Early Mathematics Learning and Development

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Early Engineering Learning

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Early Engineering Learning

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Preface

Early Engineering Learning is a volume within the Springer series,*Early Mathematics Learning and Development.* The collection of volumes published in this series explores a range of perspectives on young children's developments in mathematics and allied fields. One such field that draws on and fosters young children's mathematical capabilities is engineering. Despite early childhood being a period of experimentation and curiosity with the natural world and its myriad challenges, children's natural propensity for engaging in engineering experiences remains untapped.

As the chapters in this volume illustrate, we need to capitalize on children's skills as independent problem solvers who relish challenges, persevere in the face of failure, and learn both from what "works" and what does not. Educators, including parents, need to be cognizant of how children's talents can be harnessed and enriched to sow the seeds of engineering education.

Engineering has received almost no attention in the pre-K and beginning school years, even though the need for quality STEM education across all age levels is advocated by many nations. The "E" in STEM tends to be ignored in these significant formative years when an interest in and awareness of engineering and engineering design processes can be fostered. The early years of a child's life are too valuable to deprive them of the rich learning opportunities that engineering can offer.

Because engineering shapes so much of our actual and virtual worlds, it is an ideal discipline to both link and promote the varied capabilities young children bring to informal and formal learning environments. The chapters in this volume attest to the rich opportunities engineering affords. The authors report on research illustrating several intervention programs, together with assessment frameworks, which aim to facilitate beginning engineering learning. These include the use of robotics as a playful vehicle for fostering engineering, computer science, and mathematics (Chap.11), and the incorporation of literature as a familiar and meaningful basis for learning across the entire STEM curriculum (e.g., Chaps.9 and 10). A focus on spatial skills including intervention experiences, which are so important to success in engineering, is also featured (Chap. 5). Other chapters highlight the nature and role of engineering design processes and habits of mind, which are not unique to the engineering field, rather, are applicable across the curriculum.

Engineering design has been described as the “disciplinary glue” (Chap. 9) that assists children to apply their learning in STEM to an engineering design challenge. Indeed, the practice of engineering inherently requires the practitioner to call upon other disciplinary knowledge in order to solve engineering problems. Engineering design challenges are usually described as strongly iterative, open to many possible solutions, and engendering thinking processes or “habits of mind.” These thinking skills underline design processes and include systems thinking, innovative problem finding and solving, visualizing, and collaborating and communicating (as addressed in Part I and Chap. 13).

Readers might notice that this volume comprises only 13 chapters, a reflection of the embryonic nature of the field. As such, the volume presents a seminal set of research-based studies that provide empirical evidence of what can be achieved in implementing engineering experiences in early childhood. *Early Engineering Learning* raises the profile of an overlooked discipline that is as natural to early childhood as is mathematics, science, and technology. A STEM agenda is not complete without engineering, nor is a child’s early learning and development. We can no longer ignore this core discipline.

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Contents

Chapter 1
Early Engineering: An Introduction to Young Children's Potential

Lyn D. English

Abstract *Early Engineering Learning* comprises two main sections presenting a mix of research studies, theoretical advancements, and classroom empirical examples. As such, this book provides a rich resource for researchers, policy makers, curriculum developers, and classroom teachers alike. Engineering learning is a significant yet underrepresented field in early education, despite being one of the most practical and real-world domains that all children can engage in. As evident in the chapters of this book, young children are eminently capable of solving engineering-based problems; indeed, they do this on a daily basis. Engineering education integrates readily and meaningfully not only within the other STEM domains, but also with literature and the arts more broadly. Various approaches to early engineering learning are showcased throughout this book, with engineering design processes and habits of mind featured prominently. Not only are these design and thinking processes foundational to early engineering but can also enhance learning across several other disciplines.

The chapters of *Early Engineering Learning* comprise a mix of research studies, theoretical advancements, and empirical examples for classroom use. As such, this book provides a rich resource for researchers, policy makers, curriculum developers, and classroom teachers alike. Engineering learning is a significant yet underrepresented field in early education, despite being one of the most practical and real-world domains that students of all ages can experience with success and enjoyment. Indeed, young learners are natural engineers, as has often been stated (e.g., https://www.eie.org/eie-curriculum/why-engineering-children).

Despite the ubiquity of engineering throughout our environment, education has yet to capitalize fully on the domain's potential for early learning—in essence, we are ignoring young children's capabilities for engaging in engineering experiences.

