Early Engineering with THINK, MAKE, TRY®

A LITERATURE REVIEW

Bay Area Discovery Museum

THINK, MAKE, TRY,

About the Bay Area Discovery Museum

The Bay Area Discovery Museum has been helping children and families grow and thrive since opening its doors in 1987. Located in Sausalito, CA, the museum is a special place where every child can immerse themselves in play, connect with others and make new discoveries through exciting (and often messy!) hands-on learning.

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Introduction

The U.S. Bureau of Labor Statistics (2022) has predicted that between 2021 and 2031 the United States will see an 11% increase in STEM (Science, Technology, Engineering, and Mathematics) jobs. Engineering, the "E" in STEM, is the least studied and taught of the STEM fields, especially in children's younger years (Bustamante et al., 2018; English, 2018). Yet, to meet the needs of infrastructure rebuilding, energy usage, and robotics, many engineering jobs will need to be filled (Torpey, 2018).

In an effort to prepare students to join the STEM pipeline at our universities and beyond, K-12 educators have been pushed to bring more and broader STEM experiences to children. The Next Generation Science Standards [NGSS] for K-12 education (National Research Council [NRC], 2013; www.NextGenScience.org), recommend that science education focus not only on core concepts but also include practice (i.e., students should "do" science with real-world applications). Further, this education should be integrated across different domains of science as well as with technology, engineering, and math (for a summary, see Wilson & Bintz, 2014). In fact, when the NGSS refer to *science*, it is often used in conjunction with engineering (i.e., "science and engineering").

In this paper, we set out to define engineering, both broadly and in detail. What are the traits of engineering? How is engineering different from scientific inquiry? How does it connect and interact with other disciplines? Although we know society will need many types of engineers in the future, we also know that the engineering profession is not for everyone, so why focus on it?

Research suggests that children who are exposed to engineering tasks at a young age may be more likely to pursue STEM-related coursework in subsequent years, but importantly, the skills involved in engineering will benefit all children, improving their success in many aspects of school and life. Engineering requires observation, exploration, risk taking, problem solving, and collaboration. These skills, which young children can learn and practice from a young age, are applicable to real-life situations and will help children develop empathy for others.

We use the Bay Area Discovery Museum's **Think, Make, Try**® approach to early engineering as a framework to provide details about specific cognitive skills that are facilitated while engaging in the engineering design process. We reviewed more than 150 studies in cognitive and developmental psychology and education. Due to minimal focus on engineering-related curriculum, training for educators, and research with very young children, engineering-relevant research in the early childhood years was not always available. Therefore, to paint the most cohesive picture of the skills we describe, we have included studies that focus on the other areas of STEM as well as some with participants through the middle school years and beyond. In addition to peer-reviewed journal articles, we have included classroom practice examples from educator resources.

What Is Engineering?

The National Academies of Sciences, Engineering, and Medicine (2020) have defined engineering as a way to solve problems as well as the knowledge of design and processes used in this process. Engineers design and advise on most human-made objects and systems, such as the development of bridges, cars, and water supply networks; road and tunnel construction; computer networks; fuel and natural gas systems; and medical tools and devices. The major disciplines or branches of engineering consist of chemical, civil, electrical, mechanical, and interdisciplinary (e.g., biomedical or software). In Table 1 (at the end of the publication), we highlight these major branches of engineering, describing their work and links to our lives and providing examples of current and historical engineers.

The Engineering Design Process

Although engineering is a distinct piece of the STEM acronym, engineers use learnings from all the STEM disciplines, along with art, as they design products. (Some people use the STEAM acronym to acknowledge the important role of art in developing projects and solutions.) Many people wonder about the difference between engineering and science, and while the two overlap, they are fairly distinct in their goals. Scientists seek to understand how the natural world works, whereas engineers design processes and products for society. Both disciplines involve some trial and error to get their process or product to work effectively, but scientists generally use the scientific method, or hypothesis testing, to test theories while engineers use findings and knowledge from science (as well as the other STEM disciplines) to inform their design process.

