The Integration of Literacy, Science, and Engineering in Prekindergarten through Fifth Grade

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Introduction

> A pair of kindergarten students points to shapes they traced from the shadows made by different objects when a light shown on those objects; they point to the tracings as evidence for a claim they wish to make that the distance between the object and the light source makes a difference in the shape of the shadow because of how light interacts with objects.
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> Interacting with a simulation on their Chromebooks, a class of third graders predicts what will happen to a cart when the amount of force on one side of the cart is increased.
>
> In a "gallery walk," fourth-grade students critique one another's models designed to explain how a water wheel works; they notice that some of their peers have used thick arrows, as well as thin arrows, in their models and they wonder if the thickness of the arrow is meaningful.
>
> Third graders read and discuss the biography of Dr. Lonnie Johnson, NASA engineer and entrepreneur designer of the "Super Soaker." The teacher uses the text to facilitate a discussion about engineering practices, as well as the persistence of this Black scientist in the segregated South.

Each of these is an illustration of young students engaging the use of literacy to advance their learning of science and engineering. As Lemke (1998) noted, literacy "consists of a set of interdependent social practices that link people, media objects, and strategies for meaning making" (p. 283). In the examples above, the children are using reading, writing, drawing, and speaking to acquire ideas and communicate their thinking about science and engineering; they are sensemaking with books, digital simulations, drawings as well as tracings, and designed objects.

There are many reasons to be interested in the integration of literacy, science, and engineering in the instruction of young children when one's goal is to improve the teaching of science and engineering in pre-K through Grade 5. Here are a few. We begin with the most important reason; as this review will demonstrate science learning supports literacy learning and literacy learning supports science learning. Furthermore, it has been well documented that teachers prioritize the teaching of the English language arts (ELA) in the elementary grades as measured by the sheer amount of time they allocate for ELA instruction (Blank, 2012) to the detriment of science teaching. While this has often been attributed to the role of high-stakes standardized assessments that feature ELA, a less sinister explanation is that teachers of young students aspire to equip their charges with the tools that will support their independent learning; these tools clearly include reading, writing, and oral language. If we can identify ways in which students develop these tools in the context of engaging in science and engineering practice, we have a "win-win" situation.

It is much easier to engage learners in learning to use tools if there are interesting and meaningful reasons to use them; consider how tedious it would be to practice playing musical scales if you did not put those notes together to play actual music that you and others can sing and dance to. Using science, we figure out explanations for phenomena we experience daily and use that figuring out to predict, and possibly influence, these phenomena. Using engineering, we figure out how things work and use that knowledge to make things work better, including more efficiently. These are powerful reasons to learn sensemaking tools in the context of science and engineering.

Finally, if we do not begin teaching literacy and science/engineering in an integrated fashion and in the early grades, it will be very hard, if not impossible, to ensure that our citizens leave school with the capacity to make informed decisions regarding the world they wish to live in and leave for the next generation (Hynes & Swenson, 2013; Priest, 2013). We are writing this paper in the context of the SARS-CoV-2 pandemic and are reminded daily of the essential literacy skills requisite to making sense in these times: graphs depicting shifts in the incidence of infections vs. hospitalizations vs. deaths; articles regarding the likelihood and advisability of developing vaccines at "warp speed," and conflicting reports on means of transmitting – and therefore mitigating – the disease. The authors of this paper have been struck by the very public way in which science is being conducted during this pandemic and the burden that places on laypeople to make sense of it all.

How literacy, science, and engineering ever became so disparate in school curricula and instruction is hard to understand given the prominent role that literacy plays in the conduct of science and engineering. Indeed, scientists and engineers cannot advance their work without calling upon very sophisticated literacy skills (Osborne, 2002). We suspect there are multiple explanations for the separation. One has to do with the suspicion that "integration" ends up as "usurpation" with science instruction becoming a pale semblance of itself as curriculum and teachers focus on reading, writing and oral language in the context of science teaching (Yore, 2000). A second possible explanation is that, while this an emerging area of research, there are not that many well-documented models providing a clear vision of engaging in this kind of instruction with integrity. Finally, providing instruction at the intersection of science and literacy is demanding work, requiring common content knowledge specific to science, as well as literacy development, as well as all the other forms of knowledge that support competent teaching (Ball, Thames, & Phelps, 2008). Research, such as that conducted by Davis and her colleagues (e.g., Davis, Petish, & Smithey, 2006), cautions that teachers may not be equipped with this knowledge.

In this paper, we summarize research on the integration of literacy, science, and engineering in pre-K through Grade 5, drawing principally upon peer-reviewed empirical literature. To identify this literature, we consulted landmark reports (e.g., *Taking Science to School: Learning and Teaching Science in Grades K-9*, 2007; *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, 2012; and *English Learners in STEM Subjects*, 2018). We did a hand search of premier journals of the past seven years (since the conduct of the National Academies' *Literacy in Science* workshop in 2014) in science education, reading, writing, the learning sciences, and engineering education. Finally, we contacted researchers engaged in germane research to request current, in-press papers.

Following an introduction, in which we briefly review the science/literacy landscape through the lens of Standards, we present the empirical work beginning with those studies that investigate the integration of science and literacy with attention to both science and language outcomes (i.e., full curricular integrations of science and literacy); beginning with the literature on Grades 3 through 5 and then proceeding to the literature on pre-K through Grade 2. A preponderance of the research at the intersection of science and literacy is not for the purpose of studying integration, but rather explores components of literacy specific to science (for example, particular features or uses of text in science, or writing in science); we address this literature next. This is followed by sections on writing and the use of multiple representations, emergent bilingual speakers, and the support of professional learning. We chose to present the research in engineering education as a separate entry since scholarship in engineering education for the elementary grades is emergent and there are fewer definitive studies; research in this area is useful for identifying opportunities for future research. We limited our search to the age-span identified in our charge (i.e., pre-K through Grade 5). To explore how well the research addresses students in under-resourced communities, who are likely to be underrepresented in the pursuit of science and engineering in secondary school and beyond, we paid particular attention to the demographics of the students with whom research has been conducted.

We begin by briefly characterizing how current standards documents, specifically the *Common Core State Standards-English Language Arts* (CCSS) and *Next Generation Science Standards* (NGSS) address the integration of literacy, science, and engineering.

How Current Standards Shape the Integration Landscape

Two prominent sets of standards support the integration of literacy in science: the *Common Core State Standards for English Language Arts* (National Governors Association, 2010) and the *Next Generation Science Standards* (NGSS Lead States, 2013). At the heart of the *Common Core State Standards* is the argument that "Just as students must learn to read, write, speak, listen, and use language effectively in a variety of content areas, so too must the Standards specify the literacy skills and understandings required for college and career readiness in *multiple disciplines*" (NGC and CCSSO, 2010, p. 3, emphasis added). The reference to "multiple disciplines" signals the designers' awareness that teaching generic literacy skills, such as identifying main ideas, drawing inferences, and using text structure to summarize text, needs to occur in the context of reading disciplinary-specific texts (e.g., natural science and social science texts, literary texts) for disciplinary-specific purposes.

Furthermore, the framers of the CCSS were concerned that students learn to engage in “close, attentive reading” of challenging text, which they urged must include informational text. Science texts are a good example of the challenging informational text to which the framers of the CCSS refer. These texts often present information that is conceptually rich but also conceptually dense and abstract; science texts often include terminology that is unfamiliar to many students, and they present explanations using language in ways that students do not encounter in their everyday uses of language, or in their reading of fictional and narrative text (O’Hallaron, Palincsar, & Schleppegrell, 2015).

In addition, the framers of the CCSS advocated that students, throughout the grades, learn to engage in argumentation; that is, learn to prepare arguments in which they present claims with clear reasons to support their claims and relevant evidence that speaks to their claims. While it is not uncommon for elementary students to be asked to write persuasive texts in which they try to convince someone of a particular position (e.g., persuading the principal that the school needs better playground equipment), children have not typically had experience arguing with the use of evidence gathered from text or from experience (e.g., the experience of doing an investigation).

Within the NGSS, Practice 8: *Obtaining, evaluating and communicating information*, represents the most obvious intersection of literacy and science. In Table 1, we represent parallels between the science and engineering practices, inquiry processes, and the processes by which students comprehend text. We suggest that these parallels can help the science and literacy communities to identify synergies in our respective areas; synergies that can support our efforts with educators, guide curriculum development, and guide future research. As we review the empirical literature, we will consider the evidence in support of these synergies.

Table 1

Similarities Among the NGSS Science and Engineering Practices, Processes Involved in Scientific Inquiry/Engineering Design, and Processes Involved in Text Comprehension

Science / Engineering Practices	**Processes Involved in Scientific Inquiry / Engineering Design**	**Processes Involved in Text Comprehension**
Asking Questions / Defining Problems	Monitoring understanding and taking measures to restore meaning (e.g., through questioning, predicting, and drawing inferences)	Monitoring understanding and taking measures to restore meaning (e.g., through questioning, predicting, and drawing inferences)
Developing and Using Models	Interpreting and generating multiple representations	Interpreting multiple representations
Planning and Carrying Out Investigations	Constructing meaning from systematically manipulating phenomena	Constructing meaning from text
Analyzing and Interpreting Data	Coordinating data across “texts” (e.g., student notebook data, group posters, class conversations, models, print texts)	Coordinating information across texts
Using Mathematics and Computational Thinking	Understanding numerical representations and identifying patterns	Understanding numerical representations and identifying patterns in text
Constructing Explanations / Designing Solutions	Awareness and use of scientific explanation	Awareness and use of text structure
Engaging in Argument from Evidence	Adopting a skeptical stance	Adopting a skeptical stance
Obtaining, Evaluating, and Communicating Information	Managing vocabulary, terminology, and conceptual knowledge demands Communicating information through speaking, writing, or representing ideas from one or more “texts” and experience	Managing vocabulary and conceptual knowledge demands Communicating information through speaking, writing, or representing ideas from one or more texts and experience **Plus, all of the processes identified above involved in text comprehension.*

Research on Integrating Science and Literacy in Elementary Instruction

We begin with studies that have investigated the integration of science and literacy, specific to Grades 3-5, in which the researchers have collected measures of both science and literacy achievement. The approaches we review include: *In-depth Expanded Applications of Science (IDEAS)*, *Seeds of Science/Roots of Reading*, *Concept-Oriented Reading Instruction (CORI)*, and *Multiple Literacies in Project-based Learning*. While there are interesting overlapping features among these four approaches, there are features unique to each.

In-Depth Expanded Applications of Science (Science IDEAS)

The longest standing program of research on the integration of literacy and science is the *Science IDEAS* research of Romance and Vitale (Romance & Vitale, 1992, 2001, 2008, 2017). At the heart of their curricular intervention (http://scienceideas.org) is an emphasis on: (1) investigations in which students engage in scientific practices (e.g., exploring the factors that enhance mold growth), (2) the use of challenging texts that address core science ideas *and* provide opportunities for teachers to teach comprehension strategies (e.g., the use of text structure, learning new vocabulary, identifying main ideas, asking questions, and making inferences), (3) the use of propositional concept maps illustrating how ideas in science are connected to one another, and (4) writing (e.g., describing the conduct and results of an investigation). Digging a bit deeper, the concept maps play a pivotal role as a unit of instruction unfolds; as the students gain more information based on their observations, reading, and other supporting activities, they continue to add to their concept maps. With the support of the concept maps, students activate prior knowledge and identify real-world examples of the phenomenon under investigation. Teachers then introduce multiple hands-on investigations, paired with reading experiences using multiple sources, including graphs, illustrations, and print text. Students maintain journals in which they record, reflect upon, and explain how evidence gathered in the course of investigations, connect with the concepts being learned.

Across their studies, the *Science IDEAS* curriculum has replaced the district-adopted basal reading program; therefore, teachers typically were able to use a two-hour block of time daily for this instruction while teachers in the comparison – business as usual – condition spent 1-2 hours daily in ELA instruction and a half hour enacting science instruction. Romance and Vitale have conducted a number of experimental studies, beginning with studies in Grade 4. The school contexts in which these studies have been conducted are described as a large multicultural urban school system in southeastern Florida having a wide range of student demographics (e.g., ability levels, ethnicity, parental income), with the student demographics (ability, ethnicity) of the comparison groups matching those of the experimental groups.

Across their studies, using multivariate covariance analysis, results showed that the students in the experimental group, compared to demographically similar controls, not only displayed significantly greater standardized test achievement as measured by the Iowa Tests of Basic Skills reading subtest and the Metropolitan Achievement Test science subtest, but also displayed a more positive attitude toward science and reading and greater self confidence in learning science. For example, in the study reported in Romance and Vitale (2001) effects on the Metropolitan Achievement Test-Science ranged from 0.93 to 1.6 grade equivalents, while the reading achievement effects on the Iowa Test of Basic Skills-Reading and the Stanford Achievement Tests-Reading ranged from 0.3 to 0.5 grade equivalents.

In addition to the grade-specific studies, Vitale and Romance (2011) have conducted two longitudinal studies of *Science IDEAS* (2002-2007 and 2003- 2008) providing evidence that students who participated in the Science IDEAS curriculum in the elementary grades continued to show benefits for this instruction through Grades 7 and 8.

The *Science IDEAS* model uses a 2-hour time block that encompasses both science and literacy instruction. Although *Science IDEAS* was initially studied with older elementary students, the implementation of the *Science IDEAS* model was expanded to second- and third-grade classrooms during the 4th year of the program of research. Researchers describe the model as "readily implemented" by second- and third-grade teachers. Teachers and researchers alike consistently observed that students participating in *Science IDEAS* were engaged, motivated, and showed gains in science conceptual knowledge. For all students, participation in *Science IDEAS* instruction had a statistically significant impact on standardized math and reading assessments (MAT-Science and SAT-Reading) as well as an attitude/self-confidence measure (the School Science Appraisal Inventory) (Romance & Vitale, 2001). More recently, Romance and Vitale adapted the *Science IDEAS* model for first- and second-grade classrooms. The Grade 1-2 *Science IDEAS* model departs from the upper elementary grade version in that it complements, rather than replaces, language arts instruction. The study occurred over an 8-week period, during which the districts' pre-existing 90 minutes of daily language arts instruction was complemented by 45-minute long *Science IDEAS* lessons. These lessons focused on core "clusters," which included Solids and liquids, Using your senses, Measuring tools, Gases, Phases of matter, Forms of energy, Energy transfer, Pushes and pulls, Types of forces, Simple machines and Physical changes. In Grade 1, instructional activities in the *Science IDEAS* lessons included: (a) teacher reading aloud science texts, (b) hands-on activities, and (c) journaling and concept mapping. Grade 2 included the same instructional activities as Grade 1, and additionally included student reading of science texts and student writing about science. Students who participated in the Grade 1-2 *Science IDEAS* model consistently outperformed their counterparts in the comparison condition on the Iowa Basic Skills test in both reading and science. All studies reported for both the *Science IDEAS* program and the modified Grade 1-2 *Science IDEAS* program were conducted in a multicultural urban school district in southeast Florida with a wide range of student demographics. Researchers argued that the results of these studies support a K-5 curriculum policy advocating more instructional time invested in supporting students' content knowledge in ways that lead to "meaningful cumulative learning."

The comprehensive, long-standing, longitudinal studies of *Science IDEAS* provide robust evidence of the potential benefits of enacting instruction that takes advantage of the richness of science investigations, coupled with well-chosen literacy resources and activities that are carefully scaffolded, for supporting both science and literacy achievement.

Concept-Oriented Reading Instruction (CORI)

Important to understanding CORI is an understanding of the motivation research that preceded its development. Guthrie and Wigfield (1997) and Wigfield and Guthrie (1997) drew upon survey and interview data to identify motivations for reading; they concluded that these motivations included: curiosity, experiencing beauty through language or art (aesthetic involvement), interaction with others on both a personal and academic level, the right level of challenge, and the self-efficacy associated with feelings of competence and capability.

Informed by this research, Guthrie, Wigfield, and their colleagues designed a program of research to investigate the hypothesis that key to the improvement of reading is *engagement*, which is attained when learners are provided rich conceptual challenges that they are pursuing in collaboration with others, supported by strategies that promote self-directed learning. Furthermore, students participating in CORI demonstrate their learning using multiple forms of representation, including drawing, notes, and compositions. All of these features are presumed to enhance motivation. What does this have to do with science? The architects of CORI chose science topics and activity as the rich conceptual space that could lead to engagement. Examples of units of study included an earth science unit on the formation of, for example, volcanoes and rivers, and a study of structure/function relationships in various ecosystems (e.g., deserts and ponds). Examples of science activity included: building birds' nests and spider webs, dissecting owl pellets, locating crickets in the school yard, and building weather stations. Integral to each unit of study were text sets that included both informational and narrative texts and were designed to enrich the knowledge students could bring to their inquiries. For each unit of study, there were four phases: (1) observe and personalize, (2) search and retrieve, (3) comprehend and integrate, and (4) communicate to others (Guthrie, Anderson, et al., 1999).

The initial, quasi-experimental, studies of CORI were conducted in Grades 3 and 5 in low-income schools that served students diverse with respect to race (i.e., 55% African American, 22% White, 15% Hispanic, and 7% Asian). Teachers within each school were assigned to treatment or comparison conditions. Teachers in the treatment classrooms enacted 16-18 week-long units of instruction in both the fall and spring. For Grade 3, the fall unit of study addressed adaptations and habitats of birds and insects, while the spring unit was weather, seasons, and climate. For Grade 5, the fall unit concerned the life cycle of plants, while the spring unit was earth science, including the solar system and geological cycles. Teachers in the comparison classrooms used a traditional reading series for their reading instruction, and a textbook for science instruction, selected for focusing on the same conceptual content as planned for the experimental classes.

The data the researchers collected were extensive; they included measures of: reading, strategy use, motivation, writing, drawing, conceptual understanding (for example, specific to ecology, they studied students' understanding of mutualism, commensalism, predation, and amensalism, in concert with survival concepts such as feeding, locomotion, communication, and reproduction). Science knowledge was assessed using 19 multiple-choice items on concepts, illustrative evidence, and vocabulary. While the complexity makes it difficult to provide a gloss of this study, the highlights are that students who experienced the CORI intervention: showed higher levels of reading engagement and conceptual learning when compared with students in the traditional instructional condition. Perhaps most intriguing was the finding that students who experienced CORI applied the engaged strategies to which they were introduced to a new domain of study, exhibiting transfer of learning.

In subsequent studies (e.g., Guthrie, Wigfield, et al., 2004), CORI researchers sought to tease out the influence of CORI when compared with strategy instruction (SI) in reading and when compared with traditional instruction (TI). This research was conducted in Grade 3. For our purposes, what is interesting about this research is that it brings to the fore the question of what constitutes a motivating context that engages students in knowledge building *and* strategic learning from text. In CORI, explicit Strategy Instruction was provided for the following reading comprehension strategies: (a) activating background knowledge, (b) questioning, (c) searching for information, (d) summarizing, (e) organizing graphically, and (f) identifying story structure. Each strategy was taught for one week in the order presented previously (6 weeks), and in the next 6 weeks, strategies were systematically integrated with each other. The SI condition focused exclusively on the teaching of the same strategies included in CORI and they were presented in the same sequence. Teachers selected the texts they would use to enact strategy instruction. There were two six-week phases of instruction in CORI that featured trade books selected and sequenced to support building the concepts key to the CORI units of study. A similar complement of measures were used in the Guthrie, Wigfield, et al. 2004 study as in the 1997 study. The findings revealed that students experiencing CORI scored higher than students in the SI condition on the following measures: multiple text comprehension, passage comprehension, the reading strategy composite, and the reading motivation composite, although CORI and SI were not significantly different on these variables on the pretests. Students in both conditions outperformed the students in the traditional instruction condition. What is most noteworthy about this study is that students who were in the CORI condition were more motivated and, in fact, more strategic than students in the SI only condition.

In an additional investigation of CORI, Guthrie, McRae, et al. (2009), explored the use of CORI with low- and high-achieving readers in Grade 5. This is an especially relevant study because it is so often the case that low-achieving students are denied the kind of ambitious teaching and learning offered to high-achieving students. In this study, low-achieving readers were provided explicit instruction, working in small groups of three to six students, with word reading skills, in addition to the comprehension strategies that are integral to CORI. In addition, low-achieving students were provided leveled texts that were selected so that they could be read independently by the students. In this study, CORI was compared with traditional instruction. Once again, the research indicated that CORI students performed higher on reading comprehension and word recognition speed, as measured by the Gates-MacGinitie Reading Tests, as well as on science content knowledge specific to plant and animal interactions in their respective ecosystems. But, very importantly, with the additional supports for low-achieving readers in place, CORI was equally effective for low- and high-achieving readers.

