and technological advancement. Bad actors have often purposefully limited the pursuit of enlightenment ideals to a privileged few, promoting the efficient

✉ Doug Lombardi
lombard1@umd.edu

[1] Department of Human Development and Quantitative Methodology, University of Maryland, 3942 Campus Drive, 3304 Benjamin Building, College Park, MD 20742-1131, USA

[2] Rossier School of Education, University of Southern California, Los Angeles, USA

[3] Department of Teaching and Learning, Temple University, Philadelphia, USA

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spread of racist, sexist, and other dehumanizing falsehoods (Hind, 2020). In the past 100 years, scientific and technological discoveries have unleashed the power of the atom, influenced Earth's biosphere and climate, and created an overwhelming global flood of information, all of which have benefited global citizens while also being weaponized to expand power for self-proclaimed elites and threatened the very survival of the human species (Haff, 2014). During this turbulent stretch, psychological, sociological, economic, and educational research have endeavored to better capture and understand the nature and characteristics of scientific thought and actions. Much of this work has been centered on the idea of building both a workforce and a citizenry that is more scientifically and technologically literate (see, for example, National Research Council [NRC], 2011).

Our work in psychological and educational research has, in some ways, paralleled this dynamic path of scientific advancement. Both collectively and individually we have developed theoretical models and perspectives of scientific knowledge construction and reconstruction (Dole & Sinatra, 1998; Lombardi et al., 2013, 2016a, 2016b), engagement in the science classroom (Sinatra et al., 2015), evaluation of scientific information (Lombardi et al., 2016a, 2016b; Sinatra & Lombardi, 2020), active learning in undergraduate science instruction (Lombardi et al., 2021), and the development of scientific habits of mind during childhood (Butler, 2020). We have approached our research with the central goal of improving scientific thinking and learning for all, for the benefit of society and the planet. Even so, our perspectives have been unavoidably influenced by our histories, peers, and academic communities, with a predominance of Western, White, and privileged perspectives characteristic of many academics in the United States and Europe (Henrich et al., 2010; Kumar & DeCuir-Gunby, 2023; Prather, 2023). We further realize that a fully coherent theory of scientific thinking development has remained elusive to both the research and practitioner communities. Therefore, on one hand, we approach this article with the hope that a better conceptualization of scientific thinking development would benefit these communities, as well as help all people thrive and succeed in our increasingly scientific and technological societies. And, on the other hand, we acknowledge that our experiences and cultures have shaped our worldview in a way that requires us to be vigilant and welcoming of other positions.

The purpose of this article is to examine the structural similarity and transformations of our theoretical ideas and to outline the factors important for constructing a theory about the development of scientific thinking as an example of theory building in action. Over the course of the article, we will describe the history and evolution of the contributing models, leading toward a new, synthetic perspective that is informed by each of these. Although it is beyond our scope to develop and defend a full theory, we seek to chart the pathway toward one as an example of theory building. We do this within the context of our prior work and how that prior work connects to psychology, science education, learning science, and educational research literatures. With this hope, we keep in mind a goal for a thriving planet for all human and non-human constituents. We begin with a summary of our models and how they evolved before taking a closer look at each one and their influence on the proposed future work. However, before doing that, we first acknowledge the excellent and important work highlighting marginalized voices in the scientific community and how these perspectives may inform a full theory on the development of scientific thinking (see, for example, Adjapong & Emdin, 2015; Agarwal & Sengupta-Irving, 2020; Bang & Marin, 2015; Medin & Bang, 2014), and note that we have not fully incorporated these perspectives into our theorizing due to our insufficient expertise.

In the Beginning

Any model or theory is—and should be—inspired by prior work; it must be so to both build on and extend the thinking of researchers in the field. For example, prior conceptual change and persuasion theorists inspired the work of Dole and Sinatra (1998). As conceptual change theorists themselves, they were struck by Pintrich and colleagues' (1993) groundbreaking article expressing a clarion call to move "beyond cold conceptual change" (p. 167). Working collaboratively and also inspired by feedback from Stellan Ohlsson, who saw their initial ideas presented at a conference and noted how models of persuasion might advance their thinking, Dole and Sinatra (1998) constructed the Cognitive Reconstruction of Knowledge Model by drawing on aspects of a model of persuasion from social psychology, the Elaboration Likelihood Model (ELM; Petty & Cacioppo, 1986), key features of the classic conceptual change model (Posner et al., 1982), and motivation theory and research to extend the cold, rational models of conceptual change into the warmer realm of motivation and emotion. Pintrich, then serving as editor of *Educational Psychologist*, encouraged Dole and Sinatra (1998) to include a model in their paper, which was originally submitted as a review article.

For the next 15 years after the publication of the CRKM, Sinatra and others tested and extended features of the model, going deeper into important and underdeveloped constructs. As this research team's thinking developed over time and iterated on aspects of the model, Lombardi et al. (2016a, 2016b) recognized how critical plausibility judgments were to scientific thinking and knowledge construction and how too many questions had been left unanswered by the CRKM. Lombardi et al. (2016a, 2016b) drew on philosophical and scientific views of plausibility to construct the Plausibility Judgments in Conceptual Change (PJCC) model.

Still, even as different components of the original CRKM model were tested empirically and the thinking about the model inspired the PJCC, the notion of what "deep engagement" meant in the CRKM needed further refinement. There were two significant efforts to advance research on engagement and what it meant for scientific thinking. Sinatra et al. (2015) and Lombardi and Bailey (2024) drew on existing views to both clarify the definition of engagement in science activities and expand discussion of engagement measurement in science learning research. The engagement continuum proposed by Sinatra et al. (2015) is not a theory but a framework for considering the grain size of engagement measurement, spanning from a focus on the individual to the individual-in-context to the context itself. The continuum thus characterizes which slice of the complex nature of science learning a particular study chooses to explore. The continuum design was not only a collaborative process across the authors of the article but was also informed by the other research in the Special Issue in which it was published. Sinatra et al. (2015) drew on those contributions to construct a way to conceptualize the various approaches to defining and measuring engagement, which extended the research team's thinking about how to characterize engagement as scientific thinking in practice. Lombardi and Bailey (2024) then used this engagement conceptualization to frame science teaching and learning within the dimensions of major theoretical research areas (conceptual development and change; scientific inquiry and expertise; argumentation, modeling, and computational thinking; and socio-scientific issues).

Several years after the initial efforts of Sinatra et al. (2015), Lombardi et al. (2021) brought together researchers from cognitive and educational psychology with discipline-based education research (DBER) teams from scientific fields to synthesize what is meant by active learning in the undergraduate classroom. Each of the seven DBER teams first drafted white papers to define active learning within their fields and describe the associated research. The first two authors looked across the white papers to identify commonalities, differences, and outstanding questions. DBER teams next responded to these initial findings and provided clarification where needed. Finally, the authors produced a definition of active learning that goes beyond the commonly used "anything other than lecture" idea (Lombardi et al., 2021). The role of engagement was a critical component throughout the various white papers and in the subsequent Construction of Understanding Ecosystem (CUE) framework.

As individuals, our early experiences include working as a research engineer, a military meteorologist, an educational psychologist, a discipline-based education researcher, a cognitive scientist, and a high school science teacher. These experiences provided different entry points into the following models and perspectives about construction of scientific understanding and reasoning. However, before we further reflect on our past positions, we begin by introducing an operational definition of scientific thinking, starting with our conceptualization of thinking, science, and scientific practices.

Scientific Thinking: A Working Definition

Many have suggested that thinking differs from other cognitive processes, such as perception, attention, and memory (Holyoak & Morrison, 2012). Bruner (1986) suggested that thinking is comprised of a suite of inferential processes (e.g., categorization, relational reasoning, and analogical reasoning, among others) used to attain, construct, and categorize concepts. Other pioneers of the cognitive revolution suggested that thinking relies on the mental interplay of beliefs and knowledge during the process of concept construction and evaluation (Bloom et al., 1956; Glaser, 1984; Halpern, 2014; Newell & Simon, 1961). Holyoak and Morrison (2012) said, "thinking is the systematic transformation of mental representations of knowledge to characterize actual or possible states of the world" (p. 1). Lombardi (2023) noted that "thinking is a broad term that includes many mental activities such as conceptualizing, remembering, reasoning, deciding, and planning" (p. 3).