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As evident in the chapters of this book, young children are eminently capable of solving engineering-based problems; indeed, they do this on a daily basis. Young children's natural curiosity, inquiry, and desire to explore their world form not only the cornerstone of early childhood development (Brophy, Klein, Portsmore, & Rogers, 2008), but also "a key component of thinking like an engineer" (Elkin, Sullivan, & Bers, Chap. 11; Tippett & Milford, 2017). One only has to observe how young children investigate, experiment, manipulate, and create with everyday objects to realize how they are engaging in the foundations of engineering education. As children are exposed to these foundations, they are developing core discipline knowledge that enriches not only their mathematics, science, and technology curricula but also other content areas. As Petroski (2016) highlighted, "Engineering is not an end in itself. It operates in a moral, social, economic, and aesthetic context" (p. 21).

Unfortunately, we have neglected the "E" in our STEM education for too long (Di Francesca, Lee, & McIntyre, 2014; English & King, 2017; Moore et al., 2014). Despite a lack of specifically developed resources and associated teacher professional development, as I note in the final chapter, the contributions of engineering to our world need greater recognition—and what better way to start than through nurturing an early awareness of how engineers and engineering shape our world.

The present chapters are arranged in two main sections, in addition to introductory and concluding chapters. In addressing early engineering learning from Pre-K through to the early years of formal education, the chapters in the first section focus primarily on engineering thinking, design, and habits of mind, while those in the second section target early engineering curriculum development. There is naturally some overlap in these sections as curriculum and resource development necessarily takes into account engineering design and thinking.

1.1 Why Focus on Engineering Thinking, Design, and Habits of Mind?

The chapters in the first section lay frameworks for early engineering learning, with studies ranging from capitalizing on spontaneous play as opportunities for introducing engineering (e.g., Chaps. 4 and 6) through to fostering early spatial skills as a core habit of mind in both engineering and STEM more broadly (Chap. 5). Combined with chapters presenting examples of observation protocols and specifically designed assessment tools (e.g., Chaps. 6 and 7), the first section draws together a range of research and classroom tested ideas that collectively pave the way for further studies and advancement.

As one peruses the chapters in each section, it will become apparent that engineering design processes feature prominently. Some might even argue that there is too much emphasis on these processes, yet as Tank, Moore, Gajdzik, and Sanger (Chap. 9) aptly state that engineering design is the "interdisciplinary glue" in STEM education. Research has indicated how engineering design, a core construct in the discipline, enables learners to appreciate that there are multiple ideas and approaches to solving complex problems with more than one solution possible, that numerous tools and representations can be used in different ways to produce a desired end-product, and that it is acceptable for initial designs to "fail" necessitating redesign and improvement (e.g., Dorie, Cardella, & Svarovsky, 2014; English & King, 2017; Tank et al., Chap. 9). Indeed, repeated studies have illustrated how engineering design processes provide a meaningful tool for all learners, across ages and grade levels, in solving not only engineering-based problems but also numerous other real-world challenges. The chapters in Sect. 1.1 provide many examples that collectively convey the message that young children have substantial potential for engaging in engineering thinking, applying engineering design processes, and displaying foundational habits of mind. Although providing somewhat similar evidence of these capabilities, the chapters nevertheless reinforce the urgent need to attend to *all* of STEM in early education, not just mathematics and science.

Apart from advancing engineering learning, these first section chapters contribute to early curriculum development more broadly—not only with respect to STEM education but also the arts including literature, as addressed in the second section. The broadening of STEM to STEAM education is gaining in popularity as the advantages of incorporating components of the arts are recognized (as revisited in Chap. 13).

1.2 Early Engineering Curriculum Development

As a seminal, early engineering program, *Engineering is Elementary* (Chap. 8; Cunningham & Hester, 2007) builds specifically on designed engineering stories and has laid the groundwork for many subsequent engineering programs, as indicated in Chap. 8 (Cunningham, Lachapelle, & Davis). The many contributions of engineering to our environment and our lives more broadly are reflected in the ease with which the discipline can be integrated within early educational programs. Engineering shares more than mathematics and science components—it lends itself to a range of literature and to the natural problem-solving situations that occur in our everyday lives. To cite Petroski (2016) again, "Engineers have come to be recognized as the creative people who bring us innovations like the smartphone, the personal computer, the internet, and the world wide web" (p. 21). The world revolves around these technological innovations, but do we stop to think of those creative engineers responsible for their development?

As young children interact with these technological tools, they too can begin to appreciate the powerful ways that engineers enhance our world. Indeed, our future team of engineering students need to be nurtured from a young age, at a time when children's curiosity is at its peak. Sparking such interest can ideally begin with support from literature, as studies in the second section demonstrate. Portsmore and Milto (Chap. 10), for example, discuss their *Novel Engineering* program, which replaces real-world clients and contexts with those from popular literary texts as a basis for creating engineering design challenges. Children draw information from the given literary text in identifying engineering problems, where story characters are considered as clients and details from the story are used to impose constraints, as solutions are developed for the characters' problems. The numerous other examples illustrate the need to utilize more the power of literature, an often ignored resource that can enrich so many disciplines (Luedtke & Sorvang, 2017).