Decades of research on CORI supports the researchers' hypothesis that science content provides a context in which students, curious about the ways the world works, engage in strategic and motivated reading that yields comprehension achievement and conceptual understanding. Integral to the successful enactment of CORI is teacher support, interesting texts, and a coherent curriculum.

Seeds of Science/Roots of Reading

Seeds of Science/Roots of Reading instruction exploits the similarities that were identified in Table 1; the designers purposefully selected strategies that lend themselves to the conduct of scientific inquiry, as well as text comprehension (Cervetti, Barber, et al., 2012). Specifically, students in the treatment condition were taught to make predictions before conducting a first-hand investigation (e.g., regarding the interaction of light with material), make predictions before and during reading, and revise their predictions based on evidence gathered either from their investigation or reading. The use of semantic maps supported the teachers to teach scientific vocabulary as concepts. There was a metacognitive component to the curriculum to the extent that the students were encouraged to reflect on the similarities and differences of making and using predictions in the two contexts. Students in the treatment group also read texts that were specifically designed to complement the first-hand investigations (e.g., they read about the speed of light).

There were 94 fourth-grade teachers recruited to this study, half of whom were randomly assigned to the treatment condition; teachers in the comparison condition taught similar content, using whatever curriculum, text, and materials they would typically use. More than 50% of the students in both the treatment and comparison groups qualified for free or reduced-price lunch (FRL). To qualify to participate in the study, treatment teachers had to agree to dedicate a minimum of three hours per week for a minimum of eight weeks. Forty percent of this time was dedicated to first-hand investigation, while 20% of the time was dedicated to reading books. Uniting both the first- and second-hand investigations was the use of talk and writing.

Students in the *Seeds of Science/Roots of Reading* classrooms attained higher scores on measures of science conceptual knowledge and vocabulary when compared with the control students. In addition, they performed equivalently or higher than comparison students on measures of science reading comprehension and science writing. Finally, *Seeds of Science/Roots of Reading* classrooms also had more student-to-student talk. Evaluations revealed gains in science measures with effect sizes as great at .61 compared to control classrooms after a single 8- to 10-week unit of instruction, with no losses in literacy scores despite the fact that there was less explicit focus on literacy skills.

Research on *Seeds of Science/Roots of Reading*, suggests that pairing first-hand investigations with second-hand (text-based) investigations, when these investigations are carefully designed and sequenced for the purpose of addressing a shared scientific question, promotes greater depth of knowledge and understanding for students.

Multiple Literacies in Project-based Learning

We conclude this section with a yearlong case study by Fitzgerald (2018, 2020) examining the design, placement, and teacher enactment of texts and related tasks in a third-grade project-based science curriculum, *Multiple Literacies in Project-based Learning (ML-PBL)*. The ML-PBL curriculum integrates science, English language arts, and mathematics and is designed to address the three-dimensional learning goals of the NGSS and select CCSS. ML-PBL is designed to include features that are characteristic of project-based learning, including: (a) use of a "driving question" that is both meaningful to students and anchored in real world problems (e.g., *How can we design gardens to grow food for our community?*); (b) student participation in designing and conducting first-hand investigations and creating artifacts to pursue the driving question; (c) discussion and collaboration among students, teachers, and other community members; and (d) use of cognitive tools, such as digital technologies and texts, to scaffold learning, inquiry, and collaboration. The ML-PBL approach to integrating science and literacy braids reading, writing and oral language with first-hand investigations to create opportunities for students to engage in science practices and build knowledge about core ideas.

Case study participants included one experienced third-grade teacher and her 31 students in a rural district in the midwestern United States. Approximately 65% of students in the K-5 elementary school were eligible for FRL, 20% received special education services, and 5% were English learners. Sixty-five percent of students were White, 25% were African American, 5% were Hispanic, and 5% were two or more races.

The third-grade ML-PBL curriculum includes four, six-to-nine week units that are designed to address the three dimensions of the NGSS. Each unit is framed by a driving question that is meaningful to students and anchored in real-world problems (i.e., *Why do we see so many squirrels but can't find any stegosauruses? How can we design fun moving toys that other kids can build? How can we help the birds around here grow up and thrive? How can we design gardens to grow food for our community?*) Within and across ML-PBL units of instruction, students have multiple and varied opportunities to read and interpret a variety of traditional print, multimodal, and digital texts as they engage in project-based learning, including: (a) published trade books about science concepts and the work of scientists and engineers; (b) researcher-designed texts developed to explicitly connect to and build upon students' first-hand experiences in the units (e.g., biographical text, informational text, hybrid narrative and informational text, interviews, news articles); (c) videos; and (d) other representational forms, such as graphs, tables, simulations, and photographs. In addition to reading, students have multiple opportunities to engage in meaning making discussions, in both whole class and collaborative small group formats. Finally, students participate in multiple and varied opportunities to write across the units, including: (a) recording data from first-hand investigations (e.g., drawing and describing observations, recording measurements), (b) writing scientific explanations, (c) developing and revising models, (d) drawing and describing plans for engineering design solutions, and (d) developing interview questions to seek feedback about design solutions, among others.

The texts in the ML-PBL units are designed and integrated to serve a variety of roles. These roles include: (a) supporting students to think about their everyday experiences in new ways, (b) sharing features of the nature world that a likely unfamiliar to elementary students, (c) introduce the natural contexts in which phenomena unfold, (d) illustrating connections between students' first-hand investigations, core ideas, and crosscutting concepts, (e) connecting students' investigations with the work of professional scientists and engineers, (f) illustrating science practices, such as asking questions or planning and conducting investigations, (g) sharing information to supplement evidence students collect first-hand, (h) providing information about phenomena that students cannot observe in the classroom, (i) introducing academic language and ideas with which students build and communicate knowledge, (j) providing opportunities for students to interpret data presented graphs or tables and (k) including a variety of representational forms (e.g., models, images, diagrams) (Palincsar et al., 2017).

Findings indicated (for example) that the design, placement, and pairing of texts and tasks - in hand with the teacher's enactment - created meaningful purposes for third-graders to read and interpret informational texts across ML-PBL units. To illustrate, in the first third-grade unit, students viewed videos and participated in an interactive read-aloud of a researcher designed, informational text to build upon their first-hand observations of squirrels around their school. The teacher supported students to identify and use information from the text to revise models they constructed to answer the question: *How do squirrels survive in their environment?* The design and integration of texts in the units also provided opportunities for students to read strategically to support reading and interpreting text. For example, in the second ML-PBL unit, as the teacher facilitated an interactive read-aloud of a researcher designed, biographical text about the engineer who designed the Super Soaker, she supported students to make predictions based on ideas in the text and to make connections to their prior knowledge and experience while reading. The design and integration of texts in ML-PBL also engaged students in using text in the service of disciplinary knowledge building and engaging in science practices. For example, in the second ML-PBL unit, students participated in an interactive read-aloud of a researcher-designed text about two children who troubleshoot the design of a toy and observe how friction affects objects' motion. The text illustrated scientific practices, such as planning and conducting fair tests and closely observing phenomena, and also provided a context for and motivated students to plan and conduct their own investigations of moving toys they built in the classroom.

Table 2

Features of "Full" Integrations of Science and Literacy Interventions in Third through Fifth Grade

Features of integrated curricula	Projects containing these features
Opportunities to actively engage with scientific phenomena (e.g., through observation, prediction, inquiry, reflection)	Science IDEAS CORI Seeds of Science/Roots of Reading ML-PBL
Opportunities to read and discuss a variety of texts (including informational, narrative, and hybrid texts)	Science IDEAS CORI Seeds of Science/Roots of Reading ML-PBL
Opportunities to learn and apply comprehension strategies (e.g., making predictions, the use of text structure, learning new vocabulary, identifying main ideas, asking questions, and making inferences)	Science IDEAS CORI Seeds of Science/Roots of Reading
Opportunities to create concept/semantic maps illustrating how ideas in science are connected to one another	Science IDEAS Seeds of Science/Roots of Reading
Opportunities to write about science	Science IDEAS CORI Seeds of Science/Roots of Reading ML-PBL
Opportunities for class discussions of scientific phenomena and/or class co-construction of scientific explanations	Science IDEAS CORI Seeds of Science/Roots of Reading

	ML-PBL
Scheduling an extended block of time for science instruction that replaces English Language Arts instruction	Science IDEAS

Table 3

Student Learning Gains From "Full" Integrations of Science and Literacy in Third through Fifth Grade

Gains following use of integrated curricula	**Projects noting these gains**
Science conceptual knowledge	CORI Science IDEAS Seeds of Science/Roots of Reading
Science vocabulary	Seeds of Science/Roots of Reading
Reading achievement	Science IDEAS CORI Seeds of Science/Roots of Reading
Non-cognitive gains (e.g., reading motivation, reading engagement, attitude toward science, attitude toward reading, self-confidence)	CORI Science IDEAS
Long-term benefits specific to science knowledge and reading comprehension measured years later	Science IDEAS

Integrations of Science and Literacy in Pre-K through Second Grade

The following section will consider promising approaches used to integrate science and literacy learning in pre-K through Grade 2, including discussion of the influence of these approaches on learning outcomes. We begin by considering cases of curricula that were explicitly designed to integrate science and literacy. The curricular integrations of literacy and science, described below, have been ordered by grade level. Studies examining the efficacy of these types of integrated curricula have consistently demonstrated student learning gains in both science and literacy. The reader will notice that the instruction described in this section includes features such as read-aloud, play, a focus on oral language development, shared writing, and the use of multiple forms of scaffolding since the students are acquiring basic literacy knowledge and skill.

ScienceStart!

The *ScienceStart!* preschool curriculum consists of four modules, each lasting 10-12 weeks: measurement and mapping, color and light, properties of matter, and neighborhood habitats. Each day's lesson integrates the following: science activities (observation, predicting, and investigating), reporting their findings (e.g. through drawing, dictating to an adult, creating a skit or a song), reading aloud literature, art activities, and outdoor play activities. Math and social studies activities are also frequently integrated into *ScienceStart!* lessons. Students who participated in the *ScienceStart!* curriculum consistently showed growth on both the Peabody Picture Vocabulary Test (PPVT) and a researcher-designed content assessment. For example, in one program for low-income children, six students who participated in the *ScienceStart!* curriculum made 15 months of improvement on the PPVT over the course of 6 months. Additionally, teachers using *ScienceStart!* reported an increase in engagement and a decrease in disruptive behavior among their students, while parents reported increases in (a) their children's vocabulary and (b) types of science-related topics that students noticed and discussed at home (French, 2004).

In a follow-up study, Peterson and French (2008) identified ways that preschool teachers worked to support students to develop explanatory language in the context of scientific inquiry using the *ScienceStart!* curriculum. The context for this study was a Head Start program in a mid-sized urban city in the northeastern United States, with five teaching staff who were White and two who were Black. Forty-seven students participated in this study: 33 were Black, seven were White, five were Asian, and two were Latinx. The age range for students was 3 years 7 months to 5 years. Ten students were ELLs. All instruction was filmed during a 5-week unit on color-mixing. An analysis of teacher language revealed that teachers (a) engaged students as conversational partners, (b) positioned students as scientific investigators, and (c) dynamically co-constructed scientific explanations with students. An analysis of pre- and post-assessments revealed that students made the following gains during the unit: (a) increased use of vocabulary related to the unit's conceptual focus, (b) higher frequency of causal language in their explanations, and (c) in general, a greater proportion of comments that were "on topic" in response to interviewer's questions. Researchers conclude that this study offers compelling evidence that facilitating collaborative discussions of scientific inquiry are a valuable part of early childhood curricula.

SOLID Start

Similar to *ScienceStart!*, the *SOLID Start* (Wright & Gotwals, 2017a) kindergarten curriculum consists of two 4-week kindergarten units that integrate science and literacy: (1) *Plants, Animals, and Their Environment* and (2) *Weather and Climate*. Each lesson is approximately 45 minutes long. *SOLID Start* is aligned with NGSS as well as with some of CCSS. The *SOLID Start* curriculum was designed to include several instructional principles to support science talk in kindergarten classrooms, including: (a) discussion to scaffold young children's expression of ideas; (b) driving questions to engage students in responding to and asking their own questions about phenomena; (c) opportunities to engage activity with science phenomena; (d) interactive read-alouds to support student learning about particular phenomena and children's oral language development, in which teachers read informational trade books aloud, provide explicit vocabulary instruction, and facilitate discussion of the ideas in the text; and (e) opportunities to draw and write about science individually (i.e., in science journals) and collaboratively (i.e., through shared writing). Wright and Gotwals (2017b) distilled these instructional principles into five strategies to promote young students' science talk in each lesson: "ask, explore, read, write, and discuss" (p. 190).

A quasi-experimental study investigating the *SOLID Start* curriculum included six control classrooms and seven experimental classrooms (Wright & Gotwals, 2017a). At the start of the study, there were no significant differences between control and experiment classrooms regarding (a) demographics, (b) performance on content pretest, (c) or standardized language measures. The treatment schools had 41% and 37% students who were described as "minority" while the control group had 31% "minority" students. More children in experimental classrooms were eligible for FRL (62%), as compared to children in control classrooms (45%). Findings indicated that children who participated in the *SOLID Start* curriculum outperformed children in comparison classrooms in: (a) making claims, (b) using evidence, (c) receptive and expressive vocabulary in science contexts.

Scientific Literacy Project

The *Scientific Literacy Project (SLP)* has created kindergarten thematic units that take 2 hours per week. These units incorporate: (a) science investigations, (b) read-alouds of informational science books, (c) opportunities for students to write or draw their thinking in individual notebooks and on classroom idea boards, (d) discussions of scientific ideas, (e) home learning opportunities that are coordinated with school learning. Together, the SLP units addressed all Indiana state standards for kindergarten science, including (a) nature of science, (b) observing and communicating science, (c) force and motion, (d) living things, and (e) comparing similarities and differences. A quasi-experimental study (Mantzicopoulos et al., 2013) found that students benefited from both the in-school and at-home aspects of the program. In this study, all students were from schools serving low-income, racially diverse populations. Seventy-nine students only participated in the school portion of the program, 41 students participated in both the school and home portions of the program, and 74 students were in the control group. The study identified benefits for students in both experimental groups regarding: science learning, motivation, and achievement. Students who participated in both the home and school program showed (a) greater gains in science knowledge, (b) higher self-confidence in learning science, and (c) perceived family support for learning science. Additionally, parents who participated in the home program (a) spent more time on the science read-alouds, (b) provided more scaffolding for their child, and (c) engaged more with the text, as compared to parents who did not receive this support. Researchers concluded that the SLP was able to incorporate 2 hours of science per week into the kindergarten schedule, to the benefit of students' science learning and without detracting from students' literacy development. Furthermore, in-school science and literacy integration was most successful when additionally supported by out-of-school science and literacy integration.

Integrated Science-Literacy Units

In a series of university-school action research projects reported by Varelas, Pappas, and colleagues, literacy and science researchers and classroom teachers have collaborated to design units, for first- and second-grade students, that integrate science and literacy (Pappas et al., 2003; Varelas & Pappas, 2006; Varelas, Pappas, Kane, et al., 2007; Varelas, Pappas, & Rife, 2006). Participating schools have ethnically-linguistically diverse student populations, most of whom are eligible for FRL. The integrated science-literacy units are typically between 4 to 6 weeks long and incorporate the following features: (a) hands-on explorations and class discussions of these explorations, (b) opportunities to write and draw about the aforementioned hands-on explorations, (c) read-alouds of informational books, (d) small group literature circles focused on informational books, and (e) parent-child explorations that include both hands-on activities and a related informational children's book. Researchers have found that the design of the unit facilitated teachers and students making connections in many ways, including: connections between texts in a unit, connections between unit texts and hands-on activities, and connections to students' lived experiences. Students often made powerful connections between science ideas explored in class and their own lived experiences, in ways that debunk troubling deficit perspectives that are too often applied to learners in urban settings.

Table 4

Summary of Features of "Full" Integrations of Science and Literacy in Pre-K through Second Grade

Features of integrated curricula	Projects containing these features
Opportunities to actively engage with scientific phenomena (e.g., through observation, prediction, inquiry, reflection)	ScienceStart! SOLID Start Science Literacy Project Varelas & Pappas Grade 1-2 Science IDEAS
Opportunities to read and discuss informational texts (including read-alouds)	ScienceStart! SOLID Start Science Literacy Project Varelas & Pappas Grade 1-2 Science IDEAS

Opportunities to draw and/or write about science (including the practice of dictating to an adult, in the case of curricula designed for younger students)	ScienceStart! SOLID Start Science Literacy Project Varelas & Pappas Grade 1-2 Science IDEAS
Opportunities to create concept maps	Grade 1-2 Science IDEAS
Opportunities for class discussions of scientific phenomena and/or class co-construction of scientific explanations	ScienceStart! SOLID Start Science Literacy Project Varelas & Pappas Grade 1-2 Science IDEAS
Take-home learning opportunities to be completed with family members	Science Literacy Project Varelas & Pappas

Table 5

Student Learning Gains From "Full" Integrations of Science and Literacy in Pre-K through Second Grade

Gains following use of integrated curricula	**Projects noting these gains**
Vocabulary	ScienceStart! SOLID Start
Science content	ScienceStart! SOLID Start Scientific Literacy Project
Science practices	SOLID Start
Making connections across the unit and making connections to students' lived experiences	Varelas & Pappas
Non-cognitive gains (e.g., motivation, engagement)	ScienceStart! Scientific Literacy Project

Using Science Texts in Read-Alouds in Pre-K through Second Grade

While the research reported in the prior section reports on full curricular integrations of science and literacy, another line of inquiry documents the potential for read-alouds, which have traditionally played a key role in science/literacy integration in the pre-K and early elementary years, particularly when these read-alouds are accompanied by rich sensemaking discussions.

In their *Evolving Minds* program of research, Kelemen and Emmons and their colleagues have systematically investigated the use of storybook read-alouds to teach children as young as five about the process of natural selection (Kelemen et al., 2014). The rationale for this content is that alternative conceptions about adaptation by natural selection are widespread among adults, which the researchers conjecture arise from cognitive biases and intuitive theories emerging in early childhood. Challenging guidelines that urge delaying comprehensive instruction on adaptation until adolescence, these researchers investigated whether classrooms of kindergartners and second graders could acquire a basic but comprehensive understanding of adaptation from experiences with two picture storybooks that explained natural selection (Emmons, Lees, & Kelemen, 2017). The study was conducted in classrooms in which students represented diverse racial, ethnic, socioeconomic, and language backgrounds: 66% of students at the school identified as Hispanic, 22% African American/Black, 8% White, 2% Asian, 2% multi-race or non-Hispanic, and <1% Native American, and 85% of students were eligible for FRL. The books were designed by the researchers who also conducted the read-aloud and led a discussion focusing on similarities between the two book narratives regarding: (a) within-species variation in the past and present; (b) climate change; (c) differential access to food; (d) differential survival; (e) differential reproduction; and (f) multiple generations. Learning was assessed in near and far transfer contexts both immediately and 1 month later. Both kindergartners and second graders demonstrated substantial learning of biological information, with the second graders demonstrating near and far transfer, immediately and over time (1 month later). These results point to the value of well-designed text, supported by structured discussion, to facilitate young children's learning of complex counterintuitive scientific ideas.

Varelas, Pieper, et al. (2014) investigated the opportunities that informational science trade books and hands-on explorations provided for reasoning and meaning making among Latina/o students in a third-grade classroom. They were interested in how children engage in and reason about ideas during interactive read-alouds of trade books about science topics compared to how they reason during first-hand investigations on the same topic, and what affordances different activities provide. Across 5 days of instruction focused on the same science topic (i.e., the features, behaviors, and habitat of earthworms), Varelas et al. collected and analyzed classroom discourse and children's writing and drawing. They found that interactive read-alouds of science trade books on earthworms were tools for meaning making that involved multiple types of reasoning. They also found that hands-on explorations provided unique opportunities for children to extend their ideas about earthworms through their observations and opportunities for representing and wondering about ideas. Finally, Varelas et al. found that the texts and hands-on investigation complemented one another in terms of providing rich opportunities for meaning making in the classroom.