Science can be thought of in (at least) two distinct but interrelated ways. In everyday usage, the term "science" is often used to refer to the set of disciplines in which knowledge has been and continues to be formed or discovered through the process of empirical investigation. These include, but are not limited to, physics, chemistry, biology, environmental science, and many others, including their subdisciplines and offshoots. However, in some everyday usage, and certainly in academic circles, the term "science" can also refer to the scientific practices that produce such disciplinary knowledge.

From these perspectives, which we adopt and synthesize, science is an enterprise involving people collectively working together (i.e., the scientific community and/or various scientific communities), gathering and analyzing reliable evidence about phenomena (e.g., Earth's climate) to construct valid knowledge (e.g., explanations, hypotheses, theories, laws) that must be (re)considered through systematic evaluation and (re)appraisal. In this view, scientific thinking is an inherently social system. This conceptualization of science is rooted in the work of philosophers of science, including T. S. Kuhn (1962), Popper (1963), Solomon (1992), Pickering (1995), and Bright and Heesen (2023), among others. Further, we suggest that two primary purposes of science are to deepen understanding about phenomena and to facilitate solutions to pressing and/or vexing problems, both scientific and societal (Dillon, 2017; Nagatsu et al., 2020; Rudolph, 2023). Thus, taken together, we operationalize *scientific thinking* as *mental activities used by communities of people to identify key questions about natural and social phenomena, gather and analyze evidence pertaining to those questions, and construct explanations to support deeper understanding and effective problem solving*.

Prior Theoretical Models and Perspectives

In the prior two sections, we have endeavored to explain the *inspirations* behind several models and the *development process* that extended our views about scientific thinking; we then provided an operational definition of scientific thinking that forms the basis of our current and proposed work. But what factors influence the development of scientific thinking as operationalized here? To get to this, we must first visit the models touched on earlier in greater depth. In the following sections, we explore more details of knowledge construction and reconstruction (through the CRKM), scientific evaluations and plausibility judgments (through the PJCC), engagement in scientific learning activities, and active learning and agency. We will then zoom out to other viewpoints that inform our efforts toward providing an example of theory development in action.

Deeper Dive into the CRKM: Scientific Knowledge Construction and Reconstruction

We noted that an aim of the CRKM theory builders was to posit a "warmer" view of conceptual change that incorporated motivation and emotions into an explanatory framework. This was the proximate aim. Taking a step further back, consider the more distal aim: to conceptualize *conceptual knowledge and knowledge* *reconstruction as a key component of scientific thinking*. Scientific knowledge can be defined as information that is stored in memory which has some truth value in accordance with the social and natural world as understood by scientific consensus. Some philosophers define knowledge as justified true belief. In this definition, beliefs are all information (regardless of truth value; Ajzen, 1991; Lombardi et al., 2020) stored in memory, and thus knowledge is the subset of all beliefs that are justified (Southerland et al., 2001). Scientific knowledge, to be useful to the science learner, must be at least partially rooted in scientific consensus. For example, belief in a flat Earth is not useful to learners' understanding of the day night cycle, seasonal change, and other astronomical phenomena. Belief in a round Earth (still not entirely accurate, as Earth is a slightly oblate sphere) is more accurate and more useful to understanding astronomical concepts, while knowledge of a spherical Earth as science has best determined it would be the most useful.

A key to scientific knowledge is the development of conceptual knowledge. The nature of concepts has long been a topic of intense debate among psychologists, and an attempt to resolve that debate is beyond the scope of this paper. There is little disagreement, however, that conceptual knowledge is categorical in nature (Chi, 2008) and is foundational to scientific thinking and reasoning. Sinatra and Seyranian (2016) explain that "a key aspect of... conceptual knowledge... is that it is generative. It allows the knower to draw inferences, make predictions, and think and reason with that conceptual knowledge, which can be small units of thought, mental models, or schemata" (p. 249).

There is also a long-standing debate among those in the science learning research community as to whether conceptual knowledge is coherent (Chi, 2008; Vosniadou & Brewer, 1992) or built up from "knowledge in pieces" (diSessa, 2014). It is not our aim to discuss this debate here. Rather, we argue that scientifically accurate conceptual knowledge, in whatever form it takes, has a decided advantage for the acquisition and understanding of new scientific information. Furthermore, well-organized knowledge facilitates the deep thinking and reasoning needed to evaluate evidence and judge conflicting claims (Lombardi et al., 2013). Having inaccurate prior conceptual knowledge has been shown to be a barrier to acquiring accurate and useful explanations of the natural world (NRC, 2007). Thus, researchers in science learning have often explored ways to promote conceptual change, or a change in the conceptual knowledge needed for more accurate scientific understandings (see Vosniadou, 2013). Indeed, it is our view that any theory of scientific thinking must take conceptual knowledge, and its construction and reconstruction, into account.

Views of the conceptual change process had been "re-imagined" many times over the past decades (Vosniadou, 2013). After the cognitive revolution, during which the dominance of the purely behaviorist model in psychology started to give way to a more interdisciplinary, cognitive science approach to psychology (see Miller, 2003, for an in-depth history), theories of conceptual change tended to focus on development and learning from a constructivist point of view, building on foundational assumptions about how knowledge is acquired through construction and elaboration of domain-specific structures that function much like scientific theories do (see Vosniadou, 2007). Theoretical and empirical investigations explored the nature of conceptual change across important areas of conceptual development, including but not limited to biological knowledge (Carey, 1985, 1992; Hatano & Inagaki, 1997; Keil, 1994), social cognition and theory of mind (Wellman, 1992), the nature of matter (Smith et al., 1985), and astronomy (Vosniadou & Brewer, 1992, 1994), as well as the very nature of conceptual categories and their role in learning (Carey, 2009; Gelman, 2003; Markman, 1989).

This was the backdrop against which Dole and Sinatra were considering perspectives on scientific knowledge construction and reconstruction. And yet, many of these and other theories of conceptual change that followed the cognitive revolution focused on "cold cognition" and ignored "hot constructs" such as motivation and emotion. Today, many psychologists argue that this split is artificial, and that human cognition is enacted through and with emotions, as cognition and emotions are inseparable processes (Immordino-Yang & Damasio, 2007). The so-called "warming trend" in conceptual change acknowledged and explored the role of motivation and emotion in conceptual change (Sinatra, 2005), but preceded the more current integrated perspective. The field has yet to fully embrace or understand the interconnectedness and what a truly integrated system means for science instruction, although it is clearly moving in that direction (Herrick et al., in press).

At the same time Dole and Sinatra were considering features of what would become the CRKM, motivation and emotion become more central to our view of science learning. Pintrich et al. (1993) was the spark that ignited these embers. Dole and Sinatra's (1998) model drew on the broader context of science learning, cognitive psychology, and social psychology to explicitly consider the role of social, emotional, and motivational factors in conceptual change, just as Pintrich et al. had called for. Issues well researched in other areas of psychology such as source credibility, message framing, conceptual coherence, motivation, and plausibility were included in the CRKM and quickly became mainstream topics in conceptual change research.

The details of CRKM have been described in depth elsewhere (see Dole & Sinatra, 1998; Lombardi & Danielson, 2022; Sinatra, 2005). Briefly, characteristics of the learner (such as the strength and coherence of their prior knowledge) interact with characteristics of the message (such as whether it is personally relevant and compelling) to create a degree of engagement. The greater the level of learners' engagement with the message, the greater likelihood of change. In other words, superficial processing of messages is not likely to lead to conceptual change, whereas reflective, deep thinking or "high metacognitive engagement" (Sinatra, 2005, p. 111)—which would be analogous to deeper learning (Ohlsson, 2011)—is more likely to result in knowledge restructuring.