Along with engineering, technology learning in the younger years requires further research and curriculum development. While there is an increasing focus on early technology especially coding (e.g., Fessakis, Gouli, & Mavroudi, 2013), the links with engineering have been underrepresented. In Chap. 11, Elkin, Sullivan, and Bers provide innovative approaches to developing foundational engineering and computer science concepts. They present insightful anecdotes illustrating how robotics can serve as a playful medium to develop these concepts. Educators with little to no prior engineering experiences were able to successfully integrate robotics with traditional early childhood curriculum content such as literacy and science. Their vignettes highlight the different approaches teachers took in introducing robotics within their classrooms and how they utilized the engineering design process as a teaching tool applicable to many subject areas, not just STEM. With the increasing availability of robotic kits for young children, such as KIBO described in Chap. 11 (www.kinderlabrobotics.com), numerous opportunities now exist for early educators to explore the learning potential of robotics. With such potential extending beyond just STEM to other content domains, robotics can readily enrich existing curricula, as Elkin et al. explore. Furthermore, early technology experiences can act as catalysts for social and emotional skill development across a diverse range of students, as seen in Elkin et al.'s study for whom English was not the first language for over a third of their participants.

Early engineering education research and development have a considerable distance to go. The chapters in this book present several avenues for traveling this distance, but obstacles need overcoming. Two of the several challenges we face with respect to research, policy, and curriculum development include increasing awareness of young children's competencies in early engineering, and enhancing teacher resources and professional development opportunities, as noted in the last chapter. With respect to the latter, curriculum resources need to be integrated within the regular curriculum, otherwise engineering education will likely be viewed as another "add-on" to be squeezed into an already tight curriculum. Fortunately, engineering lends itself easily to such integration, linking not only with the remaining STEM disciplines but also with other domains especially literature. It is to be hoped that curriculum developers across the disciplines can capitalize on the many contributions of early engineering education. The chapters in this book provide rich starting points.

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Part I
Engineering Thinking and Habits of Mind

Chapter 2
Engineering in the Early Grades: Harnessing Children's Natural Ways of Thinking

Tamara J. Moore, Kristina M. Tank and Lyn English

Abstract This chapter explores engineering as it applies to students in the early grades. First, we consider engineering as a STEM foundation. We then address ways in which we can provide supportive learning environments for early engineering learning. As part of such environments, we examine how we can build on intrinsically interesting problems. In exploring ways of harnessing young learners' natural ways of thinking, we consider the role of play in early engineering learning and how we can capitalize on this play. The integration of engineering within the early curriculum is then reviewed, followed by a summary of perspectives on ways in which engineering is developmentally appropriate for, and beneficial to, young learners.

Engineering is a multifaceted field that draws not only from related disciplinary domains such as mathematics and science, but also from disciplines that serve to make engineering solutions more practical or desirable such as economics, social studies, and the arts. Technological developments such as the iPhone, robotics, and 3-D printing, all involve major engineering inputs. Young children are very much a part of our engineered world, interacting daily with the products of engineering and technology.

On entering kindergarten, children already have sophisticated ways of thinking about the world based largely on their own experiences (Baillargeon, 1994; Cohen & Chashon, 2006), which serve as a springboard for their future learning and development (Inagaki & Hatano, 2006; NRC, 2012). Early engineering education

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falls naturally within such experiences. With its focus on iterative thinking—that is, trying something, testing it, learning from what does not go well, and trying again—as well as working in teams and communicating current ways of thinking, engineering is an ideal avenue for enriching and extending young children's natural talents. As Lippard, Lamm, and Riley (2017) noted, "… Pre-kindergarten children are primed for engineering thinking" (p. 455). Furthermore, engineering provides a platform for young children to be introduced to technology, not just as digital media, but as all aspects of the designed world. Children inherently alter their environment to fit their needs. These alterations are the beginnings of engineering thinking, which can promote structured decision making within a specified engineering context.

This chapter explores engineering as it applies to students in the early grades. First, we consider engineering as a STEM foundation. We then address ways in which we can provide supportive learning environments for early engineering learning. As part of such environments, we examine how we can build on intrinsically interesting problems. As we continue to explore ways of harnessing young learners' natural ways of thinking, we consider the role of play in early engineering learning and how we can capitalize on this play.