The Role of Genre, Features, and Content in Science Texts

In this section, we consider broad-ranging research that has explored a variety of topics specific to text in science, including: how students respond to various genres of text, how text features influence comprehension of science text, how those findings can be used to inform instruction, and how text can be used to inform students' understanding about science and the work of scientists.

We begin with a study by Cervetti, Bravo, et al. (2009), in which they examined third- and fourth-grade students': (a) ease of reading, (b) comprehension, (c) recall, and (d) preference for different types of text (informational or fictional narrative). While students' oral reading accuracy and fluency (i.e., reading rate) were comparable across the informational and fictional texts and students did not express a preference for one type of text over the other, students recalled more key concepts and answered more comprehension questions correctly about the informational text.

Cervetti, Wright, and Hwang (2016) also examined the hypothesis that "knowledge can be built and leveraged simultaneously in the interest of students' literacy development through the use of conceptually coherent text sets" (p. 761). Participants included 59 fourth-grade students, who were identified as reading on grade level by their teachers, from a rural school in the Midwest. Fourth-grade students were randomly assigned to either the treatment (reading conceptually-coherent texts) or control (reading texts that were not conceptually coherent). Students in the treatment group either read a set of informational texts that were focused on a set of concepts related to birds, while students in the control group read or a set of texts that addressed a range of topics. Cervetti et al. found that students who read the conceptually-coherent texts demonstrated more knowledge of the concepts in the texts they read, more knowledge of target words/vocabulary in the texts, and learned more from a novel text about a related topic (i.e., birds) than the students who read about unrelated concepts.

In a study specific to informational text, Pyle et al. (2017) conducted a meta-analysis investigating the effects of expository text structure interventions on reading comprehension. Text structure refers to the way in which information in a text is organized. Structures common to science texts include sequencing (for example, in describing a process), cause/effect, and compare/contrast. Text structure instruction is likely effective for supporting students' expository text comprehension because it provides students with an organizational framework for approaching complex text with rich academic vocabulary. Pyle et al.'s (2017) meta-analysis revealed that expository text structure instruction produced large effects on reading comprehension, especially when the text structure instruction employed scaffolded instruction; for example, following a gradual release of responsibility in which the teacher modeled identifying and using text structure to support approaching the text, using increasingly complex expository texts, and including signal word instruction (e.g., "however," "possibly," "therefore") and instructional feedback that was tailored to students' performance levels.

A common feature of science text is its multimodal nature (Lemke, 2004) leading researchers to explore how students manage this feature of science text. For example, Prain and Waldrip (2006) investigated elementary-grade teachers' and students' beliefs and practices related to using multi-modal representations in the context of science instruction. Using a multi-site case study approach, Prain and Waldrip found that, while teachers used multiple modalities to engage students in science learning and to assess student learning, they did not systematically support their students to translate across multiple representational forms. They found that multiple factors influenced students' understanding of various modes, and that students who did recognize relationships among modes demonstrated greater conceptual understanding that students who did not recognize those relationships.

Jian (2016) conducted a study that reinforced the Prain and Waldrip (2006) finding. Focusing on fourth graders, Jian investigated their learning strategies and cognitive processes for reading illustrated biology texts using eye tracking technology. Jian compared the (high reading ability) fourth graders' reading strategies and reading comprehension of illustrated biology texts to the performance of adult readers. Participants read a biology-focused article from an elementary-grades science textbook, which contained two illustrations (one significant to the content and one decorative). University students outperformed fourth graders on all tasks, and eye movement patterns differed across groups. Notably, Jian found that fourth graders made fewer references to both text and illustration than the university students, which suggests that the fourth graders struggled to perceive connections between text and illustrations (i.e., multiple representational forms). This study suggests that young students need to be supported to avail themselves of the multimodal features of science text.

There have been a number of studies designed to analyze the content of science texts designed for young readers. For example, Ford (2006) analyzed 44 trade books for their explicit and implicit representations of science. The majority of the sample consisted of informational texts, followed by experiment books and artistic books. Her analysis revealed that scientific knowledge was generally represented as facts, with limited connections to the producers of those facts. The practices of science typically featured experiment or observation, with little attention to data analysis or theory development. Artistic books focused on nature encouraged an aesthetic approach to nature, primarily through creative observation. Ford concluded that these books were unlikely to convey a sophisticated image of the nature of science to young children without the mediation of teachers.

A more recent study by Kelly (2018), analyzed 28 picture books from the Outstanding Science Trade Books recognized by the National Science Teachers Association (NSTA) in 2016. Informed by the literature on culturally relevant science instruction, and similar to the study by Ford (2006), Kelly was interested in the portrayal of scientists as conveyed by images in the text (i.e., gender and racial background), the scientific disciplines represented in texts, what aspects of the nature of science were represented in the books, and the language used to describe the work of scientists. Despite being award-winning texts, the sample did not reflect diversity of scientific fields or scientists. Most of the scientists depicted were white and male, and most books presented life science, frequently specific to animals. However, the findings also showed that the extent to which books represented the nature of science varied widely. Some books contained no references, and others contained many references to different aspects of the nature of science. The study noted that biographies and books that described in detail the work of scientific teams attended most to the nature of science. The study collected and categorized all the verbs used to describe scientific activity and found that these descriptions of scientific activity have a wide scope and show scientists engaging in work ranging from data collection to activism.

In another content analysis of science trade books, May et al. (2020) analyzed 400 NSTA Outstanding Science Trade Books for Students K-12 from 2010 through 2017. They focused their analysis on examining how science trade books represent science knowledge, and the array of genres represented among the books. The researchers first sorted the books either as primarily communicating accepted science knowledge or allowing readers to learn about how science knowledge is generated. May et al. then categorized the trade books into genres (e.g., historical fiction, biography, or refutation text), and coded the primary content domains and text structures. They found that 135 of the books focused on the lived lives of scientists, which they divided into four genres: (a) biographies of scientists; (b) fictional accounts of kids as scientists; (c) history and science; and (d) literature of problem solving, which recounted the work of contemporary scientists. A larger proportion of the books (*n* = 217) focused on communicating accepted science knowledge. This category included nine genres: (a) browsable books, which included brief sections with descriptions; (b) experiencing a day in the life, which provided experiential accounts of events or animals; (c) expository literature; (d) observing in nature; (e) playful participation, which invited active participation from the reader, such as through questions and answers; (f) refutation texts; (g) resources for scientific inquiry; (h) science-themed poetry; and (i) traditional survey books. Across all categories, "experiencing a day in the life" was the most prevalent genre identified (*n* = 51; 12.75%) whereas refutation text was the least prevalent genre (*n* = 2; 0.5%). May et al. concluded that each of the genres has the potential to offer different affordances for science instruction, and cautioned against the use of oversimplified categories, such as narrative versus informational text, that may encourage privileging or excluding a particular genre or discourse. The researchers emphasized the importance of providing students' access to books that foreground the lived lives of scientists in order to communicate that science fields are open to them. May et al. also noted the hopeful finding that the "lived lives of scientists" books analyzed contained higher percentages of scientists who are women than identified in Kelly's (2018) research; however, May et al. reported similarly few representations of scientists of color and other minoritized populations.

Interventions that Leverage Genre, Features and Content

Picking up on the theme of how texts can influence young students' understanding of the nature of science, Brunner and Abd-El-Khalik (2020) argued that an important goal of science instruction, integral to preparing informed citizens, is teaching students about the nature of science (NOS). Acknowledging that this is a contested issue in science education, they nonetheless suggest that it is possible to identify what a curriculum might look like that addresses NOS. They further argued that teachers are typically ill-prepared to engage in this type of instruction because of limitations in their own understanding of the nature of science; however, when taught well, even kindergarten students can learn productive views of the nature of science. To address teacher knowledge, they included curricular supports designed to enhance teachers' knowledge regarding the NOS. The researchers selected three trade books, which contained content that was interesting, accurate, and supportive of earth and space science (the unit of study). The researchers reviewed the texts for instances when the authors provided information that spoke to the NOS; they pointed these examples out in the curricular supports. In a number of cases, they made the information more explicit; for example, pointing out when scientists were making an inference or when they were drawing upon evidence. The study was conducted with fourth and fifth graders. Using a within-subject design, the trade books were read aloud by teachers in three conditions that were described as levels: Level I served as a control and consisted of a trade book that remained unmodified, Level II consisted of a trade book that had been modified to include explicit references to NOS, and Level III consisted of a modified trade book accompanied by educative curriculum materials that were aimed at improving the teachers' views of NOS, as well as supporting teaching about NOS. Using a NOS survey (Views of Nature of Science Questionnaire-Form CE, Abd-El-Khalick, 1998, 2014), interviews, and recall measures, the researchers determined that both teachers and students developed more informed views of the targeted NOS aspects after the intervention and that teachers addressed NOS more often, and in a more informed manner, when they taught with the trade books that explicitly supported NOS instruction and accessed educative curriculum materials that supported their learning about NOS.

In a study reminiscent of Brunner and Abd-El-Khalik's study, Farland (2006) investigated the influence of historical, nonfiction trade books on children's images of scientists. Farland's study was motivated by the goal of expanding young students' awareness of who can become a scientist, as well as the nature of scientific work. There were 13 self-contained third-grade classrooms (n = 156) participating in the study; six randomly assigned teachers were instructed to read one trade book each week for six weeks to supplement their modular/kit-based instruction (n = 72). The other seven classrooms received only modular/kit-based instruction (n = 84). The books that were selected: (a) contained a simplified story about scientists and their work that went beyond facts, dates, or time-lines of scientists' lives, (b) demonstrated a non-stereotypical portrayal of scientists, (c) contained accurate information, (d) used age-appropriate language, (e) displayed a common theme of perseverance in the face of struggle, and (f) contained colorful illustrations and accessible text that students would choose to reread. The method used to assess the influence of the inclusion of these texts was to have the students draw a picture of a scientist using a modified Draw-A-Scientist Test (mDAST, Farland, 2003) and respond to four questions that asked about the gender of the scientist, where the scientist was working, and what they were doing in the picture. Evaluations of these drawings revealed that the treatment group demonstrated a broader perception of who does science, where science is done, and what activities scientists do; furthermore, participants maintained their broadened perception 4 weeks after the intervention occurred.

Researchers working at the intersection of literacy and science have also been interested in designing innovative genres of text. Magnusson and Palincsar (2004, 2005, 2006) conducted a program of research that culminated in the development and study of an innovative genre of text – one written as a scientist's notebook – that was specifically designed to support children and teachers to approach science text as an inquiry. Their initial collaborations with teachers revealed that teachers thought that the risk inherent in using text was that their students might defer to the authority of the text, seeking answers from the text when, in fact, the students themselves had a key role to play in working toward explanations, and were indeed quite capable of generating their own "answers" in the course of investigating phenomena (Palincsar & Magnusson, 1997). This led the researchers to develop a text modelled on a scientist's notebook in which a fictitious scientist documents: the purpose of her investigation, the question(s) guiding her inquiry, the investigation procedures in which she is engaged, the ways in which she is gathering and choosing to represent her data, the claims emerging from her work, the relationships among these claims and her evidence, the conclusions she is deriving and the new questions that are emerging from her inquiry.

These texts were actually a hybrid of: exposition, narration, description, and argumentation. They were designed in conjunction with the programs of study used in the *Guided Inquiry supporting Multiple Literacies (GIsML)* classrooms *(i.e., How Light Interacts with Objects*, *The Study of Floating and Sinking*, *The Study of Soils*). Furthermore, the texts included multiple ways of representing data, including: tables, figures, and diagrams. For example, diagrams were used to illustrate the set-up of the investigation materials. Figures were used to depict data that students can interpret, along with the scientist. Tables modelled the various ways in which data can be arrayed and the narrative accompanying the table modelled the activity of interpreting these data. There were opportunities for the scientist to revise her thinking based on the collection of additional or more specific data. Students were supported to trace the source and nature of these revisions For example, in a notebook entry regarding light, the scientist included what she has learned from studying Newton's investigations of light and color. This provided the opportunity for the scientist to model the use of a second-hand investigation as she critically read and interpreted the reference information and indicated how she would formulate claims from this information to advance her own inquiry. These reference materials were also useful to enriching the conceptual information with which students can work. A final feature of these notebooks was their portrayal of the ways in which scientists interact with one another and observe particular conventions to facilitate these interactions. For example, in one entry the scientist notes that fellow scientists were not persuaded by her data because they were inexact, leading her to use an instrument that will provide more exact data and a process that can be more readily replicated.

The researchers conducted a quasi-experimental study to compare the process and outcomes of using the innovative text, when compared with considerate-expository text (herein referred to as traditional text) to support a second-hand investigation, in the absence of any first-hand experiences (Palincsar & Magnusson, 2001). The innovative text was modeled after the scientist's notebook and contained the features described above. The traditional text was designed as a considerate, non-refutational, expository text. They used a within-subject, across-group, design in which each student served as his or her own control and read both the notebook and traditional version of a text. Recognizing the role that background knowledge plays in comprehension, both versions of the text addressed the general topic of light. Both a notebook and traditional text were constructed for the subtopic - reflection, and both a notebook and traditional text were constructed for the subtopic - refraction. Children who read the notebook version of reflection read the considerate-expository version of refraction, and vice versa. The overall length, number of propositional units, and readability of the texts were comparable across texts. Excerpts from the two text types are provided in Figures 1 and 2 below.

Figure 1

Sample Text: Traditional Version

When scientists have measured the light reflecting from objects they have found that <u>some</u> light is always reflected. That is, for all objects, some but not all of the light reaching them is reflected. The light that is not reflected can be absorbed by the object. Scientists have wondered what determines the amount of light reflected. They have found that light or white objects reflect most of the light and absorb only a little. Dark or black objects, on the other hand, mostly absorb the light energy and little is reflected from them. You may have experienced this fact about light in your own life as you have touched objects that have had some light shining on them.

Figure 2

Sample Text: Notebook Version

Scientist Lesley Park ***Date 10/28/97*** ***Page 2***

What I concluded from these data:

1. The light reflected from each solid object was always less than the amount of incoming light on the object.
2. The type of material seems to make a difference in how the light is reflected.

Questions for me to think about:

- Why are there different amounts of reflected light?
- Does the amount have to do with the color or the texture of an object?
- What happens to the light that is NOT reflected?

I wondered what other scientists have learned from their investigations of light, so I read about some of their claims.

Paper and pencil assessments were administered before and after the students read each text. There were seven items on each assessment (some with multiple parts – totaling 14 points). Of these items, three were designed to measure the recall of factual information. The remaining items were designed to assess students' ability to engage in inferencing from the text. With respect to the items requiring inference, two dealt solely with substantive knowledge and two with a combination of substantive and syntactic knowledge (the ability to engage in scientific reasoning). For example, on the refraction assessment, students were provided a table with the optical densities of five materials (glass and four other materials). They were asked to indicate which material would bend light the most when the light was moving into this material from glass. The concept of optical density was described in the text; however, to be successful on this item, students needed to know how to read the data represented in the table, be able to compare the materials as relevant to the issue of optical density, and they had to complete the comparisons required to determine which material would bend light to the greatest extent. While both versions of the text were supportive of students' learning across the two topics concerning light; in three of the four conditions in which the relative benefits of the text genre could be assessed, the results favored the notebook genre.

Subsequent observational research conducted with teachers using the notebook texts revealed the ways in which they supported students to acquire vocabulary, consider how they might most effectively represent their data during their own first-hand investigations, assume a more critical stance in which students questioned claims in the text. Finally, students and teachers reported enjoying using the innovative form of text.

Table 6

Summary of Interventions that Leverage Genre, Features and Content

Value of well-designed science texts	**Studies**
Can support students to learn complex counterintuitive scientific ideas	Kelemen et al. (2014)
Can complement hands-on investigation to provide rich opportunities for sensemaking	Varelas, Pieper, et al. (2014)
Implications for teaching	
Provide access to texts sets that are conceptually-coherent	Cervetti et al. (2016)
Provide access to a wide variety of genres of science text	May et al. (2020)
Provide instruction on the structure and features of expository text	Pyle et al. (2017)
Support students to make connections between multiple modalities in science text	Jian (2016) Prain & Waldrip (2006)
Mediate the content of texts conveying an unsophisticated image of the nature of science	Ford (2006) Kelly (2018) Brunner & Abd-El-Khalik (2020)
Implications for curriculum designers	
Embed explicit references to the nature of science within science texts	Brunner & Abd-El-Khalik (2020) Farland (2006)
Provide material aimed at improving teachers views of the nature of science	Brunner & Abd-El-Khalik (2020)

Feature diverse protagonists in science texts	Farland (2006)
Use texts to give students the opportunity to perform second-hand investigations and engage in scientific practice	Magnusson & Palincsar (2004, 2005, 2006)

Supporting Students' Writing of Scientific Explanations and Arguments

Much of the research on writing in science has been conducted with middle school and secondary students (e.g., Hand, Wallace, & Yang, 2004), but there is a healthy body of research specific to supporting younger students' writing of scientific explanations and arguments. With respect to explanation, the researchers whose work we reviewed adhered to Berland and Reiser (2008) and McNeill and Krajcik (2008), maintaining that scientific explanation consists of three components: a *claim*, which is the answer to a question, *evidence*, which is the data used to support the claim (including numerical data, observation, and facts), while *reasoning* entails making logical connections between the evidence and the claim. Argumentation, in contrast, is typically regarded as more complicated than explanation to the extent that an argument seeks to justify and debate the validity of any explanation (Driver, Newton, & Osborne, 2000).

A study conducted by Seah (2016) is helpful to setting the stage for reviewing elementary writing research. Seah examined the use of linguistic resources by elementary students in order to determine the conceptual and language demands encountered when constructing written explanations. The data were derived from classroom observations conducted in four fourth-grade classrooms (Chronological age ~10) taught by three teachers. The data also included students' written explanations and the instructional language (whole-class discussion and textbook) in use as the students studied the life cycle of plants. Students' written explanations were analyzed for both content and linguistic features, using selected analytical tools from the systemic functional linguistics framework (Halliday, 1997). The diversity of linguistic resources and meanings identified from the students' explanations revealed both the extent to which the students were able to employ linguistic resources to construct written scientific explanations and the challenges they encountered. Interestingly, teachers' expectations of the students' written explanations were seldom reflected in their oral questioning, nor were they made explicit during the instruction. The findings of this study suggest that a focus on conceptual development is not sufficient in itself to foster students' ability to construct explanations; teachers should also attend to the linguistic features of explanations.

In a naturalistic study of classroom instruction, Zangori and Forbes (2014) sought to understand how teachers' ideas about and instructional practices support students' formulation of scientific explanations. They examined third-grade students' formulation of explanations about seed structure and function within the context of a commercially published science unit. The data, collected during a long-term plant investigation, included: classroom observations, teacher interviews, and students' written artifacts. The findings pointed to a relationship between the teachers' ideas about scientific explanations, their instructional scaffolding, and students' written explanations. Teachers who emphasized a single "correct explanation" rarely supported their students' explanation-construction, either through discourse or writing. However, the teacher who emphasized the importance of each student generating his/her own explanation and more frequently supported students to do so in the classroom has students whose written explanations were found to be much stronger than those from students in the other two classrooms. The important take-away from this study is that teachers' conceptions about scientific explanations are crucial to their instructional practices, which may in turn influence students' explanation construction.

Chambliss et al. (2003) investigated fourth graders’ explanations of the effects of a pollutant on an ecosystem, following their reading of texts on this topic and engaging in inquiry activities as well (i.e., constructing eco-columns to which they added a pollutant) . The primary interest of the researchers was whether the activity of writing an explanation would support students’ reasoning about the causal relationships entailed in recounting the effects of pollutants on an ecosystem. The students also read several explanations and were supported to notice the characteristic features of an explanation. They were then instructed to write explanations regarding the effects of pollutants on ecosystems for younger (third-grade) students. They found that all 20 students used rhetorical devices to connect with their audience. Sixteen students synthesized personal experiences and text content to report information, gave examples, and shared scenarios to support reader understanding. Nine students explicitly used a scientific model to explain phenomena. Of particular interest to the researchers was the finding that a number of the students included scenarios in their explanations; this was not something to which they had been introduced, but the scenarios provided evidence that the students used the scenarios to reason about the model they were explaining. The authors concluded that writing explanations supported the students to both reason about and understand a scientific model.