As the CRKM describes, there are a number of different aspects that contribute to the process of knowledge construction and reconstruction. Furthermore, knowledge construction and reconstruction lie at the heart of scientific thinking. It is required for asking questions, identifying and evaluating evidence, and constructing (and revising) explanations.

Deeper Dive into the PJCC: Scientific Evaluations and Judgments

Research on the CRKM focused on empirically testing various aspects of the model (see, for example, Heddy & Sinatra, 2013; Thomas & Kirby, 2020). Lombardi and colleagues were interested in the specifics of plausibility and how it manifested in scientific thinking and reasoning but found this construct underspecified in the CRKM. Based on a premise found in the CRKM, which said "it is interesting that plausibility has not been studied in detail" (Dole & Sinatra, 1998, p. 124), Lombardi et al. (2016a, 2016b) merged prior theoretical perspectives from psychology and education research (Chi, 2005; Chinn & Brewer, 2001; Connell & Keane, 2006; diSessa, 1993; Posner et al., 1982) and philosophical positions (Rescher, 1976, 2003, 2009; Walton, 2005) to build their framework. Central to this framework is the mechanism of the plausibility judgment, which may involve implicit and/or explicit cognitive processing. Implicit processes related to cognitive bias, intuitions, and dispositions, as well as social cultural contexts, prior knowledge, and learned behaviors, can all influence plausibility judgments. For example, perceptions of a source's credibility (e.g., the trustworthiness and/or expertise of the source; Lombardi et al., 2016a, 2016b) may depend on corroborative and coherent alignment with prior knowledge, topic emotions, and personal beliefs, as well as message characteristics such as perceived degree of conjecture or uncertainty. However, Lombardi et al. (2016a, 2016b) also posited that when evaluations are more explicit and reasoned, they can lead to reappraisal of plausibility toward a more scientific stance. This is an example of how the CRKM, specifically the notion of high metacognitive engagement in the form of more critical evaluations, might facilitate knowledge reconstruction and deeper learning.

Empirical research involving both the construction, calibration, and validation of Lombardi et al.'s (2016a, 2016b) framework has been conducted over the past 15 years. Central to the framework's development and revision were initial empirical studies examining the role of epistemic motivations, source evaluations, and emotions in implicitly and explicitly forming plausibility judgments during scientific knowledge construction (Lombardi & Sinatra, 2012, 2013; Lombardi et al., 2014, 2016a, 2016b). Then, after the framework's initial completion and publication, Lombardi and colleagues systematically interrogated and revised the framework via a sustained program of empirical studies that tested—over a variety of contexts (e.g., rural, suburban, and urban classroom settings, with participants ranging from age 12 to adult)—the dynamic relations between (a) evaluations about the connection between scientific evidence and alternative explanations about scientific phenomena, (b) shifts in plausibility judgments toward a more scientific stance, and (c) knowledge gains about fundamental scientific principles (Bailey et al., 2022; Dobaria et al., 2022; Gans et al., 2024; Klavon et al., 2024; Lombardi et al., 2013, 2018; Medrano, 2020; Robertson et al., 2024; Schoute et al., 2024). The studies used instructional scaffolding to make evaluations explicit with the intent of increasing metacognitive engagement about scientific evidence and explanations.

If plausibility reappraisal can, as suggested by these empirical studies, support larger knowledge gains (i.e., knowledge construction and reconstruction), then it also contributes to our broader perspective of scientific thinking. Plausibility judgments may be present in the gathering and analysis of evidence as well as in the construction—and particularly evaluation and reevaluation—of scientific explanations.

Deeper Dive into Engagement in Scientific Learning

Another aspect of the CRKM that needed to be further explored was engagement. The CRKM posited that deeper, more metacognitive engagement that involved actively considering claims and arguments for those claims was the linchpin predictor of learners' likelihood of changing their conceptual understandings. It has been noted for some time that there is a strong association between levels of classroom engagement and science achievement (e.g., Lee et al., 2016), which was one reason for exploring its role in science learning (Sinatra et al., 2015). Engagement has also been seen as a key component of a framework that characterizes "active learning" (LaDue et al., 2021; Lombardi et al., 2021). Lombardi and Bailey (2024) define engagement as "the degree of involvement in the learning task, topic, or domain, with greater levels of engagement related to deeper science learning" (p. 532). With this in mind, engagement can be categorized as cognitive, social-behavioral, affective, or agentic (Fredricks et al., 2016; Lombardi & Bailey, 2024; Reeve & Shin, 2020; Sinatra et al., 2015), although there is likely overlap among these characterizations.

Learners' cognitive engagement is based upon their thinking and learning (Chi et al., 2018), particularly with respect to higher order thinking such as but not limited to self-regulated thinking processes. The application of these processes toward understanding scientific content and the construction (and reconstruction) of scientific knowledge is a key aspect of science learning (Berland et al., 2016; Kang et al., 2016). Higher cognitive engagement occurs through interactive and constructive learning tasks in science, such as those that support the creation, analysis, or evaluation of scientific inferences, and through deep processing strategies, such as those that help learners integrate prior knowledge with new science conceptions (Chi et al., 2018).

Individual and social behaviors that indicate participation—for example, paying attention, taking notes, or on-task listening and talking during group work—comprise social-behavioral engagement (Bae & Lai, 2020). These behaviors can be common across all disciplines or specific to the field. Science-specific social-behavioral engagement includes participating in scientific practices (Lombardi et al., 2022; NRC, 2012; Ryu & Lombardi, 2015).

Affective engagement refers to how differing levels of feelings, such as interest or confusion, facilitate participation in the learning processes (List, 2021). Both short-term emotions (e.g., joy) and longer-term moods, interests, and attitudes toward science (Hong & Perez, 2024), and the complex interactions between them, impact affective engagement. Affective engagement in science may be facilitated by having positive attitudes about science, feeling a sense of belonging or identity within a particular science domain (Kim et al., 2018), or valuing science and its relevance for society.

Agentic engagement comprises students' initiative-taking contribution to their learning community. This would include participating in science instruction in a manner that helps support both their own and their peers' understanding of science. Learners who are agentically engaged can create their own contributions, hold themselves accountable to the larger learning community, and feel they have the power to solve problems (Nussbaum & Asterhan, 2016). Increasing agency is characteristic of transitioning across developmental progressions (i.e., from childhood to adolescence and then to adulthood; Bandura, 2006), and during this transition, students actively seek agency in their learning (Schunk & DiBendetto, 2020). Cognitive, social-behavioral, and affective engagement may all contribute to agentic engagement, and it can be improved through increasing learners' relatedness to learning tasks, autonomy in constructing meaning, and improving their competency in learning tasks (Patall et al., 2019). Agentic engagement in science classrooms includes the development of epistemic understanding and the use of science resources, such as collecting, analyzing, and evaluating data, evidence, and explanations (Lombardi et al., 2022).

The challenge of measuring engagement led Sinatra et al. (2015) to propose an engagement continuum from person-oriented to context-oriented. On the person-oriented end of the continuum they placed individual aspects of engagement such as the degree of cognitive, motivational, and emotional engagement an individual has for a particular academic task. Individual engagement is typically measured in each person with, for example, self-report surveys or physiological measures (such as heart rate). At the other end of the continuum, they describe context-oriented approaches to measuring engagement. Here, context is analyzed through such methods as discourse analysis or classroom observations. In the center of the continuum, they described the person-in-context approach, which is measured through an interactive method such as experience sampling or triangulated observations aligned with self-report. Sinatra et al.'s key argument in proposing the engagement continuum was to suggest that researchers explicitly describe the grain size of their definition of and analysis of engagement.

As with plausibility judgments, engagement in learning activities was a critical component of the CRKM that needed additional exploration and expansion. Without deep engagement, knowledge construction and reconstruction are unlikely to occur, and thus neither is scientific thinking.