Many organizations and educational institutions have described the engineering design process, and some offer curricula or activities to support adults in facilitating this process with children. Despite a variety of approaches, common themes exist. Several models and their accompanying resources created for PreK-grade 12 children and educators include:

- **Science Buddies** – Science Buddies provides free online STEM resources for children, caregivers, and educators including descriptions of topic areas and hands-on activity ideas. They describe a nine-step process: define the problem, do background research, specify requirements, brainstorm/evaluate/choose solution, develop and prototype solution, test solution, evaluate whether the solution meets requirements, and communicate results. With this model, if the solution does not fully meet the requirements, children are directed to go back to the brainstorm, prototype, and testing stages.

- **Engineering is Elementary Curriculum (EiE®)** – EiE® includes curriculum and activities as well as professional development offerings for purchase from the Museum of Science, Boston. They describe the engineering design process as a cyclical process that includes five steps: ask, imagine, plan, create, and improve. As children evaluate whether their design works as planned, they are encouraged to "improve" their creation as necessary.

- **NASA's BEST Engineering Design Model** – The NASA's Best website provides a series of free

STEM professional development resources and activities for educators as well as activities and games for children. Their engineering design process was adapted from the EiE® model and is a cyclical process that includes six steps: ask, imagine, plan, create, test, and improve. Based on their tests, children identify and justify changes to their designs.

The engineering design process generally involves many steps that move through various stages of planning and testing designs. An important feature of all the processes is that they are iterative. In other words, as children create a product, they do not simply move sequentially through all the steps. Rather, they may move back and forth through steps, or even start over from the beginning, as they create and test their design to determine whether it meets the requirements defined by the problem that needs solving.

Design-Based Education

Traditionally, the engineering design process had been reserved for high school and college-level courses, however, research suggests that using an engineering design process is valuable for students of all ages and can be implemented across a variety of disciplines. In education, curricular approaches to applying the engineering design process are sometimes referred to as design-based or project-based learning. Design-based curricula require students to be hands-on learners or creators as they are designing their project to solve a problem. During the process, students need to take a "design stance" or use "design thinking," which is understanding the intentional purpose behind creating a specific object and includes stating a problem, brainstorming solutions, and testing and evaluating them. When adults encourage and facilitate a design stance, they empower children to be creative and develop confidence in taking charge of their own learning and development of ideas (Carroll et al., 2010).

Young children naturally engage in the design process through play, and research suggests that children are successful with design challenges that are presented in familiar, meaningful, and engaging situations (English & Moore, 2018). Crismond et al. (2013) examined how young

students incorporated design and inquiry as they created and tested a spinning toy called a whirligig. In their study, teachers instructed two groups of children (PreK – grade 2 and grades 3 – 5), on how a whirligig worked. Teachers used slow motion cameras to help students visualize differences in design and outcomes and then challenged students to design a better whirligig. The researchers found that students understood their goals for building the whirligig and that their own abilities could improve its design. However, the youngest students had more difficulty recognizing and troubleshooting design issues as they arose, and at times, the order of the release of the whirligigs distracted them from the ultimate task of observing the whirligigs for design expertise or flaws.

English and King (2017) found that fourth grade students were fairly successful at using an interdisciplinary engineering design process to design a tower with specific constraints. Specifically, the tower needed to be three stories, use 14 pylons (cardboard tubes), and have three platforms (cardboard sheets). Researchers observed students working collaboratively while designing and redesigning their towers, and students' sketches demonstrated their thinking about how different parts of the tower worked together to increase stability. English and King suggest that using engineering design-based problems can assist students with application and integration of their STEM knowledge.

While engineering requires design, design-based education also has been used as a process to teach a variety of academic disciplines such as math, science, and social science (Cellitti & Wright, 2019; Penner et al., 1998; Puntambekar & Kolodner, 2005). Wicklein (2006) argues that engineering design curriculum provides a platform for integrating science, mathematics, and technology, and research shows that using engineering-based curricula for teaching these disciplines improves important academic skills across all disciplines (Brophy et al., 2008; Gold et al., 2020; Li et al., 2016; Marulcu & Barnett, 2013; Wendell & Rogers, 2013).

Penner et al. (1998) used a design-based approach to teach third grade students about the biomechanics of elbows. Students worked in pairs to build model elbows and then engaged in full-class discussions as groups shared their models. Following discussion and evaluation by the class, students revised their models. The researchers argue that the design process was important in helping the students understand the true functionality of an elbow as it relates to muscles and force.