Songer and Gotwals (2012) investigated the outcomes of implementing three curricular units that included sets of activities culminating in guided explanation construction to address a scientific question in upper elementary grade classrooms. The three units were adopted by the participating school district as the life science unit for 8 weeks of instruction in fourth through sixth grades. Regardless of how much of the intervention was used, all teachers were provided with professional development workshops that focused on supporting students to construct explanations about focal science content across the life sciences (e.g., biology, biodiversity, ecology). Songer and Gotwals found strong learning gains across each grade level, but also noticed strong developmental trends, with the youngest (fourth-grade) students developing the least complete explanations and struggling to generate valid evidence.

Informed by their earlier study, Songer et al. (2013) conducted an exploratory study to identify the types of verbal scaffolds teachers provided when guiding upper elementary students to develop scientific explanations about focal science content; they were curious to know how teachers’ verbal scaffolds complemented written scaffolds provided in inquiry-focused curriculum materials. They argued that exploratory research was warranted because virtually all research on supporting scientific explanations had been conducted with much older students. What they found is that teachers used a variety of verbal scaffolds including: orienting to a hint (e.g., think about….), writing format (e.g., remember to use complete sentences), clarifying terms (e.g., Let’s go back. What is an ecosystem?), directing to necessary content (e.g., what do plants need to grow?), formatting sentence content (e.g., “you wrote something very specific; bring it back to something real general”), and providing answer options (e.g., “Just answer the question: yes or no”). They also found that some types of verbal scaffolds tended to be used in similar ways across grade levels, while others were used more frequently with lower or upper grades students. For example, orienting-to- hint and clarifying-terms scaffolds were more frequently used with sixth graders than with fourth and fifth graders, while writing format, formatting sentence content, and answer option scaffolds were more frequently used by lower grades teachers (in the fourth and fifth grades). This exploratory study indicated that, while written scaffolds were useful to supporting written explanations, the verbal scaffolds that teachers provided were useful to bridging between unfamiliar terms and ideas and the students’ real world experiences as students constructed explanations.

A study by Yang and Wang (2014) was an instructional study designed to investigate a teaching model for scaffolding fourth-grade students’ written scientific explanations. The “DCI” model that they investigated integrates *Descriptive* explanation writing activities, *Concept* mapping, and *Interpretative* explanation writing activities, designed to improve elementary grade students’ science explanations and understanding. DCI was compared with “traditional instruction,” which was characterized as lecturing. The topic of study was changes in the moon as a function of moon phase and lunar calendar. One noteworthy feature of this study is that the writing proceeded from descriptive to interpretive. Instruction took place three hours a week for a total of four weeks. Students in the treatment group were introduced to concept maps (characterizing the position and phases of the moon). They made observations of the moon over time, experienced a simulation of the moon’s phases, and were guided to critique written explanations for the moon’s phases. The effectiveness of DCI was investigated with the use of pre- and post-tests, as well as the analysis of students’ written explanations. Yang and Wang reported that students in the intervention group outperformed the comparison group in both written science explanation (statistically significant) and understanding of science concepts (although not statistically significant). Specifically, students who participated in the DCI intervention made claims that explained the regular change of moon phases, provided more clear evidence, and provided more logical reasoning than students in the comparison group.

McNeill (2011) investigated how fifth-grade students’ views of explanation, argumentation, and evidence developed across the school year; she was also interested in their abilities to construct arguments across the school year. In this design-based research, McNeill drew upon multiple data sources, including pre- and post-student interventions, student writing, and videos of classroom instruction. The student body at this urban school was ethnically diverse with approximately 15% African American, 60% Latino/a, 12% White, 12% Asian, and approximately 82% of the students eligible for FRL. The research began with interviews in which McNeil sought to understand the students’ views of explanation, argument, and evidence when these terms are used in everyday, school, and professional contexts. Based on these findings, McNeill and the classroom teacher designed lessons, instructional strategies, and curricular scaffolds that supported students to develop scientific arguments. She observed, for example, that the teacher employed a range of strategies (including modeling and critiquing, classwide debate, and connecting to everyday use of argument) over the course of the year. With this type of scaffolding, McNeill found that elementary students’ understandings of explanation, argument, and evidence for science class and in the work of scientists changed across the school. Furthermore, by the end of the school year, the structure of students’ arguments was stronger while varying in accuracy, appropriateness, and sufficiency. This indicates that, given instructional support to apply the practice of argumentation to new and more complex tasks, young students are indeed able to write scientific arguments.

Table 7

Summary of Interventions Supporting Students' Writing of Scientific Explanations and Arguments

Gains from supporting students to construct scientific explanations	**Studies**
Improved student understanding of scientific models and ideas	Chambliss et al. (2003) Songer & Gotwals (2012)
Improved quality of scientific explanations written by students	Yang & Wang (2014)
Improved student understanding of what constitutes evidence	McNeill (2011)
Implications for teaching	
Provide support regarding linguistic features of explanations. This may include providing sample explanations.	Seah (2016) Chambliss et al. (2003) McNeill (2011)
Support each student to generate their own explanation, rather than emphasizing a single "correct explanation"	Zangori & Forbes (2014)
Provide verbal scaffolds while students write explanations (e.g., prompting students to think about relevant science content, clarifying scientific terms, etc.)	Songer et al. (2013)
Support students to provide peer feedback regarding each other's scientific explanations	McNeill (2011)
Help students make connections between scientific argumentation and everyday use of argument	McNeill (2011)

Students Creating and Learning From Multiple Representations

Traditional definitions of literacy often consider the four primary modalities of literacy to be reading, writing, speaking, and listening (National Governors Association, 2010). However, many literacy scholars have encouraged expanding the modality of "writing" to include many different types of multimodal composition, including increasing students' opportunities to use drawing or other image-based media to represent their learning or ideas (Dalton, 2012; Dalton & Palincsar, 2013; Siegel, 2006). Multimodal composition and learning from multimodal representations are particularly well suited to the study of science, given that the literacy practices of professional scientists often involve creating and interpreting multimodal models or other representations that bring together words, images, symbols, audio, graphical displays, and (in some cases) animation to pursue research questions (Lemke, 2004). Some researchers studying multimodal learning in science do so in the context of digital environments as we will see in a subset of the following studies.

Recent research has found multiple benefits to young students engaging in multimodal composition (e.g., drawing, creating models) while engaged in science. For example, in a quasi-experimental study, Fox and Lee (2013) found that kindergarteners who drew animals (a turtle and a parrot) noticed more details compared to children who only observed but did not draw the animals. Participants in this study were 42 kindergarteners. Twenty-one students identified as Latino, 18 as African American, two as White, and one as Asian American; 97% of whom qualified for FRL. Students in the treatment condition observed an animal, drew the animal, and then answered questions about its appearance, location, actions, color, size, shape, and sounds. Students in the control condition observed an animal and then answered the same questions, but did not draw the animal. Students who were in the drawing group for the turtle were in the non-drawing group for the parrot, and vice versa. For both groups, the animal was present in the classroom during the entire duration of the lesson, including the question-asking. However, despite the fact that all students could observe the animal while answering questions about it, students in the treatment condition provided more accurate answers to all questions. Researchers hypothesized that the process of drawing supported students to engage in observation of "what was actually there," whereas students who did not draw were more likely to engage in speculation. As such, the process of drawing supported students to engage in accurate observation, a fundamental practice of science (as depicted in Table 1).

Students who have the opportunity to draw during science not only pay more attention to detail, they may additionally retain more scientific knowledge, as demonstrated in the following quasi-experimental study conducted by Samarapungavan et al. (2017). This study compared two second-grade classes engaged in modeling activities designed to complement FOSS kits focused on states of matter and phase change. There were a total of 34 students in the study: 65% were White, 26% were Hispanic, 3% were Asian, and 6% were multiracial; 47% percent of students eligible for FRL. Students engaged in three lessons (each of which was implemented over several days). Lessons included both (a) hands-on explorations drawn from the FOSS kit, and (b) modeling activities designed by researchers and teachers. In both classrooms, classroom discourse was recorded and coded at the turn-of-talk level. This coding revealed that, in one classroom, the creation of models was more teacher-led, whereas in the other classroom the students played a larger role in both developing and revising models. The class where students played a larger role in authoring/revising models made greater pre/post gains on content assessments. Researchers theorized that when students were actively involved in both model creation and model revision, they became more able to apply these models to a wider variety of phenomena, as opposed to students who had only been provided with a teacher-generated model. This is consistent with our claim regarding the parallels between literacy and science depicted in Table 1.

Just as it is helpful for students to have the opportunity to *represent* their learning using multiple modalities, research also shows that it is helpful for students to have information *presented* through multiple modalities. These may include: science children's books, photographs, videos, physical specimens, class discussions, or interactive computer-based simulations, among others. The presentation of information through multiple modalities is a commonality among studies focused on science literacy integration. In addition to studies described above, smaller studies have focused specifically on the benefits of conveying information through multiple modalities. For example, Wilson and Bradbury (2016) found that using multiple modalities to convey information supports both science learning and literacy skills. In this study, first-grade students participated in a curricular unit focused on the structure and function of carnivorous plants. This unit incorporated both (a) information presented through multiple modalities including videos of Venus flytraps, photographs of Venus flytraps, texts about Venus flytraps, and live specimens and (b) students sharing their ideas through multiple modalities including both drawing and writing. Following the units' completion, researchers found that, not only did students make pre/post gains in content knowledge, but students were also successfully able to "synthesize information from multiple modes." Furthermore, researchers reported both writing and drawing had different affordances when it came to communicating student knowledge. Students included more different structures of Venus flytraps in their drawing, as compared to their writing. However, students more clearly explained the function of Venus flytrap structures in their writing, as compared to their drawings. The 31 participants in this study attended a public rural Title I school in the southeastern United States.

A study conducted by Henderson, Klemes, and Eshet (2000) found benefits to students having access to information presented through a computer-based interactive simulation. In this study, second-grade students spent six weeks working with a microworld simulation focused on paleontology, *Message in a Fossil*. In this simulation, students assumed the role of a paleontologist who is conducting an excavation looking for plant and animal fossils. Students choose how to excavate (using a hammer, pick, or brush) as well as where to excavate (selecting a location on a virtual grid.) Over 200 fossils are available for excavation, including fern leaves, dinosaur bones, and shark teeth. Once students identify a fossil, they can identify it by comparing and contrasting it with pictures available in the simulation's "fossil database." Students can use the fossil database to learn more about the environment of different organisms and then construct museum exhibits that represent ancient habitats. While using the simulation, students have access to a virtual notebook, a tape recorder, videos that show how a fossil forms and how paleontologists work, and built-in scaffolding tools including an avatar entitled "Mr. E. Solver." After the 6-week unit, students showed: (a) improved content knowledge, (b) increased use of scientific language, and (c) improvement in cognitive skills, including classification skills and making inferences as measured by a researcher-designed pre/post-test.

Similarly, Dalton and Palincsar (2013; DeFrance, 2008) conducted an experimental study to investigate the effects of learning in one of three versions of a (researcher constructed) digital science text. The three versions featured the same prose and graphics and addressed the topic of how our eyes use light to see (including: the reflection of light, the functioning of the eye, and how we see color). Version 1, the *static* version, offered text-to-speech and embedded vocabulary support. Version 2, the *interactive diagram* version, contained the same supports as the static version; in addition, students could access a *prose/diagram interaction feature* (PDI) that would animate the graphic that corresponded with information presented in the prose; furthermore, students in this condition were directed to use a *diagram manipulation feature* (DM) to explore ideas that were presented in the prose. For example, they could activate the light source and observe how the light traveled from the source to an object, enabling the eye to see the object. Version 3, the *interactive diagram /coaching* version, contained the same features present in Version 2 and was further enhanced with the addition of two animated pedagogical agents, who provided both procedural and conceptual support. The procedural support prompted using the features optimally, while the conceptual support was designed to provide metacognitive information as the agent shared his or her thinking about the information that was presented in the environment. A total of 70 rising fifth-grade participants were assigned to one of three versions described above; the students were yoked based on a norm-referenced measure of reading comprehension and a researcher-designed assessment of subject-matter knowledge, and then randomly assigned to one of the three conditions. This was an experimental study in which a researcher sat with each child and - following a prescribed protocol - monitored the child's activity in the environment. In addition, the students responded to a writing prompt on most screen pages. The students in the interactive conditions (interactive diagram and interactive diagrams + pedagogical agents) significantly outperformed their peers in the static condition, demonstrating the benefit of going beyond providing typical hypertext access supports such as read-aloud functionality and glossary hyperlinks, to providing supports that made explicit the relationship between the prose and diagram and that, furthermore, could be manipulated to reveal relationships and processes conveyed in diagrams. These positive results were consistent for struggling and typically achieving readers, suggesting that flexible supports can benefit students across a range of reading skills.

Using the same environment, DeFrance (2008) compared the effects of the *highlight and animate* feature in the digital text with the use of the *manipulating graphics* feature, and found that, while there were no significant differences by condition in the amount of knowledge gained, there were significant differences in the quality of knowledge expressed. Transcripts revealed that understandings about light and vision, expressed by those who used the Highlight & Animate Feature, were more often conceptually and linguistically 'complete.' That is, their understandings included both a description of phenomena as well as an explanation of underlying scientific principles, which participants articulated using the vocabulary of the text. This kind of careful, systematic, and close study of children's use of these environments will support future development of etext environments and will also refine theory regarding knowledge building in these environments.

Finally, Easley (2020) conducted a case study to explore how third-grade teachers supported their students to engage in scientific sensemaking while using computer-based, multimodal simulations. This work was conducted in the context of *Multiple Literacies in Project-based Learning (ML-PBL)*, a project-based learning curriculum that integrates science, literacy, and mathematics described in greater detail earlier in this report (see the work of Fitzgerald, 2018, 2020).

Participants in this study were two third-grade teachers and their 54 students. Both teachers were experienced: one was in her 20th year of teaching the other was in her 10th. The school was located in a rural district in Michigan. The student population is approximately 60% Caucasian, 25% African American, 5% multiracial, 5% Latinx, and 2% Asian. Approximately 45% of students are low income and approximately 20 % of students have disabilities. Furthermore, the school context is one where students have a high need for high-quality curriculum and powerful instruction, as evidenced by the fact that only one quarter of the school's third-grade students attained proficient performance on state-wide measures of reading.

In this case study, each teacher supported her students to engage with three different simulations, which were designed by PhET (phet.colorado.edu) and the Concord Consortium (concord.org) and integrated into the ML-PBL curricular unit. The simulations introduced the following scientific concepts: balanced and unbalanced forces, friction, and natural selection. The simulations were integrated into curricular units focused on (a) Force and Motion and (b) Plants and Weather. The case study asked how teachers supported students to engage in scientific sensemaking processes while working with online, multimodal simulations, as well as what were teachers' perspectives regarding the utility of the simulations as learning tools.

Results indicated that teachers supported students' scientific sensemaking in multiple ways, which included: (a) engaging in careful pre-planning before teaching with the simulations, (b) prompting students to discuss observations, make predictions, and support predictions while using the simulation, (c) supporting students to plan and conduct investigations using the simulations and to use the results of these investigations to formulate scientific claims, (d) supporting students to interpret complex visual features of simulation representations, (e) supporting student understanding of key scientific concepts presented in the simulations, (f) revoicing and extending student sensemaking, and (g) publicly recording students' learning. Furthermore, despite some challenges using the simulations (including problems with hardware and internet access), teachers overall felt that the simulations provided valuable learning experiences that both engaged students and provided new kinds of opportunities to engage in scientific sensemaking.

Table 8

Summary of Interventions Supporting Students' Creating and Learning From Multiple Representations

Benefits to students representing their learning using multiple modalities	**Studies**
Support students to engage in accurate observation	Fox & Lee (2013)
Support students to retain more scientific knowledge	Samarapungavan et al. (2017)

Support students to communicate their scientific knowledge including types of detail students might not share in writing	Wilson & Bradbury (2016)
Types of modalities that can be beneficial in science curricula	
Videos	Wilson & Bradbury (2016)
Photographs	Wilson & Bradbury (2016)
Texts	Wilson & Bradbury (2016)
Live specimens	Wilson & Bradbury (2016)
Simulations	Henderson, Klemes, & Eshet (2000) Easley (2020)
Digital texts with supportive features	Dalton & Palincsar (2013) DeFrance (2008)

Science and Literacy in Out-of-School Contexts

In the next section, we explore empirical studies that have examined the integration of science and literacy in out-of-school contexts. This research has been conducted with children in early childhood or primary grades and has been conducted in a number of locations, including museums, family-based workshops, nature preserves, and homes. What these studies have in common are findings that family-based experiences may play a key role in simultaneously supporting the development of students' scientific sensemaking and key literacy practices. The majority of the studies considered below examine family support for children's development of scientific sensemaking through oral language, although some additionally contain support for other literacy practices (e.g. reading). This emphasis on oral language makes sense, given both the age of the participants in these studies and the informal nature of the spaces studied. This section begins by considering studies that examine the support of science-literacy integration in informal environments such as museums and outdoor spaces

Supporting Science-Literacy Integration in Public Museums, Outdoor Spaces, and Other Informal Learning Environments

Callanan and colleagues (2017) explored the relationship between parental talk and children's engagement with the *Mammoth Discovery* exhibit at the Children's Discovery Museum in San Jose, CA, and made a surprising discovery regarding the potential unintended consequences of researcher-designed interventions supporting families scientific talk. Children in this study ranged from 3 - 11 years old. Participants in this study were diverse with respect to ethnicity, levels of parental schooling, and family home language. When asked to self-disclose ethnicity, 35% of participants identified as White, 21% as Asian, 18% as South Asian, 12% as Hispanic or

Latino, and 12% as mixed heritage. Parental education ranged from 12 to 24 years. Participants reported 19 languages other than English that were spoken at home. In this study, participants both (a) participated in a researcher-designed intervention intended to scaffold parental support of children's sensemaking talk and (b) engaged with the museum exhibit; half the participants began at the intervention and the other half began at the exhibit. All talk was filmed and transcribed, with talk that occurred in languages other than English being translated into English. Talk was then coded into mutually-exclusive categories focused on scientific sensemaking. In this study, researchers found that parents in both conditions engaged in roughly the same amount of talk that supported sensemaking; furthermore, this sensemaking-supportive talk on the part of parents was a consistent predictor of children's engaged conceptual talk. Nevertheless, researchers further encountered the somewhat unexpected result that parents who began with the researcher-designed activity engaged in fewer types of sensemaking talk while visiting the exhibit, as compared to parents who were not "primed" prior to their exhibit visit. The researchers concluded that caution was warranted when designing interventions to support family oral language in informal science learning spaces, as well-intentioned interventions might have "unintended effects." In this case, the unintended consequence was that parents who were primed with specific strategies for supporting oral sensemaking subsequently drew from a more restricted repertoire of sensemaking strategies, which was contrary to the intention of the intervention.

However, in other studies, researchers have found benefits to programs designed to support parents' use of language when discussing science with their children. In a quasi-experimental study conducted at the Phipps Conservatory and Botanical Garden, in Pittsburgh, PA, researchers examined the impact of providing conversational strategy training to parents. Participants were 79 parent-child pairs including 68 mothers and 11 fathers. Ninety percent of participants identified as Caucasian, 6% as Asian, and 4% as African American. Ninety-two percent of parents had a college degree and 71% reported that their families visited museums at least four times a year. In this study, half the parents were trained in conversational strategies, while the other half used their natural conversational styles. Even after controlling for parent's initial knowledge about pollination, researchers found that parental conversational training had a positive association with higher levels of disciplinary talk between parents and children. In turn, the levels of disciplinary talk predicted how much children learned from the experience, as measured by a pre/post-test (Eberbach & Crowley, 2017).

Similarly, Luce, Goldman, and Vea (2016) identified benefits to resources that support family members to engage in scientific sensemaking as active, playful, co-generative exploration. The *Anytime Anywhere* resources support families to (a) locate scientific phenomena in outdoor settings, (b) provide cues for playful sensemaking activities, and (c) provide conversation starters for sensemaking-rich discussion. Three families field-tested these resources at a coastal beach. The families were all middle class and had children between two and nine. The families had diverse heritage including Cuba, Brazil, Europe, and Mexico. Analysis of videos of the field testing and of participant interviews showed that the families engaged in three features of scientific sensemaking while engaging with the *Anytime Anywhere* resources. These were: (a) eliciting ideas and mechanistic processes, (b) formulating ideas, and (c) testing hypotheses using experimentation. These features of sensemaking emerged both in response to specific prompts in the *Anytime Anywhere* resources as well as spontaneously. Based on the field test, researchers proposed three design recommendations: (a) support the exploration of specific phenomena from localized contexts, instead of the exploration of more generalized, abstract principles, (b) support exploration of phenomena where "nobody knows the answer," and (c) support the exploration of phenomena that is likely to generate multiple competing ideas for discussion.