Deeper Dive: Active Learning and Scientific Agency

Active learning has long been touted as an important approach to developing scientific understanding (see, for example, NRC, 2000). What active learning looks like in a science classroom, however, has not always been clear. Lombardi et al. (2021) formulated the Construction of Understanding Ecosystem (CUE), which defines *active learning* in science, technology, engineering, and mathematics (STEM) as:

> …a classroom situation in which the instructor and instructional activities explicitly afford students' agency for their learning. In undergraduate STEM instruction, it involves increased levels of engagement with (a) direct experi-

> ences of phenomena, (b) scientific data providing evidence about phenomena, (c) scientific models that serve as representations of phenomena, and (d) domain-specific practices that guide the scientific interpretation of direction observations, analysis of data, and construction and application of models. (p. 16)

This framework, with direct student engagement with the four content areas of STEM, is contrasted against a traditional didactic approach in which only the instructor has direct engagement with the areas and all student engagement is indirect and mediated through the instructor. Lombardi et al. note their framework falls short of a complete theoretical proposal, as it lacks predictive opportunities. It is instead intended to provide insight into the various components within the system of science instruction and to facilitate communication about active learning.

This activity framework integrated engagement and agency into science knowledge construction and meaning making. Building off Bandura's conception of agency, active learning in classroom contexts allows students to "(a) exercise agency to be interactive learners, (b) have forethought to set achievement goals, (c) react accordingly in the classroom to achieve these goals, and (d) evaluate how well they are progressing (or have progressed) to achieve their desired learning outcomes" (Lombardi et al., 2021, p. 17). With agency as a principal component, active learning would position learners to have autonomy in shaping the instructional environment along with their peers and the classroom teacher. In this way, learners develop scientific understanding by becoming an "agent of science," where they have a license to seek understanding about phenomena, engage in knowledge construction, and contribute to science meaning-making relevant to themselves and their societies.

The CUE framework focuses on the overall environment in which the various elements of scientific thinking are supported through deep engagement and student agency. It takes into account the interactions between both expert (i.e., instructor) and novice (i.e., student) members of the scientific community to provide opportunities to ask questions and engage with evidence relating to those questions in order to construct understanding.

Incorporating a Developmental Perspective into the Study of Scientific Thinking

The models described thus far—the CRKM, PJCC, engagement continuum, and CUE—provide foundational material for scientific thinking. However, none of them account for how scientific thinking may be rooted in and built on foundational capacities that develop during childhood, nor how it emerges from those capacities over time as children progress through formal (and informal) education. As we considered how to bring our prior work on scientific thinking together into a more robust model, addressing the question of development seemed particularly salient. In this section, we discuss extant developmental perspectives on early scientific and quasi-scientific reasoning and inference. We then focus more specifically on a novel theoretical framework for the development of scientific thinking as rooted in empirical habits of mind (Butler, 2020). We discuss this framework as a promising example of how developmental theorizing addresses parallel questions to those asked by work in educational psychology and learning sciences, and discuss how a developmental perspective could be integrated with our prior work in charting the path towards a more robust model of scientific thinking by understanding its development.

Developmental investigations into how the next generation of scientific thinkers—young children—come to understand, engage in, and learn from the scientific process have progressed in parallel, though often not in dialog with, the progression of research in the educational and learning sciences. Classic theories of cognitive development tended to dismiss the notion that young children could engage in anything resembling scientific thought. Indeed, Piaget (1964) proposed that it was not until about age seven that children are able to reason logically, and even then, only about the concrete. Not until age 11 did Piaget hold that children could think and reason in the symbolic, abstract, and systematic ways necessary for scientific thinking. Interestingly, though Piaget's stage theory is quite conservative about when in development children can engage skills necessary for actual scientific thinking, his proposed *mechanism* for conceptual change—assimilation and accommodation of new evidence into existing and ultimately revised schema—bears a striking resemblance to the process that even professional scientists engage in.

New empirical and theoretical work since the cognitive revolution has illustrated that, as much as he got right about cognitive development, Piaget substantially underestimated young children's ability to engage in logical, abstract, and symbolic thinking. Even very young children show some evidence for abstract understanding of many aspects of the world (Gopnik, 2012). In some ways that understanding appears to be analogous to the process of scientific reasoning, although children hold many misconceptions across scientific content that persist throughout development (Shtulman, 2017). Further, they use their understandings—often inconsistent with scientific consensus—to guide behaviors that reflect something akin to scientific thinking, albeit potentially at a less explicit or less conscious level than that which adults can (but do not always) engage in. Children illustrate an everyday understanding of the physical, biological, psychological, and social world—which are often referred to as "naïve" or "intuitive" theories of those domains, although these conceptions are not always accurate. Regardless of their accuracy, children use those intuitive theories to guide prediction, inference, and exploration (Schulz, 2012), much like scientists use their own theories to guide empirical investigation. The focus of this line of research, throughout at least the first decade or so, remained primarily on the "cold" mechanics of when and how children acquire the ability to think and reason in terms of variables, evidence, inference, and exploration. Though developmental psychologists have long considered children's social development a core area of investigation, research on the development of scientific thinking—largely from the "theory-theory" or "child as scientist" perspective—tended not to fully capture the fundamentally social nature of the scientific enterprise.

More recently, developmental research has progressed to more fully considering and investigating the ways in which children engage in scientific thinking *as a social endeavor*. As it turns out, children are highly sensitive not only to the data themselves—the variables and patterns that support the inferential processes underlying scientific thinking—but also to the social context or social history of those data. Even toddlers are sensitive to not only what pattern of evidence they see in drawing inductive inferences, but to how and why that evidence was manifested for them (Gweon et al., 2010). By the time they are in preschool, children are sensitive to a variety of social cues or influences, including whether an empirically-testable question was posed to them prior to observing patterns of evidence (Butler & Markman, 2012a), and whether evidence was produced explicitly for their learning benefit (Bonawitz et al., 2011; Butler & Markman, 2012b; Butler et al., 2020; Yu & Kushnir, 2016). More broadly, the way in which posing scientifically relevant questions ought to be asked, and indeed how to engage in inquiry in general, is heavily socialized in ways that vary across social groups and even cross-culturally (Callanan et al., 2020).

One comprehensive attempt to systematically capture the ways in which children integrate the evidential and the social in their scientific thinking was proposed by Butler (2020): a theoretical framework that breaks the development of children's scientific habits of mind into three empirical steps of scientific practice. Although it is only one of several contemporary developmental perspectives addressing children's scientific (or at least proto-scientific) thinking, this framework is particularly promising for our purposes because the framework's proposed steps of empirical thinking in childhood are precisely the steps scientists engage in in their own work: (a) asking questions and forming hypotheses, (b) collecting and analyzing data, and (c) communicating evidence. Butler (2020) further breaks each step into, on one hand, children's cognitive capacities for using these scientific practices and, on the other hand, the struggles and obstacles that they encounter, particularly in social contexts typically found in many learning environments. Again, this closely mirrors true scientific work, especially in formal academic and research contexts. We train our students and postdocs to become independent scientists by equipping them with the set of skills necessary to conduct scientific research in our field. However, success as a scientist is about far more than a set of skills. It also includes "soft" skills such as interpersonal abilities, team management, rhetoric and argumentation, and even savvy communication. It is the developmentally appropriate, child-friendly analogues for these skills (from question-asking to careful exploration and inquiry to the ability to evaluate competing sources and claims) that Butler proposes is necessary to foster a sturdy foundation on which true scientific thinking can be built.

Example of Theory Building in Action

In this section, we provide an example of how synthesis of our work might reflect theory development. In doing this, we have suggested some factors, linked within a tentative structure, reflecting how our combined theoretical perspectives might begin to spawn a nascent and useful theory on the development of scientific thinking.