In another study, Wendell and Rogers (2013) looked at the impact of an engineering design curriculum, *Science through LEGO® Engineering*, to teach science content to elementary students. Third and fourth grade students were asked to design an animal model, model home, people mover, or musical instrument. After engaging with the engineering curriculum, students not only improved from pre- to post-tests, they also demonstrated greater performance gains as compared to if they had learned their school's typical science curriculum. Gains, seen in both physical and life science, were also evident compared to the status quo teaching methods of the districts. Further, students in the study said they enjoyed the engineering lessons and wanted to do more of them.

Li et al. (2016) found that using an engineering design-based process to teach science concepts (e.g., physics) can significantly improve students' problem-solving abilities. They assigned fourth grade students a series of tasks, such as building a crane to lift weights or a platform scale to weigh goods, and then small groups used LEGO® to construct these designs. Students in the control group were instructed using a common science pedagogy that included creating situations, analyzing problems, and building and testing a prototype. Students in the experimental group were instructed using an engineering design-based pedagogy that included describing the problem, analyzing constraints, and deciding on an optimal solution. While students in both groups improved in learning performance, further analyses showed that students in the experimental group experienced significant improvement in their ability to identify optimal solutions. The researchers argue that the engineering design-based process provides a scaffold for learning science by providing a step-by-step method for working on a problem.

Crismond and Adams (2012) outlined best practices in teaching design strategies at all age levels. They argue that the ability to adapt big picture perspectives can help a designer prioritize the problem-solving steps that are important starting points in design stance. For young children, taking time to think through a plan before grabbing materials and trying to create a solution is the first step. When children are older or more experienced, higher-level planning might include asking constraint and criteria questions and incorporating sketches before embarking on a design solution.

In taking a design stance, children are not simply focused on the end-product, but explore all aspects of the problem, including different possible solutions and multiple iterations of a design (Carroll et al., 2010). Being able to effectively use these design strategies contributes to successful problem solving and solutions. Ultimately, researchers suggest that children who are provided with opportunities to engage in design thinking while working through problems not only learn content knowledge but also express excitement and engagement about the work and practice important skills such as collaboration (Carroll et al., 2010; Penner et al., 1998).

Engineering's Foundational Competencies

Problem solving and collaboration are foundational skills that are crucial to success across the entire engineering design process. Regardless of the specific engineering discipline or career, all engineers need to master these skills. Children can learn and practice problem solving and collaboration at a young age, and when these skills are taught with a focus on engineering, children learn that they can apply to real-life situations. Ultimately, the ability to effectively problem solve and collaborate will benefit not only future engineers but all children as they navigate school and life.

Problem Solving

Problem solving occurs when we encounter a problem for which we do not know the answer. It is one of the most important skills in our everyday personal and professional lives (Jonassen, 2000). In general, engineering problems are what many researchers call "ill-structured," meaning that there are many possible solutions and multiple ways to reach those solutions. Some parameters may be known, but the best materials or design are up for discovery. Furthermore, engineering solutions can always be improved upon. With engineering problems, if two groups are given the same problem, two divergent solutions are inevitable.

Moore et al. (2018) argue that young children instinctively engage in engineering thinking because their natural curiosity and motivation to explore the world leads them to alter their environments to fit their needs (p. 11). For example, babies throw objects off their highchairs to observe the phenomena of gravity, force, and motion as well as the rebound properties of certain objects like spoons or cups of water. Children can see problems for which the solution is not prescribed but worked out in everyday life, such as when a baby uses use a cloth or string to retrieve a toy out of reach (Keen, 2011).

Although young children are natural problem solvers, discrepancy exists about whether adults should teach children about problem solving or allow them to make discoveries on their own; and researchers who support such teaching may disagree on how to do so. Some researchers argue that it is important to explicitly teach students about representing problems in multiple ways (e.g., Jonassen, 2000), while others suggest that defining the goal is not always the best way to present a challenge (Kapur, 2016; van Merriënboerm, 2013). van Merriënboerm (2013) says that allowing students to discover problems and then invent their own solutions strengthens their natural problem-solving abilities. According to van Merriënboerm, actions that simulate real-world scenarios can illustrate how professionals may use their expertise to determine steps for problem solving as well as what barriers may present throughout the design and implementation process. Kapur (2016), on the other hand, suggests that having students engage in problems which they may not be able to effectively solve might serve to better prepare them for future learning.