2.1 Engineering as a STEM Foundation

Research over many years has revealed that young children have sophisticated minds and a natural eagerness to engage in a range of mathematical and scientific activities a good deal earlier than previously thought (Perry & Dockett, 2013; English & Mulligan, 2013; English, 2013; Lehrer & English, 2018). Children enter kindergarten with surprising ways of thinking about the world they experience, which can be used to promote problem-solving and build understanding in the early grades (Baillargeon, 1994; Cohen & Chashon, 2006). Indeed, a range of studies in prior-to-school and early school settings have revealed how young learners possess cognitive abilities which, with appropriately designed and implemented learning experiences, can enable forms of reasoning not typically seen in the early years (e.g., Clements, Sarama, Spitler, Lange, & Wolfe, 2011; English, 2012; Inagaki & Hatano, 2006; Lehrer & English, 2018; Lehrer & Schauble, 2015; Moss, Bruce, & Bobis, 2016; Perry & Dockett, 2008). For example, young children can abstract and generalize mathematical and scientific ideas much earlier, and in more complex ways, than previously considered. These sophisticated ways of thinking and reasoning in young children provide a foundation that can be used to not only facilitate early engineering knowledge and skills but also to support early learning across other content areas, such as mathematics and science.

2.2 Providing Supportive Learning Environments

In efforts to provide supportive and facilitating environments for young learners, educators frequently overlook the potential contributions of engineering. The discipline lends itself effectively to nurturing young children's natural ways of thinking, while at the same time promoting engineering knowledge, thinking skills, and productive problem-solving. When looking at how young learners explore, interact, and think about their world, it is important to consider different ways of shaping environments that facilitate this growth. The importance of providing learning environments that capitalize on young children's natural capabilities was emphasized in Moss, Bruce, and Bobis' (2016) review of challenges and developments in early mathematics learning. Their review indicated how the development and implementation of enriched and expanded programs in the early years are being increasingly recognised as crucial for future achievement, with associations such as the National Council of Teachers of Mathematics and the National Association for the Education of Young Children (NAEYC/NCTM, 2009) strongly endorsing such programs.

Research on early science learning has also revealed young children's innate talents in the STEM fields. Studies have highlighted their fundamental understanding of observational phenomena and knowledge about the natural world that results from investigating and exploring their environment (Eshach & Fried, 2005; French, 2004). This innate curiosity and sense of wonder about the world around them leads to a natural tendency to observe, explore, and try to explain their everyday experiences (Eshach & Fried, 2005). Even before entering school, young children are able to recognize patterns and then use those causal and relational patterns to reason about living things and natural phenomena (Inagaki & Hatano, 2006). As these young learners are exploring their environment and acquiring knowledge, it is their personal experiences that form the foundation for their understanding of and interactions with the natural and manufactured world (French, 2004).

While the focus for these experiences is often the natural environment, there are also interactions within the designed, human-crafted world. Engineering comes to the fore here, with opportunities to build upon and engage children's desire to make things and to learn how various objects work (Brophy, Klein, Portsmore, & Rodgers, 2008). Engineering also provides an avenue for young children to be introduced to technology, not just as digital media, but also as all parts of the designed world.

In sum, with children's curiosity and motivation to explore their world, they inherently alter their environment to fit their needs. These alterations are the beginnings of engineering thinking. In harnessing children's innate ways of thinking within their environments, engineering experiences can foster structured decision making within a specified engineering context.

2.3 Building upon Intrinsically Interesting Problems

Along with this natural curiosity to learn about and investigate their world, young children spend substantial time troubleshooting and designing as they explore various problems in their surroundings. For example, Bairaktarova, Evangelou, and Brophy (2011) observed students during exploratory play where they intentionally modified existing structures or artifacts to solve a problem. They also continually tested the limits of their experimental designs by adding "one more block" and observing what works and what does not (Bairaktarova, Evangelou, & Brophy, 2011). These examples illustrate the idea that young children often spend time-solving problems, which tend to be open-ended or ill-structured, with parallels to problems and problem-solving skills that are characteristic of engineering (Brophy et al., 2008; Watkins, Spencer, & Hammer, 2014). In fact, many common behaviors expressed by young children, such as their desire to ask questions, explore, and develop creative solutions, resemble highly desirable traits within engineering. As such, these behaviors can be viewed as precursors to engineering and engineering thinking (Brophy & Evangelou 2007; Lippard, Lamm, & Riley, 2017; Van Meeteren & Zan, 2010).