We have endeavored to synthesize our prior work on scientific knowledge construction and reconstruction (Dole & Sinatra, 1998; Lombardi et al., 2013), engagement in science learning (Lombardi & Bailey, 2024; Sinatra et al., 2015), evaluation of scientific information sources and claims (Lombardi et al., 2016a, 2016b;

Sinatra & Lombardi, 2020), and active science learning (Lombardi et al., 2021), as well as the development of children's thinking (Butler, 2020). In considering factors that would contribute toward a more comprehensive theory of the development of scientific thinking, we structured our synthesis around three "virtues" favorable for desirable and/or useful theories: (a) integrity, (b) practicality, and (c) beneficence. As shown in Table 1, we simplified Greene's (2022) list of criteria for selecting and integrating psychological theories into these three virtues, which closely reflect fundamental elements of classical pragmatism focused on scientific thought and theory development (McDermid, 2006). Under the pragmatic philosophical perspective, people use scientific theories time and time again to better understand phenomena and meaningfully solve societal difficulties and problems (Dewey, 1910; James, 1907; Peirce, 1878). Therefore, using a pragmatic approach, we operationally define *integrity* as scientific acceptance based on the probity of reliable and trustworthy evidence supporting a theory and sufficiently repeated, but failed, attempts to render this theory false via contradictory evidence (Popper, 1963). Second, we define *practicality* as a parsimonious mechanism(s) underlying a theory, resulting in sensible predictions and problem solutions related to the phenomenon(a) for which the theory provides an explanation (Rescher, 1966). Third, we define *beneficence* as a scientific community's aim to construct a theory that will promote the collective, societal good (Murphy, 1993).

These three virtues focus our synthesis on the development of scientific thinking as a social endeavor to promote thriving communities, rather than as a neutral tool that dispassionately unravels reality (Levin, 2006; Sinatra et al., 2014). Development of scientific thinking, then, is characterized by seeking to better understand phenomena and engaging in construction of both personal and collective science knowledge in honest, fair, and practical ways to act in a manner that benefits society as a whole.

We also built upon prior work on conceptualizing scientific thinking development, primarily the work of D. Kuhn (2010), who thought of "scientific thinking as knowledge seeking" (p. 497). In doing so, she made a distinction between scientific thinking and scientific understanding and suggested that scientific understanding is primarily conceptual development and change. D. Kuhn (2010) also viewed scientific thinking as a primary means toward conceptual change and understanding consistent with the scientific community. Although we agree that conceptual change as knowledge reconstruction is quite important in achieving scientific literacy and expertise, we view human thinking as fundamentally linked to knowledge. Lombardi (2023) specifically posited that critical thinking is the dynamic interaction between higher order thinking processes (e.g., comprehension, analysis, evaluation; Bloom et al., 1956) and background knowledge. He noted that, "although background knowledge, whether it be factual, conceptual, procedural, or metacognitive, is an integral component of critical thinking, a person's background knowledge may not necessarily be aligned with disciplinary knowledge (e.g., scientifically valid evidence and explanations)" (p. 38). Therefore, a person who is thinking scientifically seeks to understand scientific knowledge, engage in scientific knowledge building, and become an agent of scientific meaning.

Figure 1 shows a variety of factors that may contribute toward a theory of the development of scientific thinking. These factors are organized into related

Table 1 Virtues Contributing Toward a Theory of Development of Scientific Thinking

Virtue	Operational Definition	Link to Greene's (2022) Theory Virtues
Integrity	Scientific acceptance of a theory based the probity of reliable and trustworthy evidence supporting a theory and sufficiently repeated, but failed, attempts to render this theory false via contradictory evidence	Plausibility, Accuracy, Testability, Internal and External Coherence
Practicality	A parsimonious mechanism(s) underlying a theory, resulting in sensible predictions and problem solutions related to the phenomenon(a) for which the theory provides an explanation	Scope, Unification, Parsimony, Mechanism, Specificity, Analogy, Practicality
Beneficence	A scientific community's aim to construct a theory that will promote the collective, societal good	Fruitfulness

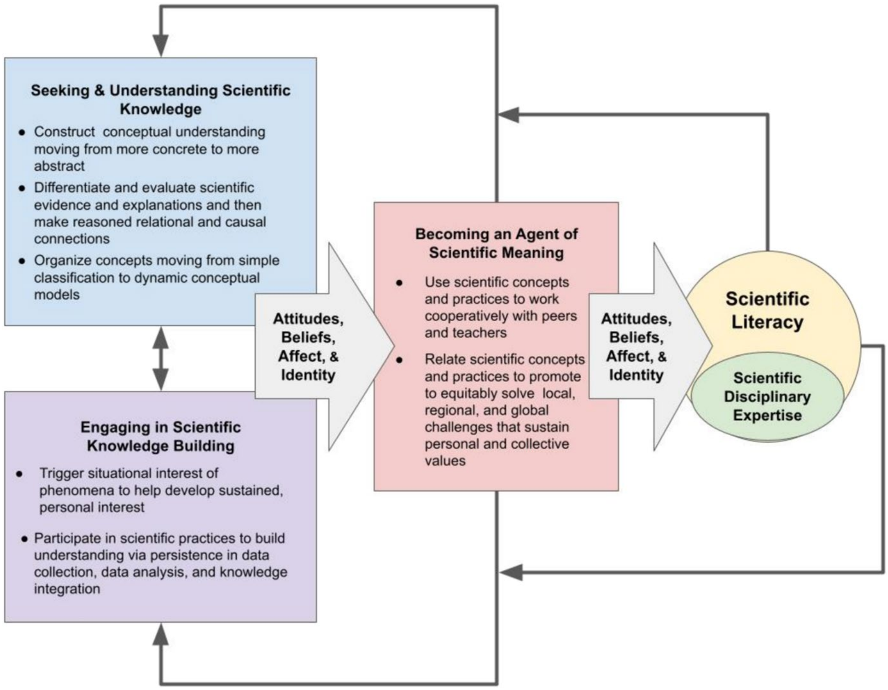

Fig. 1 Factors Contributing Toward a Theory of Development of Scientific Thinking

categories that correspond roughly to the three virtues (a) integrity, (b) practicality, and (c) beneficence. The first, which highlights the virtue of integrity, is *seeking and understanding scientific knowledge*. Factors underlying this category specifically relate to integrity of scientific evidence and explanations obtained through observations, data collection, measurements, hypotheses, models, and/or analyses. The second, which highlights the virtue of practicality, is *engaging in scientific knowledge building*. Underlying this category are factors relating to both personal and peer interest and participation in scientific practices during knowledge construction. Scientific practices here include evaluation of both evidence and explanations, which are geared toward arriving at parsimonious and sensible predictions and solutions. The third category, which highlights the virtue of beneficence, is *becoming an agent of scientific meaning*. Factors underlying this category relate to the development of personal and collective learning to enhance societal good. Although each of the categories highlights one of the virtues, they are by no means exclusive of the other two. For example, engagement and agency should involve knowledge (re) construction, thus integrating integrity, practicality, and beneficence. However, these three categories align predominantly with one virtue compared to the other two, and therefore, serve as a way for the factors to contribute toward a theory of scientific thinking development.

Figure 1 further shows that these three categories are dynamically related via beliefs, affect, and identity. Also shown on Fig. 1 are two potential outcomes of scientific thinking development: (a) scientific literacy and (b) scientific disciplinary expertise, as a specialized outcome of this literacy. In the following sections, we elaborate on these categories and underlying factors, relations, and outcomes in more detail, while cautioning that this is a beginning, rather than an end, of an exhaustive treatise. In other words, we are not suggesting that this is a fully formed theory of scientific thinking development, but rather a burgeoning consideration of some essential elements on which such a theory might be developed.