One middle ground approach to facilitate students' creative problem solving is to present cases where they might use analogical or metaphorical thinking (Lewis, 2009) – in this way, students are not explicitly taught or left to discover problem representations or solutions on their own. Holyoak et al. (1984) found that preschoolers can successfully use analogies to assist with problem solving. In their studies, children were asked to find as many ways as possible to move gumballs from one bowl to another bowl using provided supplies (e.g., poster paper, cardboard tubes, string, tape, rubber bands). Preschoolers who first listened to a fairy tale about a genie who wanted to move his jewels to a new bottle successfully mimicked the strategy they heard (i.e., using his "magic staff" to pull the second bottle closer or shaping his "magic carpet" into a tube so he could roll the jewels through) as one solution to their gumball problem.

In the study described above, children not only used the fairy tale analogy to problem solve, but they also realized that they could use an object in new ways, not as originally intended. This knowledge can be an important piece of developing creative solutions to problems. Defeyter and German (2003) conducted a set of studies with 5- to 7-year-old children that tested what researchers call "functional fixedness" – or their fixed usage of tools (e.g., the idea that a comb can only be used to run through hair). Researchers first confirmed that children knew what specific tools were used for, and then asked them to solve problems that required them to use the tools in atypical ways. The 5-year-olds showed less functional fixedness, allowing for more creativity in problem solving, meaning that they were not limited by the intended purpose of the tools. For example, a child might use a hammer to squash clay rather than to pound nails, and while the hammer is in use, another child may pound pegs into a board with a rolling pin. The researchers argue that because younger children (5-year-olds) have a less rigid concept of objects, creativity might be fostered by simply not discouraging alternative uses for tools (e.g., buckets can be used as stools or to hold water) (Defeyter & German, 2003). In contrast, providing older children (6- and 7-year-olds) a demonstration of the function of a tool obscured their ability to see other uses for it, even those that may have helped them solve the problem. The fact that this conceptual change occurs at the transition to elementary school demonstrates that allowing children to express their creativity in problem solving should be nurtured and encouraged beyond the PreK years.

Collaboration

Engineers are asked to create products meeting specific constraints to solve problems. Collaboration with others allows them to understand how the product will impact or meet the needs of the users, as well as its specific content features. In fact, sometimes several types of engineers must work together or with other field experts to jointly solve problems. For example, if an engineering firm is building a bridge, they may enlist a team that includes a structural engineer, a traffic engineer, an environmental engineer, and a geologist. Engaging this multidisciplinary team is important to better understand how the structure of the bridge will be used and will impact where the bridge will be built. To have successful collaborations, engineers must be able to communicate ideas and convey their thoughts in ways that others can understand, share information about concepts and results, and remain open to the ideas of others.

The skill of collaboration, which includes flexibility and the ability to work well with others, is essential in brainstorming and sharing workloads. Collaboration involves knowing when to take the lead and knowing when to listen to others' ideas. Researchers suggest that rich learning opportunities exist when students collaborate in hands-on projects where they can learn from one another (Darling-Hammond et al., 2020; Jordan & McDaniel, 2014). Collaborative classwork is one way that children practice working in groups, and without the teacher-student power dynamic, some students flourish. Boaler (2008) suggests that group math work allows children to learn from one another and share in the delight of solving what may seem to be an unworkable problem. There are multiple paths to math solutions and allowing children to work together may lead to a greater appreciation of other viewpoints and techniques.