An additional strand of research into literacy-science integration in informal settings points to the importance of recognizing different ways that parents may support their children in explanatory science talk in informal learning spaces, including both museums and homes. A study conducted by Tenenbaum and Callahan in 2008 explored sensemaking talk designed to support the formation of scientific explanations, with the specific intent of examining how this talk varied within families of Mexican descent living in the United States, as a function of parental education. Children in this study ranged from 2 years 10 months to 8 years 6 months, with a mean age of 5 years 7 months. Researchers divided participants into a basic schooling group, wherein participants ranged from having completed Grade 3 through Grade 11, and a higher schooling group, wherein participants had completed high school or college. All participants both visited the Children's Discovery Museum in San Jose and engaged in two home-based science tasks (one related to sinking and floating, the other involving watching a video of objects that underwent some form of change.) Regardless of education levels, all parents engaged in scientific sensemaking talk with their children. However, parents with higher levels of education were more likely to engage in specific types of sensemaking talk that are often valued at school, for example, causal explanations. The difference in talk between parents, as a function of educational level, was more notable in the museum than in the home-based activities. Researchers concluded that more research is needed regarding the wide variety of sensemaking talk that may occur between families and children in informal learning spaces.

In a similar vein, Marin and Bang (2018) worked with the American Indian Center of Chicago to document ways that indigenous families use oral language while walking through natural preserves. In one case study, they focused on a mother and her 6-year-old son, both of whom were associated with the American Indian Center of Chicago. They found that the mother apprenticed her son into "walking, reading, and storying land" (p. 89) through oral language practices that (a) coordinated joint attention, (b) generated explanations, and (c) created a story about what was observed. These nature walks developed oral language skills and scientific sensemaking in ways consistent with family and cultural practices and values, including placing leadership of both the conversation and the walk itself, into the hands of the child. The oral language literacy practice of storytelling also played a key role in the family-based robotics workshops, TechTales, developed by learning scientists, informal science educators, librarians, and staff members from Native American-serving organizations. A multiple-case study, focused on two families, found that when families engaged in storywork while creating dioramas, both robotics and computer programming became dynamic tools that supported collaborative work that honored and centered Indigenous knowledge systems and cultural practices. The two families in this case study were Seneca-Cayuga and Lakota-Paiute, with children who were 7, 10, and 13 years old (Tzou et al., 2019).

Supporting Literacy-Science Integration Through Home-School Collaboration

Other research has documented positive effects of home-school collaboration that specifically targets literacy-science integration. In the following section, we discuss two research programs that address the creation of resources designed for students to explore with their family at home. While the content of these take home materials differs between the interventions, both found positive benefits to the increased family involvement with both science and literacy.

The research project *Science: Parents, Activities, and Literature (Science PALS)* is the result of a partnership between the University of Iowa and the Iowa City Community School District, centered around the latter's commitment to restructuring their K-6 science program (Shymansky, Yore, & Hand, 2000). As part of this initiative, *Science PALS* had the goal of increasing parental involvement in a first-grade and second-grade hands-on science program. To this end, the first- and second-grade teachers created a take-home activity bag to correspond with each curricular unit in their hands-on science program. These activity packs are designed to complement and extend the learning opportunities provided by the school-based science program, while simultaneously offering parents the opportunity to become more involved with their child's education. Each pack included (a) a science-related children's book for parents and children to read together, (b) materials and instructions for hands-on activities that are related to science concepts introduced in the children's science book, and (c) discussion prompts to serve as a scaffold for scientific conversations between parents and children. In this way, the activity bag supports parents to leverage both reading and oral language in the context of scientific sensemaking. These take home activities bags were positively received by students, teachers, and parents alike. Parents became more involved in their children's science and literacy learning; furthermore, parents considered this increased involvement to be a positive experience. Teachers reported that this increased parental involvement supported students' learning. Children, in turn, shared positive responses to the opportunity to engage in science with their parents at home. Researchers concluded that the *Science PALS* Project demonstrates the potential for time-efficient and meaningful take-home activities to bolster parental involvement in children's science education (Note: this study did not provide information on participant demographics).

NURTURES (http://nurtures.utoledo.edu/index.html), an ongoing collaboration between the University of Toledo and Northwest Ohio and Southeast Michigan public schools, preschools, and community resources, is dedicated to the development of high-quality professional development, classroom extension activities, and family learning opportunities. In this section of our report, we focus on the strands of nurture associated with family learning opportunities. In a recent study conducted in the context of the NURTURES project, Strickler-Eppard et al. (2019) investigated how families engaged in science inquiry at home through participating in structured activities supported by inquiry packs. Participants included five families (three White families, two African American families), each made up of at least one adult and two or three children. At least one child in each family was within the target age range of 4-8 years old. Twenty science activity packs were designed to: (a) align to NGSS standards and to support use of science and engineering practices, (b) include probing questions to support discussion, constructing explanations, and using evidence to justify reasoning; (c) provide journal sheets for families to record their thinking, and (d) include talk moves to support adult participants to facilitate collaborative interaction (e.g., re-voicing, restating, agree/disagree, prompting, explain your thinking, wait time). Strickler-Eppard et al. (2019) were interested in whether and how the activity packs would support engagement and inquiry related to science and engineering practices and family member discourse. Drawing upon multiple data sources (e.g., demographic surveys, videos of activities in homes, phone interviews, family packs, and observational field notes), they found that the directions in the activity packs supported families to engage in science and engineering practices, such as asking questions and constructing explanations. They also found that talk moves that were embedded in the family packs were used 55% of the time: use of wait time and re-voicing children's contributions occurred most frequently across families. Strickler-Eppard et al. (2019) also found that families added their own questions and talk moves beyond those provided in the activity pack directions. Overall, the adult questions and talk moves supported discourse focused on the featured science concepts as well as participation in science and engineering practices.

Table 9

Summary of Science and Literacy in Out-of-School Contexts

Public museums, outdoor spaces, and other informal learning environments	**Studies**
Supporting parental talk can support children's learning and scientific sensemaking	Eberbach & Crowley (2017) Luce, Goldman, & Vea (2016)
However, supporting parental talk can also artificially limit family discourse around science	Callanan et al. (2017)
Family sensemaking talk may draw from cultural practices and traditions, may be influenced by parental education, and may encompass a wider variety of conversational strategies than those typically valued in school settings	Tenenbaum & Callahan (2008)
Researchers, community members, and educators can work together to structure family-based learning opportunities that incorporate and honor cultural practices	Tzou et al. (2019)
Home-school collaboration	
Home activity packs may include: science books, science investigations, prompts to support discussion, and prompts to support shared writing	Strickler-Eppard et al. (2019) Shymansky, Yore, & Hand (2000)

Benefits to home activity packs to support science literacy integration may include: increased parental involvement, increased student learning, and family uptake of and discussion of science practices	Strickler-Eppard et al. (2019) Shymansky, Yore, & Hand (2000)
Home activity packs have been received positively by families, students, and teachers	Strickler-Eppard et al. (2019) Shymansky, Yore, & Hand (2000)

Approaches to Integration that are Designed to Support English Learners

Lee, Quinn, and Valdés (2013) provide a compelling argument that NGSS calls for discourse-rich classrooms if the science and engineering standards are to be met, leading to richer language learning environments of all students. They further propose that when students, especially English language learners, are adequately supported to "do" specific things with language, both science learning and language learning are advanced. In this section, we explore research that investigates this hypothesis and examines supports for advancing the learning of Emergent bilingual speakers.

Lee and colleagues conducted multiple studies in the context of a five-year professional development intervention focused on improving the science and literacy achievement of English learners in the upper-elementary grades (e.g., Lee, Maerten-Rivera, et al., 2008; Lee, Mahotiere, et al., 2009). In one study, Lee, Maerten-Rivera, et al. (2008) examined third-grade students' science achievement following the first year of the professional development intervention, which included teacher workshops and curriculum units. The curriculum units have been a part of Lee and colleagues' ongoing research since 1995 and have been iteratively designed to: (a) support standards-based, inquiry-oriented science learning, (b) consider students' linguistic and cultural experiences related to science learning to support English learners, and (c) include instructional activities and practices to foster students' literacy skills, enlisting tools of reading, writing, and oral language to support students' development of conceptual understanding. To illustrate, literacy activities integrated in the units included narrative vignettes to activate students' prior knowledge, opportunities for students to record data and report findings using multiple modes of representation (e.g., data tables, writing, drawings, graphs), strategies to support informational text comprehension, opportunities for students to communicate using a variety of language functions (e.g., describe, explain), and trade books along with other literacy-focused activities related to the science concepts students investigated. Finally, in addition to supporting general literacy development, the units also emphasize instructional practices to address the needs of English learners: (a) beginning lessons by introducing key vocabulary, (b) providing opportunities for students to use key vocabulary in multiple contexts, and (c) providing explicit instruction to support students to describe and explain phenomena precisely (e.g., positional words such as above, below; comparative terms, such as cold, coldest; affixes, such as *in* for increase).

Elementary schools in a large urban school district in the southeast United States were required to meet a variety of criteria to participate in the intervention, including that the percentage of students qualified for FRL and the percentage of English learners (who were primarily Haitian Creole or Spanish-speaking) were above the district average. Participants included approximately 1,000 students across seven treatment schools and approximately 1,000 students across eight control schools. Sixty percent of students in the district were Hispanic, 28% were Black, 10% were White, and 2% were Asian or Native American. More than 70% of students in the district qualified for FRL and almost 25% were identified as limited English proficient.

Lee, Maerten-Rivera, et al. (2008) found that students who attended the treatment schools demonstrated statistically significant increases in science achievement. In addition, there were no statistically significant differences in achievement gains among students of different language status (i.e., ESOL, exited from ESOL, never been in ESOL) or students who had been retained based on their state reading test scores. The results of this study indicate that the professional development intervention supported third-grade English learners to both perform well on high-stakes assessments and to think and reason scientifically.

In another study conducted in the context of the multi-year professional development intervention aimed at improving the science and literacy achievement of ELs, Lee, Mahotiere, et al. (2009) investigated third-grade EL's expository science writing achievement across 3 years. Specifically, they asked whether students demonstrated achievement gains in science writing and whether achievement differences between students at different levels of English proficiency changed from pretest to posttest. Participants included all third-grade treatment teachers and their students from the first 3 years of the professional development intervention research project. Lee et al. used student writing samples both as measures of students' ability to explain science concepts through writing and English proficiency. Students completed the following expository writing prompt at the beginning and end of each school year, focused on the water cycle: *Pretend you are a drop of water. Before you begin writing, think about how water changes form in the water cycle. Now explain to the reader how you are changed as you got through the water cycle.* The prompt was appropriate for this study because this topic of the water cycle was related to the three curriculum units for third grade (i.e., measurement, states of matter, and water cycle and weather). Lee et al. assessed student writing through two rubrics. The first rubric was designed to assess specific features of writing, such as style/voice, conventions, and organization (form). The second rubric was designed to assess students' knowledge of the water cycle as represented in the curriculum (content). Lee, Mahotiere, et al. found that students made significant achievement gains each of the 3 years. While the writing scores of students in the ESOL program were lower than those of students who had exited or never been in the ESOL program, ESOL students made comparable achievement gains, indicating positive results for students across levels of language proficiency. In addition, the gains students made were incrementally higher for writing form (style/voice, conventions, organization) across each of the 3 years, which suggest that either the teachers who participated in the second and third years of the intervention improved their instructional practices or the professional development intervention improved across the 3 years; however, there was no significant effect of year for writing content (students' knowledge of the water cycle).

As part of the *Seeds of Science/Roots of Reading* program of research (described in the science and literacy integration section), Bravo and Cervetti (2014) examined the efficacy of an instructional model that focused on the science, literacy, and language learning needs of English learners. All ten participating fourth- and fifth-grade teachers were experienced teachers of English learners (i.e., had at least 3 years of experience and were certified to work with ELs) and at least 25% of students in their classrooms were English learners. In this quasi-experimental study, treatment teachers taught a 40-lesson space science instructional unit that attended to reading, writing, and oral language. Across lessons, students learned important space science concepts, constructed explanations using first-hand evidence from investigations and second-hand evidence from text, used and critiqued science models, developed academic language and vocabulary, learned and applied reading comprehension strategies and skills for engaging in science inquiry. Bravo and Cervetti found that English learners in the integrated condition (treatment) outperformed the comparison group on measures of science understanding and science vocabulary; however, differences in science reading were not statistically significant.

In an experimental study of teachers' use of the *Seeds of Science/Roots of Reading* curriculum, Cervetti, Kulikowich, and Bravo (2015) examined the impact of educative curriculum features designed to support teachers' use of instructional strategies for English learners in Grades 4 and 5. While both treatment and control teachers taught the same integrated science and literacy curriculum, treatment teachers had access to additional educative curriculum materials (e.g., explanations of how to address potential linguistic challenges and suggestions for leveraging EL's unique language resources). Cervetti et al. were particularly interested in teachers' use of the strategies featured in educative materials, teachers' pedagogical knowledge for teaching English learners, and ELs' science and vocabulary learning. They found that the treatment teachers who had access to the educative curriculum features used more strategies to support ELs in the classroom, used a broader range of strategies to support ELs, and learned more new strategies than comparison teachers. Regarding student outcomes, Cervetti et al. found that all classrooms (both treatment and control) demonstrated significant, positive growth on science and vocabulary measures for both ELs and non-ELs, but found no differences between treatment and comparison groups in science or vocabulary learning. While the presence of educative features did not significantly affect student learning, correlation analysis demonstrated a close association between teachers' strategy use and science learning for ELs in the treatment group. These findings suggest potential for use of educative curriculum features to support both teacher learning and the science learning of English learners.

Translanguaging Practices in Elementary Science Classrooms

In recent years, a number of researchers have argued for bringing a translanguaging perspective to science teaching. From this perspective, language use and learning are positioned as socially mediated sensemaking processes, creating opportunities for students to leverage their familiar, everyday communication practices and to question and develop a critical awareness of standard forms of language, such as the language of science. In one example of work in this area, Stevenson (2013) conducted a descriptive study to examine how fifth-grade Latino/a, bilingual students used their linguistic resources during school-based science learning. Participants included fifteen fifth-grade students and their teacher in a transitional/sheltered classroom from a school in the southwestern United States. The school was selected because of the diversity of the student population and surrounding community, with respect to socioeconomic and linguistic status. The area in which the school is located is economically depressed and students identify primarily as Latina/o (99% of students) and bilingual (82.5% of students identified as English learners).

English was the language of instruction in science and was supported by informal peer communication in Spanish. Findings indicated that students made strategic language choices based on their conversation partners and the instructional context (i.e., teacher lecture, lab). With the teacher, they mostly leveraged their English linguistic resources, while occasionally adding in Spanish. However, when interacting with their peers to make sense of science activities and concepts, students primarily used Spanish and did so for a variety of purposes, including: (a) seeking clarification regarding concepts, materials, and instructional interactions; (b) organizing activities; (c) communicating with other students to share knowledge and complete tasks; and (d) making connections to personal experiences. Stevenson (2013) found that, when conveying understanding informally with peers, students were more likely to draw on their bilingual linguistic resources. However, when students were asked to formally write or orally share their results or conclusions, they communicated their learning in English.

In a related study focused on the fifth-grade students' language preferences, Stevenson (2015) examined how students' self-perception of being bilingual affected their linguistic choices in the science classroom and how the instructional context affected both student and teacher performance. Using multiple data sources (e.g., transcripts of student interactions, written work samples, and interviews), Stevenson found that bilingual students purposefully adapted their linguistic resources as they participated in science learning. Group interviews with students revealed that students preferred speaking Spanish to communicate with their peers but were also aware that learning English was important for their academic success and future opportunities. Students reported that they preferred speaking Spanish with their peers during science learning because they: (a) felt more comfortable communicating ideas and constructing science explanations using Spanish, (b) felt a sense of commitment to family and community, and (c) were embarrassed to speak English with their peers due to concerns their peers might react negatively. Based on the findings of these studies, Stevenson (2013, 2015) advocates for science instruction for bilingual students that explicitly acknowledges, supports, and incorporates Spanish and English linguistic resources to optimize student participation and to facilitate understanding.

In another investigation of elementary-grade students' language practices, Poza (2018) used data from recordings of students' interactions and ethnographic observations of fifth graders in a bilingual education program. Specifically, Poza examined language practices students used during science learning and how translanguaging perspectives informed teacher practice. Students attended a K-5 school in the San Francisco Bay Area, in which almost 75% of students were Latino/a and 63% of students qualified for FRL. The participants included fifth graders in two classes (18 students per class) and their teacher who led science instruction. Findings indicated extensive collaboration, allowing students to use their full bilingual repertoires, exposing students to target language varieties, and providing authentic experiences in a bilingual science classroom that supported students to learn both new linguistic forms and new science content. The fifth graders in this study used translanguaging practices (using Spanish and English across text and speech), to learn technical vocabulary and to engage in meaning making with complex, multimodal texts. The teacher supported this work by creating assignments that engaged students in reading and interpreting text and other media across multiple modalities and languages, by fostering a collaborative learning environment, and by using flexible bilingual practices himself. Based on these findings, Poza argues for a translanguaging approach to instruction, in which language and language learning are positioned as social meaning-making processes in order to support students to leverage familiar communication practices and develop a critical awareness of taught discourses, such as the language of science.

Finally, in the context of a design-based research project, Suárez (2020) examined the language practices of bilingual students in the elementary grades as they investigated electrical phenomena in an out-of-school science learning program. The program was a partnership between the author and the public library system, with the goal of providing opportunities for students to ask questions and investigate phenomena related to electrical energy. The iteratively designed program included eight sessions, which were approximately 60 minutes each. Across the eight sessions, students investigated: (a) electrical flow through a circuit, (b) properties of resistors and conductors, and (c) how conductors' geometry affects electrical resistance. The program was offered at library branches that served immigrant families. Participants in the program included 10 emergent bilingual students in Grades 1-5, four of whom attended regularly and consented to participate in the research project.

Using qualitative methods, Suárez closely analyzed students' construction of models and their interactions with one another and the instructor to understand how students leveraged semiotic resources to describe or explain phenomena and whether and how the instructor's interactions with students created a space for translanguaging. Findings indicated that students engaged in a variety of translanguaging practices as they investigated electrical phenomena and co-constructed knowledge with one another. Students drew upon a variety of both linguistic and non-linguistic semiotic resources to communicate their models. For example, all students used non-linguistic resources (i.e., gesturing) when communicating their ideas with one another. While some students used multiple linguistic resources, such as sharing resources associated with both Spanish and English, other students only shared linguistic resources associated with English. Findings also indicated that the instructor's own translanguaging practices signaled when and how students should participate in translanguaging practices. To illustrate, analyses of student and instructor talk revealed that students followed the linguistic expectations set by the instructor throughout the sessions (e.g., as soon as the instructor drew upon Spanish or English linguistic resources, students followed suit). Suárez argues that equitable science instruction must provide opportunities for emergent bilingual students to draw upon their full suite of semiotic resources to support meaning-making in science.

Table 10

Summary of approaches to Integration that are Designed to Support English Learners, including translanguaging

Techniques for supporting ELLs	**Studies**
Activate students prior knowledge (e.g., using narrative vignettes)	Lee, Maerten-Rivera, et al. (2008)
Provide opportunities for students to engage in first-hand investigation	Bravo & Cervetti (2014)
Introduce key vocabulary and provide multiple opportunities for students to use key vocabulary	Lee, Maerten-Rivera, et al. (2008) Bravo & Cervetti (2014)
Provide opportunities for students to use multiple modes of representation to record data and communicate findings (e.g., data tables, writing, drawings, graphs)	Lee, Maerten-Rivera, et al. (2008) Bravo & Cervetti (2014)
Provide opportunities to read informational text and teach comprehension strategies	Lee, Maerten-Rivera, et al. (2008) Bravo & Cervetti (2014)
Provide a wide variety of opportunities for oral language use (e. g. describing, explaining)	Lee, Maerten-Rivera, et al. (2008)
Provide explicit instruction to support students describing and explaining phenomena precisely (e. g. positional words, comparisons, affixes	Lee, Maerten-Rivera, et al. (2008)
Support students to engage in trans-languaging	Stevenson (2013, 2015) Poza (2018) Suárez (2020)
Benefits to intentionally designing instruction to support ELLs	
Increases in ELL science achievement	Lee, Maerten-Rivera, et al. (2008)

Increases in ELL writing achievement	Lee, Mahotiere, et al. (2009)
Potential for use of educative curriculum features to support both teacher learning and the science learning of English learners.	Cervetti, Kulikowich, & Bravo (2015)

Research on Professional Learning Opportunities that Support Integration

Professional learning opportunities and curriculum supports that help teachers integrate ELA and science are less well-developed areas of inquiry than research focused on examining student outcomes of approaches to integrating science and literacy in elementary classrooms. While some research in this area has focused on investigating the effects of professional learning opportunities on teachers' science knowledge, instructional practices, and beliefs, other research has focused on the design and teachers' use of educative curriculum supports. We begin by describing a set of studies that focused on the design and enactment of professional development interventions that integrated the teaching of science and literacy. We then turn to synthesizing research focused on educative curriculum supports related to integrating science and literacy in the elementary grades.