Categories and Underlying Factors

Seeking and Understanding Scientific Knowledge

Seeking and understanding scientific knowledge involves transforming the more concrete, everyday experiences associated with our surroundings to more dynamic abstractions that can often transcend ordinary human sensory perceptions. Conceptual knowledge involves mental representations linking facts (the sky appears blue), phenomena (Earth has a layer of air surrounding its surface), and theoretical explanations (Earth's atmosphere was formed via a dynamic series of interactions with the lithosphere and biosphere) (Byrnes, 2021; diSessa, 2017; Gopnik & Wellman, 2012). Zimmerman (2007) and other contemporary researchers generally reject Piagetian notions that abstract scientific thinking is not possible until one reaches adolescence (see, e.g., Inhelder & Piaget, 1958). For example, results from empirical studies suggest that children are similar to adults in using inference and hypothesis to generate explanations of everyday observations (Liquin & Lombrozo, 2020; Lombrozo, 2016). However, although children are fully capable of thinking and learning about abstractions, educational research and reform often stress that perceptions grounded in experiences can be a preferable source of entry for developing scientific thinking (e.g., "children's understanding of specific materials prepare them to move up a level of abstraction and develop an initial macroscopic understanding of matter," NRC, 2007, p. 233).

Understanding of scientific knowledge also involves organizing concepts, initially using simple classification schemes and then more dynamic sequencing and integration involving models. As a psychological construct, concepts are mental representations that serve as the basic building blocks of knowledge construction. Concepts serve two purposes: (a) to organize information we encounter and (b) to make meaning of this information (Lombardi & Danielson, 2022). Chi and Roscoe (2002) argued that concepts are cognitively sorted into categories. Furthermore, people categorize their conceptual representations into ontological categories based on mutually exclusive plausible attributes (Chi, 2005), with such categorization often inherent during development and learning (i.e., sorting without much reflective thought). For example, one might classify various physical objects based on shape and color (a dog would be categorized into objects of four-legged shape and counter-shaded colors reminiscent of natural camouflage patterns), but would probably not classify an historical event based on shape and color (a battle would not be round and blue). As humans develop, they may miscategorize concepts (e.g., infants and young children may not understand the scientific attributes of living things and might miscategorize some living things, such as animals, as being intentional and purposeful like humans; NRC, 2007). Conceptual development and change may require careful reflection of things that share plausible attributes (Lombardi et al., 2016a, 2016b).

Scientific thinking develops when conceptual organizations transition to more abstract representations via dynamic sequencing and integration. These representations are often expressed externally and shared socially (e.g., amongst a community of scientists) as models taking mathematical, physical, visual, analogical, and/or conceptual forms (Ruppert et al., 2019). Furthermore, scientific models often represent reality as complex systems that go beyond simple and linear cause-effect relations (Hilpert & Marchand, 2018). Thus, development of scientific thinking transitions from linear to dynamic understanding of conceptual relations. For example, in traditional science curricular progressions, learners are first exposed to more concrete conceptual representations of materials, such as the properties of hardness, color, clarity, and state, and later to more abstract representations, such as the atomic theory of matter and the Bohr model of the atom (e.g., NRC, 2012). Many learners can have difficulty making this transition from concrete to abstract, as well as toward more dynamic and integrated organization of concepts required in scientific and technical practice (Yoon et al., 2018). Thus, modeling and model-based reasoning as an epistemic cognitive practice is a factor in the seeking and understanding of scientific knowledge (Sinatra & Chinn, 2011).

Modeling and model-based reasoning often involve understanding the dynamic and integrated nature of scientific evidence and claims. For example, Nussbaum (2021) suggested that many disciplines, including science, are built on a social practice of critically evaluating how the credibility of evidentiary data support (or do not support) the plausibility of explanatory models, hypotheses, and theories. As such, communities of scientists evaluate evidence to claim connections in their process of knowledge construction. Furthermore, D. Kuhn and Pearsall (2000) argued that scientific thinking is a consciously controlled process of evidence and theory coordination. Children may not have fully developed this idea of scientific thinking as a reflective process, with developmental difficulties remaining in adolescence and even adulthood. Educational researchers and practitioners have endeavored to deepen students' reflections on evidence to claim connections, often using the Toulmin (1958) model in simplified forms, such as claim-evidence-reasoning (CER; McNeill & Krajcik, 2011). But such simplistic instructional practices are often insufficient to fully develop people's scientific understanding. Many topics, especially current and relevant scientific topics of social relevance (aka socioscientific issues, such as the current climate crisis; Sadler, 2009) are considerably more complex and present significant learning challenges. Scientific topics of social relevance can often be controversial, where conflicting perspectives clash from various sources of information, each with a distinct set of assumptions, points of view, target audiences, and goals (Dawson & Carson, 2020; Sinatra & Lombardi, 2020). Many scientific topics of social relevance may be associated with non-scientific information sources and alternative claims that do not reflect expert consensus (Lombardi et al., 2016a, 2016b; McGrew et al., 2018).

The coordinated process of evidence and claim evaluation may therefore be a factor in seeking and understanding scientific knowledge, specifically in a way that engages evidence collection and explanation generation via standards of integrity. In a *Call to Action for Science Education*, a panel suggested that recent events reinforce that all citizens must learn how to "evaluate evidence and distinguish between what are reliable sources of information, poorly supported claims, and unequivocal falsehoods" (National Academies of Sciences, Engineering, & Medicine, 2021, p. 9). Evaluation is an "iterative process that repeats at every step of [social and scientific] work" and requires critical thinking that can gauge and distinguish the credibility of evidence and plausibility of scientific claims (NRC, 2012, p. 46). In alignment with D. Kuhn and Pearsall (2000) and Nussbaum (2021), evaluative judgments (e.g., credibility of evidence and plausibility of competing claims) that are more critical and reflective may dampen implicit heuristics and biases and be a keystone of scientific literacy (Lombardi, 2023; McGrew, 2021).

Engaging in Scientific Knowledge Building

Engaging in scientific knowledge building requires an intersection of cognitive, behavioral, social, and affective processes. As such, we see interest development as the underlying construct to stimulate deeper engagement in scientific thinking (Hidi & Renninger, 2006; Renninger & Hidi, 2011, 2016). As a phenomenon, triggering and developing interest captures the widely studied process commonly called "achievement motivation" and its influence on facilitating knowledge construction (Renninger & Hidi, 2019). We support their implied supposition that interest is a more parsimonious account of the connections between personal and societal beliefs, affect (values, attitudes, and emotions), and identity, as well as the primary antecedent to engagement and knowledge building. Consequently, interest represents our effort to strive toward a virtue inherent in coherent, clear, and meaningful theory building that is much needed in educational psychology (Greene, 2022; Wentzel, 2021). Triggering interest in science and scientific topics can occur at any age (Maltese et al., 2014) and Pugh et al. (2017, 2020) call such events transformative experiences that emerge, in part, from sensory perceptions. The value of such experiences in developing scientific thinking is amplified when these transformative experiences connect to content-specific scientific data and analyses (Pugh et al., 2017). However, science interest generally wanes in adolescence because people often do not see the direct relevance of science to topics of societal importance and how scientists actually construct knowledge via sustained consideration of the connections between evidence and explanations (Howe & Zachariou, 2019; D. Kuhn, 2010; Manz, 2015). Furthermore, transitioning from interest triggered by situation and context to a more sustained and intrinsic interest in scientific topics is challenging. However, such deep-rooted interest, more precisely called individual interest, may provide the impetus to engage in scientific knowledge building, such as when science classroom tasks are empirically and technologically rich, and collaborative interactions with peers and more knowledgeable others (Chen et al., 2016; Renninger & Hidi, 2019, p. 268).

Engaging in scientific knowledge building includes deeper social and behavioral participation in scientific practices, such as planning and conducting investigations or analyzing and interpreting data. Children and adolescents' interest in science may be deepened when thinking about and participating in practices that promote the construction of knowledge (e.g., scientific argumentation and discourse about meaningful and socially relevant science topics, such as environmental sustainability) (Ballard et al., 2017; Gray et al., 2020; Lombardi & Bailey, 2024; Lombardi et al., 2022; Renninger & Hidi, 2020; Ryu & Lombardi, 2015). For example, Burrell (2018) found that classroom instruction embedding scientific practices within the context of issues of environmental injustice (i.e., safe and clean drinking water resources in urban centers) supported development of scientific thinking through increased knowledge and interest. Fortunately, science education reform guidelines that emerged in the 2010s support classroom engagement in scientific practices, which encourage growth of scientific thinking (NRC, 2012).