Engineering experiences can also help students and teachers move beyond simply solving problems to emphasizing a level of intentionality and motivation in their actions. Such intentionality was revealed in Fleer's (2000) study as preschool children were able to plan, design, and then use their prior experience with materials to predict which materials they need for their designs. Additionally, young children have been shown to communicate their plans for constructing products with some level of intention, which has been shown to extend even to the evaluation of their designs (Johnsey, 1995; Brophy & Evangelou, 2007; Bagiati, 2011). Furthermore, studies of pre-schoolers engaging in block-building and other free-play activities have identified instances where students solved problems and pursued goals that met a certain set of constraints and engaged in iterative cycles of problem-solving in achieving the goal (Bairaktarova et al., 2011; Brophy et al., 2008). In essence, early engineering experiences build upon young children's inherent desire to solve problems and alter their environment to fit their needs, while also promoting early problem-solving skills and encouraging progress beyond just solving problems.

2.4 Providing a Vehicle for Curriculum-Based Child-Centered Play

The important role of play in early education has a long history (e.g., see Moss et al., 2016). It is well recognized that play can foster the development of positive dispositions and habits of mind including curiosity, creativity, diverse problem-solving, and communicating ideas and emotions (e.g., Ginsburg, 2009; NAEYC, 2010). On the other hand, there are debates regarding the extent to which specific disciplines such as mathematics and science should be learned through a play-based approach.

For example, a common belief has been that all mathematics learning should emerge from child-directed play. Although the importance of young children being actively involved in constructing their mathematics and science knowledge cannot be disputed, there remain questions about the appropriate learning environments and supports needed to maximize such learning. As Moss et al. (2016) indicated, there are potential limitations in relying on unguided play for deep early learning in mathematics. While it is well acknowledged that play has an important role in young children's discipline learning (e.g., Perry & Dockett, 2008; Sarama & Clements, 2009), such an approach does not ensure maximum mathematical development (de Vries, Thomas & Warren, 2010, p. 717). Sarama and Clements (2009) further illustrated how desired mathematical concepts are unlikely to be developed when children play with mathematics-related materials and objects solely by themselves.

Referring back to our discussion on environments that facilitate early engineering learning, it is worth considering briefly Moss et al.'s (2016) review of new developments in the field. Citing a "playful pedagogy" approach, Moss et al. report on research suggest that a "middle ground" between free play and direct instruction may be most effective in improving access to a more in-depth and broader array of early mathematics learning opportunities. Such an approach integrates a child-centered play mode with curricular goals and allows children to control their learning to a large degree. Baroody's (2006) early years continuum of pedagogies for mathematics features four main aspects, ranging from traditional direct instruction, to guided discovery learning through an adult-initiated task, through to flexible guided discovery learning by means of a child-initiated task, and finally, unguided discovery involving a child-initiated task. Not surprisingly, Baroody's classroom observations revealed that the mid-way approaches, namely discovery and flexible guided discovery, were the most promising for fostering mathematics learning, although each the four approaches had an important role in early childhood environments. Additionally, Moomaw's (2014) findings illustrate the rich and varied science, math, and engineering experiences that young children routinely encounter in a high-quality early childhood classroom, where learning and play are intentionally combined. Consequently, when examining early childhood experiences within the frame of a play-based approach, early engineering provides an opportunity to establish environments that support intentional and explicit connections between science and mathematics content and the free-play environments that are frequently seen and promoted in early childhood classrooms (Bairaktarova et al., 2011).

2.5 Integrating Engineering Within the Regular Curriculum

Engineering in the early grades should include varied opportunities for students to experience examples of engineering and engage in engineering design and thinking activities that allow them to begin to understand engineering as a broad discipline.

At the same time, such activities should provide ways for them to dig deeply into aspects of the domain. Developing engineering thinking is not a straightforward task, nor is incorporating the domain within an already overcrowded curriculum (Lippard et al., 2017).

One approach to addressing these difficulties is through integrating engineering within the other curriculum disciplines, as illustrated in several chapters in this book. Indeed, engineering is seen as providing a foundational, cross-disciplinary link that contextualizes students' mathematics, science, and technology learning (e.g., English, 2017; Moore et al., 2014; Zawojewski, Diefes-Dux, & Bowman, 2008). Although engineering design processes provide important foundational links across the STEM disciplines and enable students to appreciate how multiple ideas, approaches, and tools can be applied to complex problems involving more than one solution (Purzer, Hathaway Goldstein, Adams, Xie, & Nourian, 2015), their multiple applications in the curriculum are not being acknowledged adequately.

Although frameworks for integrating engineering learning within the early school years are not prolific, Bryan, Moore, Johnson, and Roehrig's (2016) "STEM Roadmap" provides a rich source of ideas. Within their framework, engineering design and practices form a key component in linking science and mathematics, with five core instructional features advanced: (1) the content and practices of one or more of the science and mathematics disciplines comprise some of the primary learning goals; (2) engineering practices and engineering design of technologies, either as the context or the intentional learning content or both, serve to integrate the disciplines; (3) the scientific and mathematical concepts that are required for the engineering components include design justification; (4) the development of twenty-first-century skills is highlighted; and (5) the instructional context requires solving a real-world problem or task through collaborative groups.