Hart and Lee (2003) investigated the impact of a professional development (PD) intervention on teacher's beliefs and practices. The PD was designed to support third- and fourth-grade teachers to promote science and literacy achievement among culturally and linguistically diverse students, across six elementary schools in a large urban district in the Southeast United States, through the development of curricular materials and aligned teacher workshops. The instructional units are designed to support investigation-based science teaching and to foster English learner's science learning, in particular, by considering students' linguistic and cultural experiences related to science. In addition, the units included activities and instructional practices designed to foster students' literacy development specific to reading, writing, and providing linguistic scaffolds (e.g., explicit vocabulary instruction and use in a variety of contexts) to support students to understand science concepts (see the previous section in this report that describes approaches particularly supportive of English learners for a fuller description of the curriculum).

Teachers participated in three grade-level specific day-long workshops and one mixed-grade day-long workshop throughout the school year that focused on engaging students in inquiry and integrating literacy and English language learning into science instruction. The workshops were designed to support teachers to build experience implementing the instructional activities and practices addressed in the units. Workshop activities were designed to promote active involvement, asking questions and giving feedback, and reflecting on personal beliefs and practices.

The second day of the workshop focused exclusively on the integration of English language and literacy into the units. On this day, project personnel shared relevant trade books and discussed strategies with teachers for fostering students' reading and writing development (e.g., whole- and small-group reading activities, writing narrative and expository text related to science instruction). In addition to discussing supports for reading and writing, teachers and project personnel discussed how to provide linguistic scaffolding for English learners and integrate multiple modes of communication (i.e., written, graphic, verbal, gestural) to support students' science understanding. In addition to collaborative discussions among project personnel and teachers, teachers who had participated in an earlier research project shared a variety of literacy activities they developed and used in their science instruction. These workshop activities culminated in teachers working in small groups to examine lessons from one of the units of instruction to identify ways to integrate literacy activities and provide linguistic scaffolding, while also making lesson activities more student centered and inquiry based. Small groups of teachers shared, demonstrated, and discussed the literacy activities and linguistic scaffolding strategies they planned with the whole group.

Hart and Lee (2003) examined the teachers' initial practices and beliefs related to teaching English language and literacy in science, as well as the impact of the professional development intervention on teachers' practices and beliefs. Prior to the professional development intervention, the amount and type of science instruction teachers enacted varied widely. Some teachers used science texts to guide instruction, while others taught very little science at all, reporting lack of knowledge about science, dislike for science, or the pressure to emphasize ELA and mathematics instruction as contributors. Hart and Lee found that, at the end of the year, teachers demonstrated more coherent and elaborate conceptions of both literacy and science instruction. Specifically, following the first year of participation, teachers emphasized the importance of using tools of reading and writing in science instruction. Teachers also provided more effective linguistic scaffolding to support students to understand science concepts. Based on the study's findings, Hart and Lee argue that teachers need ongoing support to implement and sustain reform-oriented instructional practices that promote literacy and science achievement among students who are culturally and linguistically diverse.

Further, in an end-of-year questionnaire following the first year of implementation, teachers reported that the professional development intervention (i.e., curriculum materials and teacher workshops) was effective in promoting students' science learning. Teachers also identified strengths of the intervention, including the provision of: (a) all needed supplies to implement the curriculum, (b) opportunities for students to work with various tools, (c) teacher guides that supported teaching with multiple representational forms (e.g., graphs, tables, charts, and pictures), and (d) student booklets in curriculum materials (Lee, Maerten-Rivera, et al., 2008). In another study, Lee and Maerten-Rivera (2012) investigated changes in teachers' instructional practices and science knowledge as they participated in a later iteration of the professional development intervention. Based on teacher questionnaires and classroom observations, the authors found that upper-elementary grade teachers' knowledge and instructional practices for teaching science with English learners' improved throughout the intervention, with the most growth documented during year one of the three year study. In addition, teacher growth was most pronounced at the fifth grade level, where students' science outcomes counted toward accountability measures.

Despite growth, Lee and Maerten-Rivera (2012) reported that teachers' knowledge and instructional practices typically did not meet goals of reform-oriented instruction. For example, while teachers typically followed the curriculum, the inclusion of scientific inquiry practices often received low ratings on classroom observations. Even though teachers included hands-on activities from the curriculum, they often followed routine procedures as opposed to meaningfully engaging students in science practices. The results of this study illustrate that professional development, in the form of teacher workshops and curriculum materials, can lead to positive changes in both teacher knowledge and classroom instructional practices for teaching science to English learners. However, Lee and Maerten Rivera identified a need for the focus of teacher professional development to shift from “following the curriculum” to focusing more explicitly on changing teachers’ instructional practices and views to support student reasoning.

In an earlier section, we described the instructional features and learning outcomes of NURTURES (http://nurtures.utoledo.edu/index.html). In this section, we focus on the strands of NURTURES related to professional development. This includes: (a) 2 weeks of summer professional development for pre-K-Grade 3 teachers and (b) ongoing professional development during the academic year that includes both monthly professional learning community meetings and individualized coaching sessions. A quasi-experimental study (Paprzycki et al., 2017) examined the impact of teacher’s participation in NURTURES professional development. Participants in this study attended elementary schools in a large, racially diverse urban school district in the Midwest where 64.8% of students qualified for FRL. Researchers found a significant association between whether a teacher had participated in the NURTURES professional development and their students’ scores on math and reading standardized tests. A hierarchical linear model was used to compare learning outcomes from treatment and control classrooms. This model showed that 1 year spent in a classroom where the teacher had received NURTURES PD was associated with the following increases in standardized test scores: 8.6 points for the STAR Early Literacy score, 17 for the STAR Math score, and 41.4 for the STAR Reading score. Researchers concluded that when teachers were supported in “the contextualized teaching of literacy, reading, and mathematics,” the results were supportive of student learning across multiple curricular areas.

Shymansky et al. (2013) conducted a quasi-experimental study on a professional development project - *Adapting Science Inquiry Lessons (ASIL)* - that was designed to support multiple school districts to integrate science and English language arts in elementary classrooms. Participants included K-6 teachers in small, rural districts across two midwestern states. The format of the professional development included intensive summer workshops as well as ongoing mentoring and support from the local leadership team and distance support from other teachers, invited scientists, and project staff via interactive television technology throughout the school year. Shymansky et al. reported that by the end of the project, 46% of over 1,000 teachers involved with the project participated in more than 129 hours of PD. During PD sessions, participants had multiple opportunities to both experience inquiry-oriented science and learn to integrate literacy into science instruction. Teachers worked in small groups to adapt science kits (e.g., *Science & Technology for Children* [STC], *Full Option Science System* [FOSS], *Insights*) to integrate reading and writing, building portfolios of adapted lesson plans focused on selected science topics. Notably, in addition to workshops focused on supporting teachers to engage in and adapt kits, teachers had access to PD consultants, science content experts, and practicing scientists to support their work adapting science kits as well as their content knowledge and pedagogical content knowledge.

Another important feature of the ASIL professional development program was the role of district leadership teams. Across the PD, experts from outside the district gradually transferred responsibilities related to the PD to teacher and administrator leadership teams within the districts over time. The ASIL project included an explicit focus on building leadership capacity to sustainably support the ongoing work of integrating science and ELA in K-6 classrooms. Results of the multi-year study indicated that the 33 school districts that participated in the professional development program outperformed comparison school districts on high-stakes science assessment scores in both Grades 3 and 6. In addition, analyses of classroom observations, teacher interviews, and teacher resource books (among other data sources) indicated that project teachers reported that their experience in the PD program positively influenced their professional growth, pedagogical content knowledge, and classroom practices.

In another, small scale approach to supporting professional learning focused on science and literacy integration, Fazio and Gallagher (2019) used design-based research methods to examine a collaborative professional learning group of 5 fifth-grade teachers from two elementary schools in southern Canadian school districts that integrated language and literacy in their science instruction. The teachers and researchers collaborated to integrate first-hand science activities, multimodal texts, and language skills into a science unit focused on properties and changes in matter. Their collaboration focused on co-planning the integrated science unit to include print and digital science text resources to meet the needs of each teacher's classroom and to identify: (a) learning goals, (b) instructional activities, (c) instructional resources, and (d) assessment strategies. To support this work, the researchers and teachers referenced practitioner articles focused on integrating science and literacy. Some of the teachers who had easy access to one-to-one student technology also added technology enhancements to the unit. Fazio and Gallagher found that the five teachers varied in their enactments. For example, some of the teachers adapted the unit to include more first-hand science experiences, more digital multimodal text resources (e.g., digital simulations), and more opportunities for students to communicate using multiple modes of representation. Teachers' levels of confidence in both teaching science and literacy appeared to support more effective integration, whereas lower confidence in science or literacy teaching appeared to negatively affect integration. Based on this finding, Fazio and Gallagher call for professional learning that differentiates support for teachers based on their particular areas of need.

Table 11

Summary of Research on Professional Learning Opportunities that Support Integration

Features of professional learning opportunities	**Studies**
Opportunities for teachers to practice implementing instructional activities and pedagogical strategies.	Hart & Lee (2003)

Opportunities for teachers to ask questions, give feedback, and reflect on personal beliefs and practices	Hart & Lee (2003)
Different types of support provided throughout the year (e.g. summer PD, professional learning community meetings, individualized coaching sessions)	Paprzycki et al. (2017)
Ongoing access to PD consultants, science content experts, and practicing scientists	Shymansky et al. (2013)
Gradual transfer of responsibilities related to the PD to teacher and administrator leadership teams within districts.	Shymansky et al. (2013)
Differentiation between different teachers according to their needs	Fazio & Gallagher (2019)
Opportunities for teachers and researchers to collaboratively co-plan curriculum	Fazio & Gallagher (2019)
Gains following professional learning opportunities	
More coherent and elaborate conceptions of both literacy and science instruction on the part of teachers	Hart & Lee (2003)
Improvement in teachers' knowledge and instructional practices for teaching science with English learners	Lee & Maerten-Rivera (2012)
Improvements in students' scores on math, science, and reading standardized tests	Paprzycki et al. (2017) Shymansky et al. (2013)
Teachers self-reporting improvements in professional growth, pedagogical content knowledge, and classroom practices	Shymansky et al. (2013)

Research on Design and Use of Educative Curriculum Supports that Support Integration

Several studies have investigated the design and use of educative curriculum materials to support teachers to integrate ELA and science. Some of these studies have focused specifically on supporting elementary teachers' use of text during science instruction (Arias, Palincsar, & Davis, 2015; Brunner, 2019; Brunner & Abd-El-Khalik, 2020), while others have investigated the design and teachers' use of educative supports as one component of part of broader curriculum interventions (Cervetti, Kulikowich, & Bravo, 2015; Lee, Llosa, et al., 2016). First we describe findings from studies of teachers' use of educative curriculum materials to support teaching with text in science. We then turn to broader investigations of professional learning opportunities or curriculum materials that included educative features.

Arias, Palincsar, and Davis (2015) identified principles that informed the design of educative curricular supports for teaching with text and supporting text-based discussions in science, and reported how elementary teachers used designed supports. The educative features included: (a) providing *learning goals* that outlined the conceptual focus of the reading; (b) *interactive reading guides* that provided a meta-script to support interactive reading, discussion, and integration of the reading within the unit of instruction to support comprehension; (c) *graphic aids* to support teachers' and students' understanding of texts; and (d) *narratives* that describe how fictional teachers chose to support students during reading and discussing, and the rationale for those choices. Arias et al. (2015) used tracing analyses (Duncan & Frymier, 1967) to identify evidence of the educative features in teachers' instruction. They found that the three teachers whose practice they studied implemented suggestions from the educative features with varying frequency. For example, two of the teachers drew regularly on the educative features, while the other demonstrated only modest use. While Arias et al. (2015) found that the teachers' instruction did not regularly result in discussions that would deepen student learning about the topic of ecosystems, the teachers did acknowledge the usefulness of the supports and demonstrated strengths related to using the text to support students' investigations (e.g., helping students use details from the text to support students to make detailed observations, engaging students in considering cause and effect, and discussing plants' needs).

Brunner (2019) (also described in the section entitled, *Interventions that leverage genre, features and content*) investigated eight fourth- and fifth-grade teachers' use of educative curricular features designed to support teaching about the nature of science (NOS) during trade book read-alouds in the elementary grades. In this study, the intervention materials included a set of trade books that were modified to include explicit connections to NOS content, as well as an educative teachers' guide. Each of the modified trade books focused on Earth and space science content, but were not integrated within a larger science unit/the class' regular science instruction. The teachers' guide included an introduction, which was designed to provide background information about NOS and the modified trade book. The introduction included: (a) a content storyline that outlined how the book could be integrated into a larger unit of instruction, (b) a description of the featured aspects of NOS, and (c) a description of connections among NOS, the CCSS for ELA, and NGSS. The educative features designed into the teaching section of the teachers' guide included (in the margins of photos of the trade book pages): (a) NOS content boxes that highlighted NOS content, (b) proposed discussion questions and possible student responses, and (c) a rationale for each discussion question. Brunner examined which of the designed educative features the teachers reported using to prepare for their read-aloud discussions, and found that the teachers varied in their use of the features. Teachers were more likely to use those features that targeted specific teaching moves, embedded within the pages of the teaching guide, which directly supported them to facilitate text discussion (e.g., discussion questions and possible student answers), and less frequently used the features designed to foster teachers' content understanding, standards connections, and the rationale for addressing NOS.

In a related investigation of these educative features, Brunner and Abd-El-Khalick (2020) investigated the impact of the trade books and educative supports on teachers' understandings of NOS and instruction, and teachers' perceptions of the trade books and educative supports. Using questionnaires, three classroom observations, and two teacher interviews per participant, Brunner and Abd-El-Khalick found that, while there was variability across teachers, the teachers developed more informed views of NOS and that teachers addressed NOS more frequently and in more informed ways when they used the modified trade books and educative curriculum features that explicitly supported teachers' knowledge and instruction related to NOS. The researchers call for further development of educative curriculum materials designed to support teachers' use of text in elementary science instruction, as these findings suggest that sustained use of these types of materials (i.e., modified trade books and educative supports) may serve to further deepen teachers' NOS understandings, increase their comfort with this content, and support them to engage in more effective science instruction.

Next, we turn to examinations of educative curriculum materials where the educative features were one component of broader curriculum interventions that support teachers to integrate literacy and science instruction. Cervetti, Kulikowich, and Bravo (2015) investigated curriculum materials designed to support fourth- and fifth-grade teachers to use instructional strategies for English learners as they implemented an integrated science and literacy curriculum. The integrated science and literacy curriculum included step-by-step guides for 40 lessons focused on space science, which included educative supports designed both to address linguistic challenges English learners might encounter in science learning and to leverage the unique linguistic resources English learners bring to science learning.

The educative supports embedded in the teachers' guide included: (a) science background information, (b) instructional suggestions and rationale, and (c) specific instructional strategies for English learners. The comparison teachers received the same curriculum materials but without embedded educative supports, with the exception of highlighting a suggested writing activity associated with each lesson and assessment opportunities. The educative notes in the teachers' guide included a variety of supports, specifically targeting English learners: (a) use of cognates to support Spanish-speaking English learners to access unfamiliar words in English, (b) opportunities for students to talk and writing in their first language to privilege sensemaking over focusing on the conventions of spoken or written English, (c) support for reading comprehension strategies, such as monitoring for comprehension, and (d) explanations about how to address potential linguistic challenges English learners might experience in science learning (e.g., multiple meaning words, such as *claim* or *model*; providing opportunities to rehearse ideas with language partners before participating in whole class discussion).

In this experimental study, Cervetti et al. examined the impact of 15 teachers' use of the strategies, the teachers' pedagogical knowledge for teaching English learners, and English learners' science and vocabulary learning. They found that the treatment teachers who had access to the educative supports used more strategies to support English learners in the classroom, used a broader range of strategies, and learned more new strategies than comparison teachers.

Correlational analysis demonstrated a close association between teachers' use of the strategies and English learners' learning.

Table 12

Summary of Research on Educative Supports that Promote Integration

Educative supports	**Studies**
Learning goals that outline the conceptual focus of the reading	Arias, Palincsar, & Davis (2015)
Interactive reading guides	Arias, Palincsar, & Davis (2015)
Graphic aids to support teachers' and students' understanding of texts	Arias, Palincsar, & Davis (2015)
Narratives that describe how fictional teachers chose to support students during reading and discussing	Arias, Palincsar, & Davis (2015)
Modified trade books that include (a) connections to the nature of science and (b) discussion prompts	Brunner (2019) Brunner & Abd-El-Khalick (2020)
Teachers' guide including: (a) science background information, (b) instructional suggestions and rationale, and (c) specific instructional strategies for English learners	Cervetti, Kulikowich, & Bravo (2015)

Research on Integrating Engineering and Literacy in Elementary Instruction

Engineering can be connected to, or integrated with, English language arts through a variety of disciplinary-oriented opportunities to read, write, speak, listen, view, and represent to interpret and communicate information. In fact, because reading, writing, speaking, listening, viewing, and representing are essential to the engineering design process, engineering and literacy are inherently interconnected. However, because engineering has only recently been added to the curriculum at the elementary level in the United States, the research base is still developing.

We begin with reviews of elementary engineering curricula that are well-developed and, in a few cases, widely adopted. Unlike the integrated science curricula with which we started this paper, it is, thus far, uncommon for researchers to collect measures of both engineering and literacy achievement. However, all of these approaches include literacy integration. The approaches we review include: *Engineering is Elementary*, *Project Lead the Way-Launch*, *City Technology*, *PictureSTEM*, and *EngrTEAMS*.

Engineering is Elementary (EiE)

The most studied engineering program at the elementary level is *Engineering is Elementary*, developed by the Museum of Science in Boston. Spearheaded by Christine Cunningham and Cathy Lachapelle starting in 2003, the program was developed and circulated prior to the release of the NGSS (Cunningham, 2018). While EiE does not fully integrate literacy in the manner of some of the science curricula described earlier in this paper, the program does incorporate literacy practices. All EiE units begin with a story written according to the following design principles: (1) using narratives to develop and motivate students' understanding of the place of engineering in the world; (2) demonstrating how engineering helps people, animals, the environment, or society; and (3) introducing a variety of role models with diverse demographic characteristics (Cunningham et al., 2019). EiE also makes substantial use of engineering journals, for brainstorming, sketching, and sharing ideas.

Recently, Cunningham et al. (2019) explored the impacts of EiE in the first randomized control trial of an elementary engineering curriculum in the United States. Examining 604 classrooms in 152 schools located in North Carolina, Massachusetts, and Maryland, the study included data from over 14,000 students who engaged in four of the 20 EiE units. Results shows that students who participated in EiE outperformed the control group in measures of both engineering and science content learning, regardless of demographic characteristics. The findings have implications for curriculum design, namely: the importance of introducing a context; scaffolding design by utilizing a methodical, systematic process; encouraging student collaboration; and being intentional about supports for the teacher. The implications also highlight the importance of the engineering journals, as students with more complete journals had more positive outcomes.

Over the last decade, a number of smaller-scale studies have also demonstrated positive effects of the EiE curriculum, including: an increase in engagement among Latina kindergarteners

(Aguirre-Muñoz & Pantoya, 2016), an increase in teacher knowledge regarding engineering (Diefes-Dux, 2015), and the support of student discourse in upper elementary (Hertel, Cunningham, & Kelly, 2017).