However, engagement in scientific practices is not a new research and practice paradigm in scientific thinking development and learning. Prior to the latest iteration of educational reform, the notion of a scientific inquiry cycle was relatively common and included the asking of research questions and collecting data through observation and/or experimentation for children, adolescents, and adults to deepen conceptual understanding (Lazonder & Harmsen, 2016). Many thought that engagement in the scientific inquiry cycle for children and adolescents was unstructured discovery learning (see, for example, Kirschner et al., 2006). However, some suggested that children and adolescent engagement in inquiry could be effective in science knowledge construction if explicit instruction was integrated with more scaffolded investigations that promoted the notion of persistence and revision (see, for example, Darling-Hammond et al., 2020). Therefore, NRC (2012) reframed scientific inquiry as a process involving coordinating thinking with social-behavioral participation central to the activity of practicing scientists and engineers (i.e., adoption of the scientific practices moniker).

Becoming an Agent of Scientific Meaning

As described above, agentic engagement is the process of taking initiative-taking control over one's own learning within a specific learning environment. Agency may emerge through externalized and internalized dialogues with more and less knowledgeable others (e.g., peers, parents, children, teachers, students). Pickering (1995) views the progression of scientific endeavors as a "dance of agency" (p. 21), where individuals and groups are engaged in an intentional practice involving epistemic construction and manipulation of scientific resources (e.g., data in tables and graphs). This agency is closely related to the other modes of engagement (cognitive, emotional, and social-behavioral), where people (e.g., children at play, students in the science classroom, and scientists in the field or laboratory) are authors of their own contributions, are accountable to their communities of practice, and have authority to solve problems and pose solutions (Nussbaum & Asterhan, 2016; Patall et al., 2019). For example, Campbell et al. (2024) suggested that teachers could use instructional strategies such as

> (a) Community Science Data Talks, which may orient learners to local social and environmental justice [sustainability] issues and community action; (b) critical engineering pedagogical approaches, which center local place-based and community-centered, participatory design principles; and (c) photovoice, self-documentation, and community asset mapping to support students as they develop a critical awareness of local [sustainability] issues and then tell and rewrite stories about their communities and desired possible futures. (p. 2)

Becoming an agent of scientific meaning should be directly related to the virtue of beneficence characterized by using scientific concepts and practices during collaborative processes that promote equity and the development of thriving communities and ecosystems.

Relating the Factors via Attitudes, Beliefs, Affect, and Identity

A key aspect of scientific thinking is to encourage students to adopt a "scientific attitude." McIntyre (2019) describes two key aspects of a scientific attitude: caring about evidence and a willingness to change one's thinking in light of new evidence. Scientists understand that theories must be based on evidence and as new evidence becomes available, that evidence can change scientific thinking. But all too often students and members of the public view science as a collection of facts. Presented in textbooks, these facts seem immutable. Consider how widespread the push-back was among children and adults when Pluto was reclassified as a dwarf planet (Tyson, 2009). This also became glaringly evident during the COVID-19 pandemic when new evidence about the airborne spread of COVID-19 changed thinking about the utility of mask wearing. Some members of the public viewed the change in recommendations regarding masking as dishonest or duplicitous, whereas scientists viewed this as a normal—even expected—revision during a novel situation with emerging evidence.

Beliefs are often described as all information that an individual accepts, whether or not that information is in accord with scientific points of views (Southerland et al., 2001). In other words, one may believe that Earth is flat, that humans cannot impact the climate, and that genetically modified organisms (GMOs) are unsafe to eat, even though these views are not supported by scientific evidence. Beliefs can also be religious in nature; much has been written about the role of religious beliefs in either supporting or resisting scientific points of view on topics such as evolution and climate change (e.g., Hayhoe, 2021; Rosengren et al., 2012). Beliefs are much harder to shift as they are more deeply held and resistant to change. Thus, any theory of scientific thinking should take into account beliefs that may serve as sticking points for understanding science. In the development of scientific thinking, self- and collective-efficacy beliefs that help people achieve desired outcomes as they exercise their agency may be especially important (Bandura, 2001; Chen & Stoddard, 2020; Chen et al., 2021).

We view affect as a mental state encompassing people's feelings (e.g., emotions, moods) over shorter or longer periods of time (Pekrun & Linnenbrink-Garcia, 2014). Within the context of the scientific enterprise, affect plays a crucial role in scientific thinking, with many historical and empirical accounts suggesting that passion, anxiety, wonder, anger, fear, and joy—as just a few examples—are integrally linked to meaning making and problem solving (Pekrun, 2014). In particular, Sinatra et al. (2014) suggested that affect mediates scientific experiences and impacts cognition and engagement during the science learning process.

Identity is how we see ourselves personally and socially and forms a strong basis for our understanding and acceptance of science (Sinatra & Hofer, 2021). Individuals tend to conform to the views of those within their social identity groups and often base their acceptance of science on the views of those whom they know and trust, not necessarily on experts. Scientific topics have become polarized in the United States (and elsewhere) with individuals on the right and the left of the political spectrum tending to accept explanations of vaccine safety, GMOs, climate change, and many other scientific topics based on the views of members of their political affiliated groups, which may not necessarily be aligned with the scientific consensus on these issues. It is important to consider individual and social identity in any discussion of scientific thinking and reasoning, as individuals are often likely to push back against scientific ideas that they view as in conflict with their identities. A person's scientific identity is dynamic and changeable, influenced by a variety of factors characterized by personal preferences and interests, as well as environmental affordances and constraints (Gee, 2000; Kaplan & Garner, 2017). Identifying as a scientific thinker furthers our capacity to seek and understand knowledge and make meaning about science topics to engage in community problem solving, particularly for those who have been historically marginalized in science-related contexts (e.g., women; Kim et al., 2018).

Scientific Literacy and Disciplinary Expertise

Scientific literacy has been part of the educational and cultural lexicon for several decades, with the first published appearance of the term likely in the late 1950s (Laugksch, 2000). The term's definition has varied across the years and authors, incorporating different audiences and foci at various points (Laugksch, 2000). Rudolph (2023) suggested that scientific literacy—in its beginning conceptualizations—was originally thought of as an aspiration of a modernist society where science understanding (i.e., as general science) is a useful tool for members of the public in their daily activities. The notion of scientific literacy shifted somewhat in the post-World War II era, particular in association with the space race, where scientific understanding was essential for creating an attitude among people to support research that would maintain Western competitiveness and power (Laugksch, 2000). Scientific literacy was also seen as a means to ensure a sufficiently technical workforce for this competitive, scientific enterprise (see, for example, National Academy of Science, National Academy of Engineering, and Institute of Medicine, 2007). In the past 20 or so years, the notion of scientific literacy has come under sharper criticism as a term employed by the hegemonic classes that has little utility of increasing science understanding for all people (Melville et al., 2022; Osborne & Dillon, 2008). Scholars have also suggested that a shift in language, particularly with respect to diverse learners, is necessary to build upon these learners' strengths while also designing science instruction in reform-minded ways (e.g., Lee, 2021). Although some have proposed jettisoning the scientific literacy moniker, we agree with Dillon (2009) who said that "rather than wring[ing] our hands at the inadequacies of the term 'scientific literacy' we have to accept that it will have some considerable currency for years to come" (p. 211). We therefore include scientific literacy as a primary pursuit for the development of scientific thinking (Fig. 1).