Jordan and McDaniel (2014) found that experiencing uncertainty during group problem solving facilitates student learning. They studied peer interactions among groups of fifth graders designing robots to address an environmental problem of their choice. Students were instructed using an engineering design process that included "brainstorming their problem and possible solutions, [and] building, testing, and troubleshooting the product" (Jordan & McDaniel, 2014, p. 498). Some of the final products included a robot that used a net to pick up polluting objects in a lake and one that people in wheelchairs could operate using remote control. The researchers identified three strategies that students used to manage uncertainty within their group: 1) developing a shared strategy (to address similar uncertainty), 2) providing information, arguing, or explaining (to assist a peer), and 3) addressing the uncertainty (to assist a peer who became uncertain during discussion). Jordan and McDaniel suggest that having to defend and fully explain ideas during the collaborative process helps students attain better comprehension.

Group play in both formal (e.g., school) or informal (e.g., home, daycare, playgrounds, museums) learning environments helps young children work on their communication skills. In an observational research study with 3- to 5-year-olds, Gold et al. (2015) found that children naturally engage in engineering-related communication about building and how things work during dramatic play or free play with big blocks more than when they are at an outdoor playground. Children communicated goals, design, and construction ideas, and tested their designs during the building and creating activities. Importantly, this research found no gender differences in engineering-related communication.

In the context of school, students who communicate to propose and justify solutions are more successful in solving science-related problems (Howe et al., 2007; Shin et al., 2003). This is true not only for older students but also for 4- to 6-year-old children asked to explain their reasoning and share conclusions around science explorations (Dejonckheere et al., 2016). Furthermore, research shows that the articulation of how a design is going to work, and the defense of its usefulness, can help students find flaws in designs (Crismond & Adams, 2012).

Build STEM Identity Early in Children

Verdin et al. (2018) argue that student perceptions of what it means to identify as a STEM person may provide either support or a barrier to pursuing STEM fields. Their research found that high school students thought it was important to be "good at" math or science to be a math or science person but also that anyone who was interested and worked hard could be a math or science person. However, the students had a more fixed view of what it took to be an engineer. They thought engineering was only for people who were "smart" and that students needed to be good at all STEM disciplines.

The belief that some fields, such as engineering, require brilliance or innate ability can negatively affect girls and underrepresented populations at a much higher rate (Meyer et al., 2015; Verdin et al., 2018). Further, environmental factors, such as competing with other students for instructor attention, the lack of female and people of color role models, and adult bias in STEM education due to a child's gender and gender stereotypicality, might steer some children away from STEM disciplines and careers (Newall et al., 2018; Witherspoon et al., 2016).

Providing early engineering and STEM education not only helps young learners develop skills and knowledge, but early STEM exposure also leads young children to develop positive STEM attitudes and self-perceptions (Aldemir & Kermani, 2017; Aschbacher & Ing, 2016; Clements et al., 2011; French, 2004; Fusaro & Smith, 2018; John et al., 2018). This positivity is important because early childhood is a time when learners form their own STEM identity and professional interests (McMurrer, 2008). For example, Capobianco et al. (2015) found that after engaging in activities based on engineering design, first graders developed a better understanding of the work of engineers

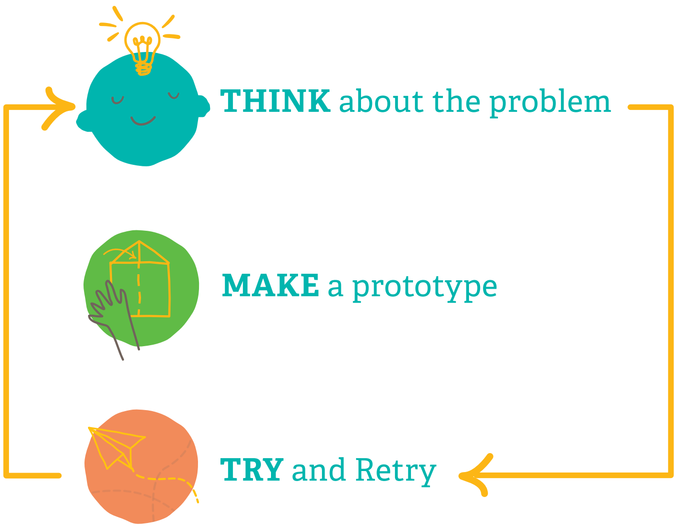
versus mid- to upper-level elementary students, who remained set in their original beliefs about engineers.