Importantly, as emphasized by both Bryan et al. (2016) and Lippard et al. (2017), STEM integration needs to be "intentional" and "specific" with consideration given to both content and context. Three forms of STEM integration are: (a) content integration where learning experiences have multiple STEM learning objectives, (b) integration of supporting content where one area is addressed (e.g., mathematics) in support of the learning objectives of the main content (e.g., science), and (c) context integration where the context from one discipline is used for the learning objectives from another (Moore & Hughes, 2019; Bryan et al., 2016). Although the integration of supporting content is frequent, it appears not to be applied in a way that effectively extends this content (Bryan et al., 2016). Unfortunately, the broad contributions of engineering education to early children's learning are not being adequately recognized in many nations. Yet as the report *Engineering in K-12 Education* (National Academy of Engineering and National Research Council, 2009) stressed, "In the real world, engineering is not performed in isolation—it inevitably involves science, technology, and mathematics. The question is why these subjects should be isolated in schools" (pp. 164–165).

2.6 Perspectives on Early Engineering

This chapter has reviewed several different ways in which engineering is developmentally appropriate for, and beneficial to, early engineering learners. Throughout the remainder of this book, there are chapters that provide different perspectives on engineering in the early grades.

Engineering thinking is broader than engineering design alone. While engineering thinking includes engineering design, it also highlights that engineers are independent thinkers who seek out new knowledge when solving problems (Moore et al., 2014). Often the ways in which engineers think beyond just design are called engineering habits of mind. According to the Royal Academy of Engineering in the UK (Lucas, Hanson, Bianchi, & Chippindall, 2017), the core engineering thinking attribute is "making 'things' that work and making 'things' work better" (p. 5). The report further separates this core attribute into the engineering habits of mind that include improving, systems thinking, adapting, problem-finding, creative problem-solving, and visualizing. Other definitions of engineering habits of mind also include optimism, collaboration, communication, and ethical considerations (National Academy of Engineering & National Research Council, 2009). It has been argued that when engineering design, combined with engineering thinking, is made an explicit outcome of learning, students have increased opportunities to become independent and reflective thinkers with the skills needed to integrate multiple ideas in solving problems (Bryan et al., 2016; Lucas et al., 2014). Furthermore, engineering design processes serve to help students make connections between engineering and the other STEM disciplines as well as assist students to recognize that engineers think through problems in a systematic way.

As we consider how to implement engineering with young learners and different ways to harness students' natural ways of thinking, we see there are several different perspectives on introducing students to engineering. From the work presented in this book, we see that open-ended challenges are helpful in fostering problem-finding and creative problem-solving, that play in engineering can foster all of the engineering habits of mind, and that more formal design is effective in nurturing specific learning objectives particularly with content outside of engineering. The chapters demonstrate that there should not just be one approach to engineering learning in the early grades, but rather a mixture of learning opportunities that should provide a more well-rounded education.

2.7 Concluding Points

With the inclusion of engineering in the early grades, it is important to examine how engineering, engineering design, and engineering thinking can facilitate student learning and support teaching and learning across content areas. When presented in developmentally appropriate ways, early engineering can help young learners by supporting the development of natural ways of thinking into productive problem-solving. Young children come to the classroom with ideas about the natural and designed world that are developed as they explore, test, and modify the world around them. Early engineering provides an environment that encourages this curiosity and motivation to explore and alter the world around them. As students are investigating their world, they often engage in creative problem-solving as they try to better understand why things work and how to improve them. Incorporating engineering into early childhood classrooms builds on these problem-solving opportunities that are intrinsically interesting for young children and provide a structure that can help them move beyond simply solving problem to a level of intentionality with their problem-solving. Engineering also has a focus on iterative thinking that encourages children to engage in multiple rounds of investigating, testing, and modifying these problems that encourage deeper understanding. Many of these problem-solving opportunities occur as students are engaged in child-centered learning and play. Early engineering provides a vehicle for facilitating more intentional content connections and content learning within this child-centered approach common in the early grades. Therefore, when thinking about the bigger picture of student learning and development in the younger grades, early engineering experiences can build up contexts that are realistic and motivating for young children while also provide a way to integrate learning across subjects.