Scientific literacy as a developmental outcome would emerge from seeking understanding about scientific knowledge, engaging in scientific knowledge building, and becoming an agent of scientific meaning. Operationally, scientific literacy would promote democratic, equitable, diverse, and inclusive thought through critical, but collaborative, discourse to achieve greater meaning and more effective problem solving for societal issues. This notion aligns with a vision that "expands the conceptual scope of scientific literacy…beyond its social contextualization [toward]…greater social engagement and citizen impact" (Valladares, 2021, p. 565).

At a time when all people are confronting serious local, regional, and global threats—such as the climate crisis; severe reductions to food, energy and water security; and deadly virus transmission—an increasing availability of information has contributed to what many call a "post-truth era," where emotions and personal beliefs override scientifically validated evidence and explanations and create an atmosphere of distrust and discord (McIntyre, 2018). On one hand, scientific and technological advances have a responsibility in ushering in the current science denial era by facilitating the virtually instantaneous and worldwide transmission of information, with little consideration of how these advances would afford the spread of mis- and disinformation (Wardle & Derakhshan, 2017). On the other hand, the development of scientific thinking is needed now, as much as ever, to critically think and make reasoned decisions about scientific and technical challenges (Sinatra & Hofer, 2021).

Science disinformation and denial set up conditions for eroding democratic principles and virtues. Purveyors of truth denial and disinformation have honed their crafts by rejecting scientific consensus on such things as tobacco-related health impacts, vaccine safety, and causes of current climate change (McIntyre, 2018). Denial and disinformation about relevant and meaningful scientific topics with social relevance have emerged from disordered identities and values, with the techniques of science now being used to suppress voting rights, community collaboration, and human agency (Gorman & Gorman, 2021). This has exacerbated inequalities and tensions across racial, ethnic, gender, and socioeconomic lines (Lombardi & Busch, 2022; Neece et al., 2020).

Although scientific literacy is critical for all, a subset of people will also seek more advanced knowledge and skills in post-secondary settings. As an outcome of scientific thinking and a subset of scientific literacy, disciplinary expertise also serves, as a practical matter, to spearhead the scientific enterprise. Alexander (2023) recently suggested that disciplinary experts are "those select few within a profession [e.g., the scientific and technical professions, including astronomy, biology, chemistry, computing, engineering, geoscience, and physics] who are widely recognized for their exceptional body of knowledge, creative insights or innovations, and outstanding problem-solving abilities" (p. 65). Thus, scientific disciplinary expertise must include a fully developed way of scientific thinking for knowledge construction and agency, as well as scientific literacy to make creative and/or innovative connections among the various scientific disciplines. Our conceptualization of scientific thinking development also aligns with Alexander's (2003) Model of Domain Learning, where expertise develops through deepened interest that sustains knowledge construction and use of appropriate disciplinary practices within a particular discipline and over long time periods.

Reflections on Theory Development: Where Do We Go from Here?

When we reflect on the development of our research, we have come to appreciate the iterative approach that has led to each model we described here. Critically, this process has led us to the next phase we aspire toward: development of a theory of scientific thinking and reasoning. This process of involving teams of researchers from different domains has provided avenues for cross-disciplinary discussion and construction in a manner uncommon to most educational research. Through our collaborative work on a variety of theory building projects and articles, we believe some lessons can be gleaned and we describe those next.

Theory Development is a Social, Collaborative Process

Theories are not, and we would argue should not be, developed in a vacuum. They build on past theoretical and empirical work. Those looking to build theory should first do a deep dive into existing theory and empirical support (or lack thereof) for that area. All theories are imperfect and incomplete but likely have aspects that are useful and an approach that builds on past successes while advancing the theory forward in areas of weakness or underdevelopment is likely to be more useful to the field.

Theory development also benefits greatly from a collaborative process. Even those theories or models that are posited by a single author draw on others' work, so we would argue that theory development is always, in some sense, socially constructed. In our own work, the collaborations have been more direct and that leads to a back-and-forth and fine tuning of the work through pressing each other to be more explicit or to clarify constructs or explanations. We recommend bringing others into the theory development process either implicitly by drawing on their work or explicitly where the contributions can be more iterative and dynamic.

Theory can be Advanced by Drawing on other Disciplines

Theory in one domain (science thinking and reasoning) can be extended by drawing on research and theory from other domains. The CRKM drew on social psychological models of persuasion. The plausibility framework (PJCC) drew on work in philosophy, science education research, and cognitive and developmental psychology. The engagement and active learning work drew on multiple disciplines and different methodological approaches. The work on the development of empirical thinking in children drew on cognitive, social, and developmental psychology, as well as cross-cultural investigations of how engagement in inquiry is socialized. We recommend looking to other disciplines to extend theory development, as often researchers in other areas have explored closely related phenomena and what they have learned can advance theory in other domains.

Theories Must be Empirically Tested

Empirical research informs theory development. Once a model or theory is posited, it must be rigorously tested. Thus, a key feature of any theory or model is that it generates hypotheses which can be empirically tested. Frameworks (such as the engagement continuum) are not theories because they simply provide a descriptive view of a phenomenon (such as grain size of engagement measurement). A framework is neither testable nor falsifiable. Theories and models must be both testable and falsifiable. Theories and models that are empirically tested can be revised and extended accordingly. For example, in Fig. 1, we have shown some relational, and potentially causal, pathways between the factors that contribute to scientific thinking. Such relations and their associated strengths must be empirically tested with the development of a more comprehensive theory.

A particularly important aspect of empirical testing is to do so with a wide and varied population that is more representative of today's world than has been the case in the past. As just one example, the CRKM has largely been tested on members of communities that Heinrich et al. (2010) call "WEIRD…Western, Educated, Industrialized, Rich, and Democratic" (p. 61). The PJCC has been tested in more diverse secondary classrooms (e.g., Lombardi et al., 2018) but should continue to expand its applicability. Empirical work on this proposed model of scientific thinking should move beyond WEIRD populations to consider how such models represent learning among all groups (e.g., those who have been historically excluded in the scientific enterprise; Graves et al., 2022), and eventually contribute to the kinds of understanding (e.g., intersection of race and class in terms of attribution, belonging, and goals) called for by DeCuir-Gunby and others (DeCuir-Gunby & Schutz, 2014; Kumar & DeCuir-Gunby, 2023; López, 2022).

Meta-Theories Guide a Productive and Thriving Discipline

The most significant ideas are meta-theoretical (e.g., people learn via cognitive and social processes) that rise above characterizing a specific phenomenon (such as conceptual change or active learning) to describe a broader, more encompassing process such as social learning. Overton and Müller (2012) say,

> In scientific discussions background ideas are often termed metatheoretical or metatheories. They transcend (i.e., "meta") theories, in the sense that they define the context in which theoretical concepts are constructed, just as a foundation defines the context in which a house can be constructed. Further, metatheory functions not only to ground, constrain, and sustain theoretical

concepts, but also to do the same thing with respect to methods of investigation. (p. 19)

For example, an important context on which any theory of development and learning should be grounded is that humans change over their life spans (Tateo & Valsiner, 2015). Another example would be that humans are biological organisms and are products of and subject to evolutionary pressures (Badcock, 2012) A metatheory of scientific thinking is perhaps possible, and it may be generative for the field to attempt to go in that direction. Here we have laid some groundwork, yet there is much work to be done before that next significant step.

Conclusions

In this article, we endeavored to present a structure that might inform a comprehensive theory of the development of scientific thinking. Full theory development is quite difficult, and some may argue that there are few, if any, paradigm defining theories in psychology (see, for example, T. S. Kuhn, 1962). With the exception of, perhaps, social-cognitive theory (Bandura, 2001), most fields in the "science of learning" are dominated by a few theoretical frameworks (e.g., motivation, self-regulated learning), with little consilience among perspectives. Therefore, we suggest that our previous work in theory building is modest, at best, and the factors we present here examining the development of scientific thinking are a formative step toward a generative and predictive theory that has the broad-based virtues of integrity, practicality, and beneficence. As such, we are excited and hopeful about a future where scientific thinking is embraced as an important foundational element to thriving and just societies.

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