Project Lead the Way (PLTW) Launch

Project Lead the Way is a series of engineering modules for K-12. While the high school curriculum was released in 1997, the elementary program, *PLTW Launch*, is relatively new, released in the fall of 2014. *PLTW Launch* was designed to incorporate the NGSS and to be taught as stand-alone units. Although PLTW does not break out schools by grade level, they report doubling the number of schools using their curriculum in the past five years, with over 12,000 schools now using their materials (Hess, Sorge, Feldhaus, 2016; Project Lead the Way, n.d.).

Similar to *Engineering is Elementary*, *PLTW Launch* uses custom-written narrative texts to set up each design challenge. Another similarity is the use of engineering notebooks for students to record their thinking and observations as they proceed through the engineering design process. From the research perspective, *PLTW Launch* is similar to EiE regarding a current lack of empirical research on the literacy components of the program. While the literacy components of each program remain understudied, EiE has amassed a body of evidence about its effectiveness with engineering outcomes. The same cannot yet be said about *PLTW Launch*: we could not locate a single empirical article in a peer-reviewed journal reporting student-level outcomes, for any metric, for student participants. For a program that is quickly becoming the *de facto* engineering curriculum for elementary schools in the United States, both because of its widespread adoption and relative lack of competing curricula, this current lack of empirical evidence provides a huge opportunity for future research. In addition to examining engineering or science outcomes, a closer look at the effectiveness of the literacy components of *PLTW Launch* would be beneficial to the field.

City Technology

In many ways, the *City Technology* project was ahead of its time. Wrapping up a half-dozen years before the NGSS were released, this project to introduce engineering at the elementary level was directed by Gary Benenson from the City College of New York, working alongside numerous teachers from New York City Public Schools. The materials they developed for *Force & Motion* and *Energy Systems* (one module of each for K-1 and 2-3, plus two modules of each for 4-5), are still available online (http://www.citytechnology.org/).

The *City Technology* work, while long dormant, is important for two key reasons. First, there has been a consistent call for equity in science and engineering education, to ensure that *all* learners have an opportunity to succeed. However, the number of studies taking a close look at minoritized students, particularly those from low socioeconomic backgrounds, remains small. True to the name of their project, in their lone published empirical piece, Benenson, Stewart-Dawkins, and White (2012) reported promising results in an urban school serving 97% students of color, with 89% eligible for FRL. Second, Benenson (2001) was a strong advocate for researchers co-designing with teachers. The *City Technology* modules were created and studied by the educators who used them Critically, one of those collaborators, Gwynn White, was a

Library Media Specialist. Having a member of the team who was deeply invested in literacy ensured that literacy features were reflected in the curricular units (Benenson, Stewart-Dawkins, & White, 2012).

PictureSTEM

PictureSTEM (http://picturestem.org/) was developed as a collaboration between Purdue University and Iowa State University as an intentional integration of STEM and literacy for Grades K-2. The work is described in a pair of practitioner articles (Tank et al., 2013; Tank, Moore, & Strnat, 2015), and while empirical findings are not reported, this project is currently rare for its focus both on the lower elementary grades as well as the developers' intentional inclusion of reading strategies embedded within an engineering curriculum. The designers created three units, each including six lessons intended to be taught over 10 days: Kindergarten - *Designing Paper Baskets*, Grade 1 - *Designing Hamster Habitats*, and Grade 2 - *Designing Toy Box Organizers*. Each lesson in each unit is paired with a picture book selected for its connection to the day's STEM activity and to reinforce the STEM concepts explored during the lesson. The teacher is provided with a comprehension strategy (e.g., identifying elements of story structure, compare and contrast, questioning, sequencing, and summarizing) to emphasize during the read-aloud. While the authors do not report empirical findings, their work is reminiscent of Varelas et al. (2014) in science education (described earlier in this paper), who found that texts supported hands-on investigations in providing opportunities for student meaning-making.

EngrTEAMS

EngrTEAMS (Engineering to Transform the Education of Analysis, Measurement, & Science), which involved many of the same researchers as the earlier *PictureSTEM* work, was a collaboration between the University of Minnesota's STEM Education Center, Purdue University, and several Minnesota public school districts. The project was a 5-year endeavor to support teachers to create integrated, NGSS-aligned STEM units for the upper elementary and middle school grades (Glancy et al., 2017). Of the 13 units that they developed and piloted, seven were for the elementary level (https://sites.google.com/a/umn.edu/engrteams/curriculum). Although literacy was not a specific goal of their integration efforts, their realistic scenarios, plus the usual work involved in engineering design, meant that their curricular units included literacy practices in much the same ways as EiE and *PLTW Launch*. Similar to the findings from the EiE randomized control study, a smaller study (n = 47) of *EngrTEAMS* indicated that maintaining engineering notebooks supported students to reflect on their design practices (Douglas et al., 2018).

Other Elementary Engineering Education Curricula and Resources

We would like to make brief mention of a selection of additional elementary curricula and resources that involve engineering. *FOSS Next Generation* (https://fossnextgeneration.com/), a longtime fixture in elementary classrooms developed by the Lawrence Hall of Science, has been revised to align to the NGSS. Many of their K-5 modules incorporate engineering design challenges. Just this year, they released *Forces in Action* for Grades K-2 and *Sound Design* for Grades 3-5 as STEM-focused supplements to the FOSS curriculum or to be used in electives or out-of-school settings. *LEGO Engineering* (http://www.legoengineering.com/) was developed by the Center for Engineering Education and Outreach at Tufts University as a fun way to use the popular building toy in engineering, programming, and robotics applications. *PBS Kids Design*

Squad (https://pbskids.org/designsquad/) is a set of resources for both students and educators to engage with engineering in an informal, yet structured, way. We would also like to make special mention of *TeachEngineering* (https://www.teachengineering.org/), a free and open digital library of engineering resources maintained by the Engineering Department at the University of Colorado Boulder. With lesson plans and units contributed by numerous other universities and K-12 partners, the site currently houses 700 items in their K-5 collection.

Despite lots of promise, we mention these other resources separately because of the lack of empirical evidence in the peer-reviewed literature. While many of them have undergone internal piloting and data collection, and while the designers of some of these materials have published white papers or presented findings at conferences, it is difficult to make claims about effectiveness when these programs have no record in peer-reviewed publications. Because many of these resources are free, they are already being used by educators across the country. Their choices of resources would be strengthened by evidence of effectiveness, regarding engineering outcomes, but also science and literacy outcomes. The field of engineering education would also benefit from systematic comparisons between the features of these different approaches.

Table 13

Summary of Notable Curricula Featuring Integrations of Engineering and Literacy in K through Fifth Grade

Features of integrated curricula	**Projects containing these features**
Opportunities to actively engage with engineering design via a child-friendly, yet still systematic, version of the engineering design process	Engineering is Elementary Project Lead the Way Launch PictureSTEM EngrTEAMS LEGO Engineering
Opportunities to read and discuss texts (including read-alouds)	Engineering is Elementary Project Lead the Way Launch PictureSTEM
Opportunities to draw and/or write about engineering, typically through maintaining a journal or notebook	Engineering is Elementary Project Lead the Way Launch City Technology PictureSTEM EngrTEAMS
Opportunities for class discussions of engineering design problems, including the consideration of criteria for success and constraints	Engineering is Elementary Project Lead the Way Launch City Technology PictureSTEM EngrTEAMS

Table 14

Student Learning Gains From Integrated Curricula of Engineering and Literacy in Pre-K through Fifth Grade

Gains following use of integrated curricula	Studies
Science content	Cunningham et al. (2019) Benenson, Stewart-Dawkins, & White (2012)
Engineering practices	Cunningham et al. (2019) Hertel, Cunningham, & Kelly (2017) Benenson, Stewart-Dawkins, & White (2012) Douglas et al. (2018)
Making connections across the unit and making connections to students' lived experiences	Benenson, Stewart-Dawkins, & White (2012)
Non-cognitive gains (e.g., motivation, engagement)	Aguirre-Muñoz & Pantoya (2016)

Integration of Specific Literacy Practices into Engineering Education

In the following section, we introduce research on the benefits of integrating specific literacy practices into engineering education. Practices we review include: (a) interventions that leverage genre, features, and content of narrative texts, (b) supporting students' writing and drawing during the engineering design process, and (c) students creating and learning from multiple representations.

Interventions that Leverage Genre, Features, and Content of Narrative Texts

Novel Engineering (https://www.novelengineering.org/), known as *Integrating Engineering and Literacy* during its pilot stage, is an approach to integrating engineering and literacy developed by the Center for Engineering Education and Outreach at Tufts University (Milto et al., 2016). Unlike the programs mentioned in the previous section, *Novel Engineering* is not a prepared curriculum. Instead, it is a flexible protocol for using existing classroom texts as the basis for engineering design projects. The process unfolds in three phases: (1) through careful attention to detail and structured discussions, students identify problems faced by characters in the story, (2) using the character as an imagined client, students consider criteria for success and constraints as they brainstorm possible solutions to the problem(s), and (3) students work in teams to design a solution. The authors highlight the affordances of students productively engaging in fictional stories or accounts of historical events as (a) understanding the perspectives of others, (b) paying close attention to the features of physical settings, (c) productively engaging with unfamiliar concepts and/or vocabulary, and (d) combining information in the text with their personal knowledge of the world to construct an interpretation of the text (Milto et al., 2016).

Taking a close look at video excerpts from two suburban fourth-grade classrooms taught by the same teacher in consecutive years, Watkins, Spencer, and Hammer (2014) explore the use of the *Novel Engineering* model applied to the classic book *The Mixed-up Files of Mrs. Basil E. Frankweiler*. As they read the novel, the teacher prompted the students to think about the characters as clients and to consider design solutions to help solve their problems. Working in groups of 2-3, students were provided with a worksheet that prompted them to sketch a design. In Year 2, this initial sketch was supplemented with a prompt requesting students to describe how they would test their design. Students shared their developing designs at a few points during the design process, including a final presentation. After analyzing the video clips, the researchers argue for three key features in problem scoping: (1) naming, (2) setting the context, and (3) reflecting. These three behaviors are complex and nuanced, involving adopting the perspectives of others, developing a functional sense of the problem space, and reflecting on multiple potential solutions to open-ended problems. The authors argue that these behaviors can easily become divorced from the task-at-hand, wherein students rotely fill out the steps on a worksheet, so leveraging the richness of plot and depth of characterization in a novel or other story can be one way to support student's meaningful engagement in engineering design while also supporting reading comprehension. While this model shows promise, McCormick and Hammer (2016) report, via vignettes of two fourth-grade girls in a single classroom in New England, that students need to be supported to focus on the needs of the fictional "clients" rather than trying to anticipate what the teacher wants.

A project that represents an interesting inverse to *Novel Engineering* is the *Storymaking* work reported by Bull, Schmidt-Crawford, McKenna, and Cohoon (2017). Rather than using an existing text to launch an engineering design project, *Storymaking* involves students writing an original play and using engineering processes to bring it to life. In a small exploratory study, including one teacher and four students at a single elementary school in Virginia, students combined making and storytelling to create animated dioramas, with the goal of providing the young students with applied experiences using recreations of pivotal inventions from history. Drawing from Papert's constructionism, as well as theories of multiple literacies that highlight the importance of visual literacy and the interplay between visual and verbal systems. The *Storymaking* process unfolded in four steps: (1) storyboarding to establish main plot points, (2) constructing a conventional diorama, (3) turning the diorama into a story written on the computer, and (4) combining the physical diorama and the digital story into an animatronic diorama controlled by a computer via the Scratch programming language and a linear motor constructed from a Smithsonian Electric Motor Invention Kit. In this way, the stage directions in the written play were translated into program directions executed by the computer. The performance was filmed and uploaded to YouTube. The project unfolded over 6 weeks: with 2 weeks each for building the physical diorama, creating the digital story, and constructing the animatronic diorama. During the course of the project, students engaged with key concepts from computer science and engineering (e.g., algorithms, functions, and data management) as well as literacy (e.g., story composition, expressing thoughts in a programming language, and writing for an authentic audience). Although this study was small, it provides a vision of multiple literacies that allows students to utilize engineering principles to express themselves in three-dimensional space.

Supporting Students' Writing and Drawing During the Engineering Design Process

A common feature of engineering programs at the elementary level involves students maintaining some variety of engineering journal or notebook, either hand-drawn (Cunningham et al., 2019; Douglas et al., 2018; English & King, 2017; Hertel, Cunningham, & Kelly, 2017; King & English, 2016) or digital (Wendell, Andrews, & Paugh, 2019). Students are typically guided in the creation of these multimodal documents, which include written notes, sketches, and numerical data, through some combination of scaffolds, including prompts, graphic organizers, suggested headings, or other supports. The number and form of effective scaffolds is an area of intense interest.

The majority of studies we reviewed looked at writing as a tool to support the engineering design process, with engineering outcomes as the focus. In contrast, Rouse and Rouse (2019) conducted a study to take a closer look at the writing itself and its potential role in facilitating engineering learning. Partnered with a high-SES private school in the South, the researchers worked with 58 third-grade students. About two thirds of the participants were female, and predominantly White (71%), with 17% of students identified as Asian American and 2% African American. Sixteen percent of the students had IEPs. Using stratified random assignment based on pre-intervention vocabulary scores, the students were assigned to treatment (n = 28) or comparison (n = 30). The intervention was a 10-day engineering unit, involving design challenges, and culminating in the creation of a 5-page pop-up book. Students in the treatment condition were prompted to engage in additional journal writing during 8 of the lessons. The comparison group responded to the same prompts, but did so orally in small group discussions. The authors found that all students made statistically significant gains on an engineering vocabulary assessment, including total words written, number of different engineering concepts used, and depth of understanding of engineering concepts in a written essay response. Acknowledging the limitations of the lack of demographic diversity and small sample size, this study has two important implications: (1) the quality of the prompts likely have more of an impact on engineering learning than the modality and (2) that engineering presents an opportunity for students to productively share their thinking via writing and that oral response is not the only way to engage young learners in engineering.

As a different approach to understanding students' thinking, Dankenbring and Capobianco (2016) conducted a study to explore students' mental models, defined as students' internal representations constructed to make sense of phenomena. The researchers worked with 67 Grade 5 students at a rural school in the Midwest, with students identified as 73% White and 23% Hispanic, with 60% of students eligible for FRL. The students were about evenly divided between two classrooms, with each classroom split into two groups: the control group engaged in traditional science lessons while the treatment group engaged in engineering design-based science lessons. Students learned about Sun-Earth relationships through activities including discussions, watching a video, keeping a moon journal, reading from a textbook, and four modeling sessions. The treatment group designed a sunshade, while the control group read a trade book and completed a graphic organizer, watched a video and did some reflective writing, and completed a modeling exercise. Data were collected via multiple-choice knowledge assessments, a draw-and-explain item, and semi-structured interviews. Both groups demonstrated statistically significant learning gains, with no significant difference in the gains between the two groups. The researchers discovered five different mental models expressed by students in both conditions. We offer an interpretation of the findings not offered by the authors. Their control group activity was very literacy-rich, including a reading by Gail Gibbons, watching a video by Bill Nye, and watching a Brainpop video. They provided their control group with multiple texts integrated meaningfully into the lesson. A more appropriate “business-as-usual” control may have been reading silently from a textbook and answering factual recall questions at the end of the chapter. The lack of a significant difference between the groups may have been a result of the high quality of the control, and may be interpreted as additional evidence for incorporating various science texts and videos, in addition to or instead of an engineering challenge, to support students in constructing their mental models.

Turning to a different form of representation, drawing, it is important to note that, while engineering is a new subject at the elementary level in the United States, it has an established history, often under the name of “Technology,” in many other countries. Anning (1994, 1997a, 1997b, 1999) in the UK as well as Fleer (2000) and English and King (2015, 2017; King & English, 2016) in Australia have conducted multiple studies on sketching and disciplinary-specific genres of drawing. Broadly, these researchers have voiced repeated concerns that drawing is “more likely to be caught than taught” (Anning, 1997a, p. 219) and is typically seen as decorative rather than as legitimate mode for communicating ideas. Unlike with written texts, young students are rarely introduced to *genres* of drawing: sketching, maintaining a notebook, annotated drawings, storyboarding, orthographic drawing (representing 3D objects via several 2D images from various viewpoints), exploded-view diagrams, blueprints, or computer-aided designing. Conducting classroom observations of children aged 5-11 in England during a period of standards reform, Anning (1994) noted that without formal professional development, teachers were left to figure things out on their own. The implication of her work was that teachers needed a clearer understanding of how students’ drawing skills develop, and a broader understanding of how and why different genres of drawing are used to support designerly thinking, in order to successfully support their students with utilizing drawing in a purposeful way during the design process.

Fleer (2000) found a similar need for thoughtful support of children’s drawing during a small-scale study of 16 White children, from 3 to 5 years old, in a daycare setting in Australia. During the 2-week teaching sequence, the teacher told the children about a mythical creature she had discovered in her garden. The children were tasked with designing and creating a friend for the creature. Students were asked to design a plan for their model before constructing it from collage materials. Fleer found a strong correlation between the children’s drawing and their constructed models. She attributed this link to teacher support, including establishing a clear purpose for the design work. When Fleer published this article, she noted the lack of research looking closely at young children engaged in design work, including the relationship between drawn plans and the resulting constructed object. Twenty years later, the field could still benefit from more studies looking at the drawing practices of very young children and how they use their draw plans during the subsequent steps of the engineering design process.

More recently, English and King (2015), also working in Australia, conducted a 3-year longitudinal study with two private and three public schools. Focusing on fourth graders from the all-girls private schools designing and redesigning 3-D model planes, the authors identified three levels of sophistication in students' sketches. The majority of plans were in level two: a drawing of the plane along with some indication of where to fold materials accompanied by some measurements. Level three plans also included written instructions and calculations. Looking at a tower-building civil engineering unit with students at the same private schools (English & King, 2017), the researchers identified four levels of design and redesign. For this activity, Level 1 was merely a representation of the necessary pylons and platforms for the tower, annotated or not. Level 2 included those features and also met the project constraints. Level 3 included evidence of a stable base or load distribution and sometimes included representation of perspective. Level 4 plans included all design features. Somewhat surprisingly, Level 4 was the most common for the first design (61% of students' plans) and also for the second design (46%). Also somewhat surprisingly, the decline in Level 4 sketches for the redesign was accompanied by an increase in Levels 1 and 2. About half of students' designs remained static between their initial sketch and their redesign, but a full 38% decreased in sophistication. Only 13% of designs improved. The researchers attributed this decline in sketch sophistication from first to second sketch to time constraints, students wanting to rebuild their design before sketching a new idea, and/or achieving a solid result with their initial plan. Turning their attention to fifth graders at the same schools (King & English, 2016), the researchers again used a five-level coding scheme to analyze student designs. Similar to their findings with fourth graders, the accuracy of the scientific understandings reflected in the sketches remained essentially unchanged from the first drawing to the second (83.3% vs. 79.2%). Taken together, the work of King and English indicates that sketching does provide for an integration of science, engineering, and literacy. Furthermore, initial sketching does seem to provide support for elementary students to conceptualize a built model. While providing an opportunity to revise those models results in improved designs, asking students to draw a revised sketch prior to making modifications may have limited utility unless this step is supported by the teacher.

The necessity of explicit instruction in drawing was explored in a study by Kelley and Sung (2017). They wanted to know instruction in sketching would affect how students approached design, and if the comparison group would improve after receiving delayed treatment. Working with four classroom teachers and 91 students in four third-grade classrooms in the Midwest, with demographics reported as 66% White, 13% Hispanic, 3% African American, with 40% of students eligible for FRL, the researchers used a two-group counterbalanced quasi-experimental design. The students engaged in a program called Science Learning through Engineering Design (SLED) wherein each lesson had a design activity with three phases of sketching: (1) individual sketches, (2) combining ideas to create a collaborative sketch, and (3) building and testing a prototype based on the team design. The treatment was a 30-minute lesson on sketching provided by the researchers, including (a) the role of sketching in design thinking, (b) examples of sketches by famous inventors, and (c) techniques for symbols, labels, and ways of representing perspective. Findings indicated that intentional instruction in sketching improved students' design and communication practices, shifting the practice from a recording of ideas to a form of communication and as a tool for refining ideas. After the initial comparison group was provided with delayed treatment, their sketching skills also improved. Confirming the findings of English and King, this study indicated a need to train teachers to understand the role of sketching in design, including providing them with authentic examples from the profession to be able to better guide their students.