While it is important to recognize the affordances that early engineering can provide, it is also important to note the multiple ways in which engineering and engineering design can be presented in a developmentally appropriate manner for young learners. There are several approaches to engineering that can be used with young children; these multiple perspectives allow students to think about and engage with engineering, engineering design, and engineering thinking in different ways. These different ideas around engineering should not be in competition with one other, but should be more of a multiple representations approach to engineering for young children, affording them the opportunity to engage more deeply with engineering content, skills, and habits of mind.

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Chapter 3
Encouraging the Development of Engineering Habits of Mind in Prekindergarten Learners

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Abstract Experiences in early childhood set the foundation for lifelong learning. Given the integrative and applied nature of engineering and children's natural curiosity, we suggest that prekindergarten classrooms are well suited for providing opportunities to promote the development of engineering habits of mind (EHM). Developmental theories suggest that children learn best through hands-on experiences that enable them to explore and discover concepts themselves and that others in the child's environment can serve as active partners in exploration. Recognizing the emphasis on integrated curriculum in early childhood and the competing demands for time in preschool classrooms, we identify the EHM as an appropriate early engineering emphasis that can be embedded in everyday classroom moments. To this end, this chapter begins by pointing out connections among science, math, and engineering for early learners, highlights theories that inform our work with engineering in prekindergarten classrooms, discusses EHM in prekindergarten learners, briefly presents a pilot study of observing EHM in prekindergarten classrooms, and ends by drawing overarching conclusions and suggesting future directions for incorporating EHM into prekindergarten classrooms.

3.1 Introduction

Within the prekindergarten environment, children are drawn to opportunities that naturally engage them in engineering processes, skills, and thinking (Bagiati & Evangelou, 2011, Chap. 6; Gold, Elicker, Choi, Anderson, & Brophy, 2015). Recent work from leading psychologists indicates that prekindergarten children are inclined to think like engineers. Children are open to taking in new information and effective at using it to formulate hypotheses, even more so than adults (Lucas, Bridgers,

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Griffiths, & Gopnik, 2014). They are more likely to attempt systems thinking when given open-ended opportunities with materials, as opposed to when they are given direct instruction (Bonawitz, Shafto, Gweon, Goodman, Spelke, & Schulz, 2011). Opportunities to engage in engineering thinking and testing are abundant in prekindergarten classrooms, as several chapters in this book have illustrated. Such opportunities may occur when children run out of a paint color and decide to mix two colors to produce the color they want, use blocks to build a bridge, or investigate how a new toy in the classroom operates. Each of these situations offers children an opportunity to engage in engineering—solving problems and making decisions within a given set of constraints to meet a goal (Katehi, Pearson, & Feder, 2009). These same situations require children to apply practical math and science principles to address their needs or wants.

Prekindergarten children who participate in engineering thinking and learning are better equipped for math and science learning. In terms of early mathematics, children's skills can be classified into those related to quantity and numeracy and those related to geography and spatial thinking (Clements & Samara, 2007). For example, Verdine and colleagues (2014) define spatial skills as "mentally manipulating information about the structure of the shapes and spaces in one's environment "(pg. 1062). They found that prekindergarten children's spatial assembly skills were related to other early mathematical skills including counting and number sequencing. Building and other design-related engineering activities challenge children to strengthen their spatial logic and geometric thinking as they attempt to fit components of a system together (e.g., see Chap. 5). In the prekindergarten classroom, performing an engineering task such as building with Marbleworks® pieces encourages children to explore how pieces of different sizes and shapes can be manipulated and formed to produce a desired structure. Indeed, early engineering play in block building is associated with children's achievement in math courses into middle school (Wolfgang, Stannard, & Jones, 2001). Beyond traditional engineering play of building, addressing engineering problems such as moving water during water play exposes children to math concepts of measurement, volume, and conservation.

Science skills are also utilized in engineering play in the prekindergarten classroom. Hypothesis generating and testing are key science skills children practice in engineering solutions to everyday classroom problems. For instance, if children drop a toy behind a shelf, they have now set up a problem to solve in trying to retrieve the toy. Children may hypothesize that the toy can be retrieved with a ruler, some string, or a long piece of tape and then move to testing each of these. In addition to testing hypotheses, children will learn about the characteristics and limitations of various materials (e.g., a long piece of tape sticks not only to the toy you intend, but also to the wall or itself; rulers are stiff which makes them better than string for pushing toys). As children encounter these problems and make use of various materials, they are likely to encounter science concepts related to textures, mixtures and solutions, density, solubility, geology, heat transfer, and even chemistry. Further illustrations of these various STEM developments appear in Sect. 2.

3.2 Theory

Prekindergarten children (3–5 years) learn through hands-on experiences and interactions with others (Dewey, 1997; Piaget & Cook, 1954; Vygotsky, 1978/1997). This understanding is guided by two theoretical perspectives—constructivism (Dewey, 1997; Piaget & Cook, 1954) and sociocultural theory (Vygotsky, 1978/1997). These theoretical perspectives work in tandem to highlight how children learn when they engage with their environment and others in that environment.