Research also shows that young children who are exposed to engineering-related tasks that require skills such as critical thinking, reasoning, predicting, and problem solving may pursue more STEM-related coursework at a later age (Cooper & Heaverlo, 2013; Dejonckheere et al., 2016). Therefore, it is important for adults to use early STEM exposure as an opportunity to teach children from the youngest ages that hard work is an essential piece to mastering subjects that seem challenging (Dweck, 2010), and to dispel myths about what engineering is and who can pursue engineering and STEM careers (Aschbacher & Ing, 2016; Brophy et al., 2008; Ozogul et al., 2017). Additionally, adults should be mindful of presenting a variety of ethnic and gender representations of STEM role models in the discussion of professions and design of programs (Ozogul et al., 2017; Witherspoon et al., 2016).

Gold et al. (2020) argue that very young children's peer play is already engineering-based; they make constructions with blocks or other building materials, a type of engineering play linked with better performance on assessments of math, spatial ability, executive function, and planning skills. These findings suggest that adults should be intentional about providing opportunities for children to engage in engineering design play. However, it is likely that both caregivers and educators need additional guidance and education in recognizing and facilitating engineering play behaviors and skills (Gold et al., 2020; Lippard et al., 2017). To that end, the NGSS recommend exposing children to engineering problems that are meaningful to their lives (NRC, 2013).

Bay Area Discovery Museum's **Think, Make, Try®** Engineering Design Process

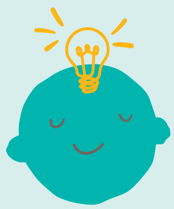
Research shows that young children benefit from curriculum based on engineering design – they show improvements in learning and understanding of STEM concepts and skills as well as other academic and socioemotional skills. However, when addressing our youngest learners, engaging in a long, multistep engineering design process has the potential to be confusing and cumbersome. The Bay Area Discovery Museum's proprietary engineering design process, **Think, Make, Try®**, describes an iterative way for young children to approach problem solving and designing using engineering skills along with math, science, technology, and art skills. **Think, Make, Try®** involves three steps that occur in an iterative cycle: 1) *Think* about a problem and brainstorm possible solutions; 2) *Make* a physical model of a possible solution; and 3) *Try* out that solution to see how it works (and then improve upon that solution by going through the process again).



Think, Make, Try® was created to build upon a child's natural curiosities and introduces the engineering design process as a mechanism to support the development of creativity, critical thinking, and collaboration. The process of building a physical model requires active, hands-on engagement, which research shows leads to better learning outcomes than more passive forms of learning (e.g., Hartman et al., 2000; Martinez & Stager, 2013). For example, Hartman et al. (2000) found that third grade students who built a model volcano retained more information about the topic than students who watched an adult build a model volcano.

By breaking down the engineering design process into three simple steps, the Bay Area Discovery Museum provides children with a framework that can guide their work and minimize frustration. Likewise, **Think, Make, Try®** provides adults with a manageable process to use while guiding young children.

When using the **Think, Make, Try®** process, children will build capacity in a number of cognitive skills that are fundamental for engineering design as well as for success in other academic disciplines and social-cognitive domains. In the pages that follow, we describe 10 core cognitive skills involved in the **Think, Make, Try®** process (see Table 2). It is important to note that while we present each cognitive skill within one domain of **Think, Make, Try®**, we recognize they are not discreetly tied to one domain; in practice, they span the entire iterative process.

THINK, MAKE, TRY® COGNITIVE SKILLS		
	Skill	**Definition**
 THINK	**Metacognition**	Ability to control and reflect on our thoughts
	Theory of Mind	Thinking about the goals and beliefs of others
	Executive Function	Keeping track of information and thinking flexibility
 MAKE	**Dual Representation**	Understanding of a connection between a symbol and what it refers to
	Spatial Reasoning	The way we visualize and navigate the world around us
	Sequencing	The ability to order different objects or events
 TRY	**Systems Thinking**	Understanding how individual parts function, how they relate to each other, and how each part contributes to the system
	Causal Reasoning	Ability to identify relationships between causes and the effects they produce
	Counterfactual Reasoning	Ability to think of alternative outcomes to past events
	Growth Mindset	The belief that our intelligence and ability can improve with practice