Students Creating and Learning From Multiple Representations in Engineering

A small study by Avery and Kassam (2011) is notable for focusing on students in a rural setting. The researchers provided 20 students in a combined Grade 5/6 classroom in upstate New York with cameras and asked them to document instances of science and engineering. Their goal was to support students to bring their home knowledge into the classroom. Analysis of the 407 photographs taken by the students revealed that students were able to identify instances of science and engineering and that these examples were tied to experiences with their families and their daily lives. However, students did not make automatic connections between their knowledge from outside of school and what they were learning in the classroom. The methodology in this study holds interesting possibilities for the integration of literacy and engineering. Although this study was conducted with students in upper elementary, the technique of asking students to take pictures of instances of engineering in their home and community and then discussing the photos in the classroom holds great promise for engineering education for younger students, especially those who have not yet learned how to write.

Sullivan and Bers (2016) also conducted a study with a unique approach for using multiple representations with very young children. The context was an urban public school in Boston, MA working with a student population reported as 72% Hispanic, 69% Limited English Proficiency, 65% eligible for FRL, and 15% of students with IEPs. The sample was n = 60 children in pre-K through Grade 2, with roughly equal numbers of participants in each grade. The students participated in an 8-week robotics curriculum called *Me and My Community* using KIWI robotics kits and a tangible programming language called CHERP, both developed at Tufts University specifically for use with very young children. The KIWI kit is easy and intuitive to put together, does not require a computer, and can be augmented with craft and/or recycled materials. Unlike traditional computer languages, CHERP does not require a screen, as it is based on interlocking wooden blocks that young children rearrange to create different commands. The colorful blocks are labeled with single words or short phrases and an accompanying icon, along with a barcode that is scanned by the KIWI robot to execute the command. Based upon assessments of foundational robotics and programming concepts, even the students in pre-K were able to demonstrate basic robotics and programming skills, while the older students were able to demonstrate increasingly complex concepts. In addition to being interesting due to the creative use of technology, this study is notable as an approach that supported students typically underrepresented in both engineering and computer science, including students minoritized due to ethnicity, language status, and socioeconomic level.

Engineering and Literacy in Out-of-School Contexts

The last decade has seen a proliferation of “makerspaces” as a popular out-of-school activity, sometimes as an after-school club, but also associated with children’s museums and as stand-alone businesses. The field is unsettled as to whether “making” is truly engineering (Smith &

Smith, 2016). On the one hand, making involves designerly thinking, provides young learners much-needed experiences with the properties of various materials, and typically requires revisions to improve the product. On the other hand, it is not always clear that students are making connections between their projects and science and engineering ideas. It is also unclear if students are applying specific engineering principles or if success is only a result of trial-and-error. Furthermore, for the purposes of this paper, makerspaces rarely include intentional literacy integration or instruction. Although we recognize the value of such spaces for fostering motivation and simply being fun, we will not review makerspace literature in this review.

We do want to highlight one small-scale study of three third graders by McVee and her colleagues (2017) at SUNY-Buffalo that is unusual along a number of dimensions. First, the majority of studies looking at the intersection of engineering and literacy have been written by engineering scholars. While some project teams reviewed in this paper have included a literacy consultant, it is unusual to find engineering education projects led by literacy researchers. Second, while the afterschool engineering club described in the study was co-ed, McVee et al. intentionally highlighted the participation of girls, as girls remain under-represented in the engineering profession. Third, the researchers selected focal students who were English language learners, as informal, multimodal interactions may be a supportive context for young people new to the language. Rather than a specific intervention, the researchers see the entire *context* of the afterschool club as an opportunity for students to practice *multimodal communication* (e.g., movement, touch, image, gesture, and body position) as one component of *productive communication*, which also includes the more historically recognized literacy modalities of writing and reading as well as speaking, and listening. The club described in the article met for 1 hour after school, two times per week for 7 weeks. The 4-day project highlighted in this article had local relevance to the students, as it involved building a better bridge between the United States and Canada. The authors provide numerous examples of these girls, who would not be considered outgoing in their classroom setting, communicating effectively to plan and enact their designs. The authors argue that productive communication involves sociocultural, linguistic, and cognitive resources augmented by haptic, spatial, gestural, and proxemic resources, all situated within a specific context. Providing opportunities for expression in multiple modalities supports the participation of students who may be excluded or marginalized on the basis of language, culture, or gender norms.

Practitioner Journals in Engineering: Emergent Work and Promising Future Directions

The inclusion of engineering in the NGSS at the elementary level resulted in an explosion of interest among researchers and practitioners. So, not only is the literature on elementary engineering education still developing, the research is even more thin when looking at the intersections of engineering and literacy. In contrast to the much more established literature presenting empirical findings regarding the intersections of science and literacy, a parallel body of research simply does not yet exist for engineering. Because of this current gap, it is helpful to turn to practitioner journals for hints about current lines of inquiry and promising future directions.

Innovative Uses of Technology in Engineering

The following articles, while not yet supported by empirical evidence, provide examples of innovative uses of technology to support the integration of engineering and literacy. Lottero-Perdue and her colleagues (2011) reported students using handheld digital video cameras to support evidence-based reasoning. During a *Designing Walls* EiE unit, a fourth-grade teacher incorporated these low-cost cameras at multiple points. For example, rather than sketching examples of walls, students filmed actual walls, zooming in on details. The teacher then displayed these videos back in the classroom to support a class discussion, with students recording their observations in journals. By relying on video rather than sketches, the teacher was able to focus attention on details that students may have overlooked in hand-drawn sketches, including the key point of staggered bricks adding strength to a wall. Then, during an investigation about the qualities of mortar, the teacher recorded her conversations with different groups as they engaged in the activity. After they were finished, the teacher again shared the videos so the class could compare and contrast the reasoning of different groups. Finally, groups used video to record the tests of their wall models. As the tests happened very quickly, having access to the video allowed for replay and slow motion observations. By deploying cameras at three critical stages in the inquiry process, the students were able to create collaboratively authored “texts.” The teacher in this article used the video evidence as a direct formative assessment, but it is easy to imagine the high-quality video data serving as an excellent resource for students writing their own scientific explanations.

Bellavance and Truchon (2015), both classroom teachers, also explored the use of video cameras. Working with second graders using the EiE curriculum, they supported their students to use iPads to collect a variety of digital artifacts (e.g., videos, voice recordings, and still photos) during the steps of the engineering design process. Already familiar with EiE’s use of journals, the students extended that idea to create multimodal electronic STEM journals that took the form of eBooks by way of the apps *Book Creator* and *Explain Everything*. Similar to the Bull et al. (2017) Storymaking work described above, students started the project by planning their eBooks on storyboards that mapped out what would happen during each step of the engineering design process. The teachers provided prompts on each page as well as elements from the CCSS-ELA: introduction, facts and definitions, and conclusion. Other than the prompts, the teachers provided lessons on the general use of the iPad, various ways that the iPad can record information, and how to use the apps. After engaging in the sail-making unit and collecting digital artifacts along the way, students used rubrics to evaluate their eBooks. As technology continues to permeate classrooms, this type of multimodal composing will be more common. However, even with an intuitive piece of technology such as the iPad, it is key that teachers continue to provide scaffolding (e.g., graphic organizers, prompts, tutorials on hardware and software use, etc.).

Another area where emerging technology provides a promising context for the integration of engineering and literacy is 3D printing. A three-dimensional printer is guided by computer-aided design files to create solid shapes from plastic resin. Cook, Bush, and Cox (2015) describe how a STEAM lab teacher worked with a group of fourth-grade students to create a 3D printed prosthetic hand to be used by a local kindergartener. Working together 5 days per week for 50 minutes over a 6-week period, the students conducted research, created 3D models using *Tinkercad*, built prototypes using everyday objects, shared their results to argue for and justify their designs, and then prepared the final design in *Tinkercad* and printed the result. In addition to the literacy skills required to transfer ideas from sketch to digital representation to final product, the project included multiple opportunities for writing and speaking about design ideas, all embedded within a local and personal context.

Inclusive Engineering

Consistent with the call in the NGSS to promote equitable opportunities for all learners, Mangiante and Moore (2015) reported on the experiences of a fourth-grade teacher in a high-poverty urban district and her 25 students, including those experiencing reading challenges, students with identified learning disabilities, and a student with Down syndrome. Inspired by a video she watched online about *Engineering is Elementary*, the teacher transformed an existing science unit about electrical circuits into an engineering design project. She launched the unit with a story that she composed, involving a soccer field across from the school that had no lights for playing at night. Each of the investigations was structured as an opportunity to seek solutions to this problem. Based on this teacher's experiences, the authors offer eight tips for inclusive engineering that may prove instructive to researchers designing future curricula integrating engineering and literacy: (1) create context for engineering challenges, particularly something local and relevant for the children; (2) offer differentiated graphic organizers and learning materials; (3) support students to prepare their own reference materials, including suggesting note-taking strategies and collaboratively developing drawn models; (4) provide access to and practice with discipline-specific language for discourse, including extra time for previewing words and providing visuals to accompany text; (5) presume the competence of all students; (6) assign students to heterogeneous groups, to learn from each others' diverse strengths, and use frequent self-evaluation to help students reflect upon their actions as group members; (7) provide structure, such as recording sheets, to support students in the evaluation and revision of their designs, and (8) provide a menu of options for students to demonstrate their learning, such as writing a report, presenting orally, designing a poster, or recording a commercial.

Research on Professional Learning Opportunities That Support Integration in Engineering

Because the engineering design process includes practices like writing notes, sketching, recording data, arguing for a particular design, and presenting solutions, any professional development opportunity including engineering automatically includes literacy. However, the extent to which literacy instruction is intentional and explicit varies greatly.

Wendell (2014) examined the design practices of preservice teachers learning about the *Novel Engineering* model (described above). The participants were 26 graduate students enrolled in an elementary science teaching methods course at a public university in the Boston area. During three sessions, the preservice teachers worked in small groups on engineering design experiences grounded in children's literature. The first experience included reading a biographical text and a selection describing the NGSS science and engineering practices as well as watching a video on the design process. The second experience involved designing furniture for a character from the novel *Tales of a Fourth-Grade Nothing*. The third and final session involved identifying problems for the characters in *The Mixed-up Files of Mrs. Basil E. Frankweiler* and developing related tasks for their future students. Wendell's analysis was focused on the developing design practices of the preservice teachers. While her findings were illuminating, we share this study more as an example of how preservice teachers, in either a science methods or a literacy methods course, could be exposed to innovative uses for combining existing classroom texts with engineering design challenges.

Table 15

Summary of Key Takeaways from Smaller-Scale or Partial Integrations of Engineering and Literacy in K through Fifth Grade

Key takeaway	Studies
Existing classroom texts may be utilized as the basis for engineering design projects	Milto et al. (2016) Watkins, Spencer, & Hammer (2014) Wendell (2014)
Students' original scripts may serve as the basis for animatronic dioramas	Bull et al. (2017)
Maintaining a multimodal journal or notebook, either on paper or digitally, is a natural context for literacy integration	Cunningham et al. (2019) Douglas et al. (2018) English & King (2017) Hertel, Cunningham, & Kelly (2017) King & English (2016) Wendell, Andrews, & Paugh (2019)
Reflective writing may help support the learning of engineering vocabulary and concepts	Rouse & Rouse (2019)
Students need to be supported, and explicitly taught, various genres of drawing	Anning (1994, 1997a, 1997b, 1999) Fleer (200) English & King (2015, 2017) King & English (2016) Kelley & Sung (2017)
Photographing instances of engineering is one technique to introduce students' home lives/knowledge into the classroom, and is particularly useful for students too young to write	Avery & Kassam (2011)
A tactile programming language (e.g., CHERP) may be used to support very young children with programming	Sullivan & Bers (2016)

After-school and out-of-school settings may support the participation of students in engineering who may otherwise be excluded or marginalized	McVee et al. (2017)
Digital video recordings may be used at various stages of the design process to collect data for replay and discussion	Lottero-Perdue et al. (2011) Bellavance & Truchon (2015)
3D printing provides a context for transferring ideas from sketches to digital representations to final prototype	Cook, Bush, & Cox (2015)
Thoughtful supports and differentiation are necessary to make sure all students are able to participate in engineering	Mangiante & Moore (2015)

Conclusion

We have argued that the deep understanding of science and engineering that is called for in current reform movements, requires the basic tools of reading, writing, oral language, viewing, drawing, and representing. Thus, learning science and engineering provides an opportunity not only to build knowledge about the physical world and come to understand how scientists and engineers have contributed to our understanding of the physical world, but also to learn about the basic tools that are used to build knowledge and represent it to others. Furthermore, learning what others have discovered about the world and sharing one's own investigations of the world are powerful motivators for learning to read, write, speak, draw and represent in particular ways.

The literature we have reviewed suggests that there is merit to this claim, particularly with respect to science learning, with much less evidence, to date, regarding engineering learning. Furthermore, research conducted at the intersection of literacy and science has been fruitful to identifying purposes and processes for using text so that it does not undermine productive and authentic engagement in science *or* literacy learning. While there is enthusiasm for the study of engineering with young students, there has been less attention in this literature to literacy outcomes as a consequence of engaging in engineering practices. This is an area that is ripe for investigation.

The research that we found most useful was of two kinds: research that was conducted programmatically and research that employed multiple methods. While this review is replete with examples of this kind of research, two exemplars of programmatic research are *Science IDEAS* (Romance & Vitale) and *Evolving Minds* (Keleman & Emmons and colleagues). In the case of *Science IDEAS*, the programmatic nature of this research enabled the investigators to figure out what the features of curriculum and instruction were for students who were on the way to independence regarding literacy knowledge and skill and then determine how the curriculum and instruction would necessarily have to be modified for younger students who were still acquiring basic literacy skills. In the case of *Evolving Minds*, their programmatic inquiry allowed the researchers to first investigate (a) the conceptual challenges associated with young children's understanding of natural selection and then (b) the construction and sequencing of texts that would be up to the task of supporting this understanding.

Research conducted with the use of multiple methods, including: classroom observations, interviews, collecting student artifacts, and assessing both science *and* literacy outcomes provided the most complete picture of efforts to teach and learn at the intersection of science and literacy.

We were surprised not to find more examples of interdisciplinary research (at least as we could discern). The examples we did find; for example, *Seeds of Science/Roots of Reading* led by science educator, Barber and literacy educator, Cervetti, illustrate the value of interdisciplinary collaboration in this area of inquiry.

Virtually to a one, the instructional research we reviewed could not have been done without careful attention to professional development and we were able to learn a lot about the features of professional development that support teachers to engage in ambitious instruction at the intersection of science and literacy. However, we found little research that focused on teacher education at the intersection of science/engineering and literacy. Davis and her colleagues (Davis, Palincsar, & Kademian, 2020) describe a teacher education program in which prospective teachers begin their program of study with a course called, *Children as sensemakers*. In this very brief course, prospective teachers learn how to interview a young child about the causes of day and night, as well as what causes sound to change. They learn to elicit children's thinking through drawing, modeling, and talk, and they learn to conduct an interactive read-aloud that explains the day-night cycle. This course is possible because of the collaboration between science educator, Davis, and literacy educator, Palincsar. If teacher educators were to partner across disciplines, more of these types of learning opportunities might support novice teachers to be prepared to take advantage of the rich teaching possibilities at the intersection of science/engineering and literacy.

While impressed with the significant number of studies we found at the intersection of science and literacy, there are still a number of questions that endure. For example, there are no research teams, to our knowledge, that have aspired to support teachers to meet all of the Common Core State Standards in the English Language Arts and the NGSS standards in K-5. Therefore, we have no models of this curriculum and instruction; nor is it clear how one would best measure the effects of such a model. Teachers are always facing trade-offs; while we do have evidence that engaging students in the learning of science can be a powerful context for teaching a number of literacy skills, we do not yet have enough evidence to guide teachers in establishing priorities and making pacing decisions. For example, we do not have the evidence that would guide teachers to determine how to prioritize the use of first-hand investigations versus second-hand investigations, or the ideal blending of narrative vs. informational science texts, or what constitutes the most powerful uses of writing in the context of learning science. While we were generally impressed with the diversity of the student demographics in the studies we reviewed, we do not have enough information to understand how instruction might ideally be differentiated to meet the needs of various demographic groups.

The convergence of the health, anti-Black racist, and economic pandemics that have a grip on our country bring issues of equity to the fore. We close by referencing research germane to these pandemics. Recently, Stefanski and colleagues (2019) investigated variations in literacy-science integration between a higher and lower income school in the same large, urban school district in the Midwest. The higher income school had a poverty rate of 45% and 62% of students identified as students of color. The lower income school was hyper-segregated, with 95% students identifying as students of color and 87% of students eligible for FRL. In each school, the principal recommended a teacher whom they considered to be highly effective. Both teachers were white, middle-class women with similar levels of teaching experience (14 and 16 years). Researchers identified four levels of inequity between the two classrooms. First, the students in the higher income school had 75 minutes set aside for science instruction, while students at the lower income school did not have a specific time for science. Second, while both classrooms had science texts, only students in the higher income school had regular opportunities to independently read science texts. Third, when using science texts, the teacher in the higher-income school focused on the scientific ideas, while the teacher in the lower-income school focused on vocabulary acquisition and decoding skills. Fourth, the students in the lower-income school were positioned as "knowledge consumers" while reading science texts: their role was to answer actual questions posed by the teacher. In contrast, the students at the higher-income school were positioned as "knowledge producers," and had the opportunity to engage in collaborative inquiry and co-construction of scientific ideas. Researchers concluded that the presence of "science literacy integration" in both the higher-income and lower-income school was no guarantee for equitable learning opportunities and calls for a shift in policy and perspective at both local and state levels.

Another recent study is instructive when asking what justice-centered science pedagogy might look like. Davis and Schaeffer (2019) conducted, and reported selected findings from, a two-year ethnographic project in which they investigated the agency and meaning making of fourth- and fifth-grade Black students. The instructional context was a socio-scientific unit that addressed water and water justice and coincided with broadening public awareness of the water crisis in Flint, MI. Davis and Schaeffer investigated Black students' affective, sociopolitical, and disciplinary meaning making related to water and water justice as they participated in the *Water is Life* unit.

Water is Life instructional activities were distributed throughout the school year (January-June) and were guided by questions designed to drive student inquiry into water and people's access to water: *How does water support life? Is water a human right? What is water justice and why would it benefit society?* Salient features of the unit included discussion, collaborative groups, debate, documentary viewings, engaging with local water activists, and a field trip to a nearby river. In addition to investigating the case of Flint, the two participating teachers foregrounded students' inquiry into issues within their own community - Riverview - which had recently been affected by mass water shut-offs that had gained national attention. The unit included three modules: (1) Flint Water Crisis and Contamination; (2) Water Use, (In)Access and Properties; and (3) Riverview Water Shut-Offs and Action. Students used literacy tools of reading, writing, and oral language for meaningful purposes throughout the modules, such as: (a) read-alouds of media reports/news articles about Flint, (b) participating in class discussions about water contamination, (c) creating posters to share information about Flint, (d) engaging in debates about whether water is a human right, (e) viewing a documentary about Riverview water shut-offs, and (f) creating short films about water in Riverview. The unit was designed to address science content, including properties of water, the role of water in the human body, and consequences of lead poisoning to support meaning making about water issues. In addition, the teachers wanted their students to deepen their understanding of people's experiences related to water injustice and the need for systemic change.

Davis and Schaeffer found that, at the beginning of the unit, students viewed access to clean water as an isolated problem in Flint. However, when students began to investigate water and water access locally, in Riverview, findings indicated that students started to develop views of water justice as both ethical and sociopolitical issues. As students made connections between the Flint and local Riverview water issues, they began to leverage their science knowledge to understand water access as a larger, systemic problem. For example, Davis and Schaeffer report that students' informational posters about Flint provided evidence that students were working with ideas about toxicity and molecular structure, and were using their developing understandings of phenomena as resources for deepening their understandings of human experiences, ethics, and politics. Shifting the instructional focus to investigating water issues in their local area toward the end of the unit allowed students to leverage lived experiences to further facilitate meaning making and action. Davis and Schaeffer suggest that the *Water is Life* unit - which engaged students in using tools of reading, writing, oral language, viewing, and representing for meaningful purposes - provides one example of how science learning might be deepened in elementary classrooms, but caution against justice-oriented science education that focuses solely on identifying and addressing problems that students, especially marginalized students, did not create. Rather, they call also for curriculum and instruction that foregrounds community ingenuity and innovation that invites students to explore how scientific expertise may be used to create desired futures. We look forward to more researchers partnering with schools, families, and communities to identify projects that will culminate in creating desired futures.

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