Key propositions we draw from constructivism are that children construct knowledge through manipulating and acting upon materials in their environment and the environment itself (Piaget & Cook, 1954) and that these interactions must be meaningful to the child (Dewey, 1997). Such behaviors as hypothesizing and testing and revising through trial-and-error are indicative of this hands-on learning. Gopnik and Wellman (2012) support the constructivist understanding of learning in their work suggesting that children learn through Bayesian modeling or a series of advanced computations that are made at a subconscious level to determine what the most likely outcome is of a given stimulus.

Sociocultural theory suggests that interpersonal interactions promote new levels of understanding, where continuous interaction with more competent others allows individuals to revise and advance their levels of understanding (Newman & Newman, 2009; Vygotsky, 1978/1997). It is imperative that teachers act as aids and collaborators in the learning process rather than providing direct instruction. This learning approach requires children to be active participants in their learning as they draw on their current skills to help them with the higher-order task. Peers may also take on the role of a more advanced other in the learning process. Like teachers, peers may ask questions or prompt ideas. Mercer and Howe (2012) suggest that sociocultural theory is well suited for explaining teaching and learning because it illuminates both how individuals gain new knowledge (acquiring it from others who possess more than them) and also how the shared knowledge of a group or society progresses through interactions. This is very fitting for learning in engineering as the individual goals children are trying to accomplish in solving problems are situated within a larger context of shared norms and goals.

Constructivist and sociocultural theories have been, at times, pitted against each other. However, the complex and interdisciplinary nature of engineering and the equally complex phenomena of child development necessitate consideration of a multi-theoretical approach. Bruner (1997), while acknowledging distinct differences, suggests integrative points of the two theories. In particular, a socioconstructivist perspective highlights that children learn not only through their own individual interactions with materials and the environment, but also that interactions with other children and teachers may impact on how children interact with materials and the world around them. Further, children learn through interactions and activities that are meaningful to them personally in the context of the meaning held by their larger social context. As we have worked to understand children's development of engineering habits of mind, we are guided by a socioconstructivist perspective that informs our work with three specific expectations: (1) children develop EHM by addressing everyday problems and goals because these problems and challenges are meaningful to them; (2) children learn through actively interacting with and acting on materials in their environment, and (3) children's interactions with materials and the environment can be enhanced by interactions with others (i.e., teachers and peers).

3.3 The Literature Review

Engineering habits of mind are a set of "values, attitudes, and thinking skills associated with engineering" (Katehi et al., 2009, p. 7). Katehi and colleagues define six engineering habits of mind (EHM) to be fostered in K-12 education: systems thinking, creativity, optimism, collaboration, communication, and ethical considerations. The EHM are not a prescribed curriculum, but rather can be viewed as developmental outcomes that arise from children's meaningful interactions with engineering concepts and activities. For this reason, EHM can be embedded and facilitated within existing classroom curricula and practices. Table 3.1 summarizes the six EHM discussed above by listing a definition for each habit and identifying several examples from the K-12 literature that explore that particular habit. It is encouraging that K-12 educators are finding ways to integrate the facilitation and assessment of EHM into existing classroom practice (Besser & Monson, 2014; Bottomley & Parry, 2013; Glancy, Moore, Guzey, Mathis, Tank, & Siverling, 2014; Tank, Moore, Babajide, & Rynearson, 2015; Chap. 4). This is in contrast to facilitation and assessment strategies for EHM that rely on units with particular activities or engineering tasks that must be introduced into the classroom by the teacher, in addition to what is already occurring in the classroom (Chiu & Linn, 2011; DeJaegher, Chiu, Burghardt, Hecht, Malcolm & Pan, 2012; Hobson Foster, Husman & Mendoza, 2013; Loveland & Dunn, 2014). Below we discuss each EHM in further depth and suggest how it might be particularly important for prekindergarten children.

3.3.1 Systems Thinking

Systems thinking facilitates higher-order thinking as children seek to identify and understand interconnectedness and how materials relate to each other and contribute to the system as a whole (NAE & NRC, 2009). The prekindergarten classroom context encourages children's systems thinking by offering opportunities to explore objects within distinct learning areas and to examine interconnectedness when materials are combined across learning areas. These opportunities challenge children to consider the properties and functions of various materials, which also promotes scientific thinking as well as vocabulary development. Rehmann, Rover, Laingen, Mickelson, and Brumm (2011) identify four features that are common to many definitions of systems thinking—(1) "viewing a problem broadly and holistically"; (2) "identify-