THINK

Think about a problem and brainstorm possible solutions

Children start working through the engineering design process when they identify and articulate their understanding of a problem. When children encounter a new or unusual setting or scenario, their curiosity is piqued, and through exploration, they may begin to find links to prior experiences or knowledge that will help them make sense of this new thing. In this way, without a formal concept of it, children begin developing their *metacognitive* skills. By observing what others are doing and attempting to determine why someone is engaging in a specific behavior, they instinctively use what is referred to as *theory of mind*. This skill may also be apparent as children share tools or allow another child to have access to a play object. Both theory of mind and metacognition are greatly facilitated by *executive function* skills which guide cognitive flexibility and impulse control. Actively working to solve a problem, either alone or with others, requires all three aspects of THINK – metacognition, theory of mind, and executive function – and facilitates children's development of empathy and their desire to be helpful, aids them in learning responsibility, and shows them that their ideas are valuable.

Metacognition

Metacognition, sometimes referred to as "thinking about thinking," is the knowledge about and ability to control and reflect on one's own thought processes (Flavell, 1979). Metacognition includes the ability to utilize that knowledge to complete or investigate a task or problem (Gok, 2010). We are more likely to find success with tasks if we draw on metacognitive skills such as assessing or considering our own knowledge, planning the steps or strategies to complete the task, and reflecting on our work. Research shows that students with better metacognitive skills are more successful learners (Darling-Hammond et al., 2020).

Metacognitive skills appear in early childhood and continue to develop gradually throughout adulthood and life (Kuhn, 2000). The skills are not specific to just one content area but can be used to improve performance or learning across all disciplines (Flavell, 1979; Schraw, 1998; Tarrant & Holt, 2016). Some children might be better at applying metacognitive skills in specific domains but not others. For example, one study found that children as young as 5 used metacognitive skills in the numerical domain but not in the socioemotional domain (Vo et al., 2014). Research suggests that younger children may have difficulty evaluating what they know and what they do not know (in fact, they tend to report that they have always known things), but importantly, children are also sensitive and responsive to learning opportunities (Hagá & Olson, 2017; Lipowski et al., 2013; Taylor et al., 1994).

In a series of four studies, Taylor et al. (1994) presented 4- and 5-year-olds with new information about animals (e.g., what cats use their whiskers for), chemistry (e.g., how to change a red spot with chromatography paper), and color names (e.g., chartreuse and taupe), and then asked the children a series of questions about when they knew the information and how they learned it. In the first three studies, the new information was presented implicitly, as part of descriptions about the materials. The researchers found that the preschoolers, especially the 4-year-old group, tended to report that they not only knew the information before it was presented, but that they had always known the information. Only when the new information was explicitly taught, by saying "I'll teach it to you," were 4-year-olds able to differentiate between new knowledge and knowledge they already possessed.

Similarly, Lipowski et al. (2013) used a method called "judgments of learning" to look at preschoolers' ability to monitor their own metacognitive processing. They taught children the names of stuffed animals and asked them to predict which ones they would remember later. After a delay, children were asked to recall the names. Through a series of three studies, the researchers varied the training and recall protocols in order to paint the most thorough picture of metacognition. The researchers found that the preschoolers in this study were overconfident in their predictions about their learning. When the researchers altered subsequent study methods to provide feedback about recall failure, the preschoolers made more accurate judgements about their own learning. These findings suggest that preschoolers do understand that their current knowledge is an indicator of their future knowledge.

In another study, Hagá and Olson (2017) looked at children's (4- to 5-year-olds, 7- to 8-year-olds, 10- to 11-year-olds) and adults' level of confidence in their knowledge about the identity of objects that were "familiar" (e.g., a hairbrush), "apparently familiar" (e.g., a cupcake that was actually a pillow), and "unfamiliar" (e.g., a nibbler, which is a tool for cutting sheet metal). They found that participants of all ages expressed overconfidence in their knowledge about the identity of objects; the 4- and 5-year-olds were more confident about the unfamiliar objects than the older children and adults, but they also were more likely to revise their beliefs based on a peer's input. Hagá and Olson (2017) suggest that although preschool-aged children tend to express overconfidence about their knowledge, or come across as "know-it-alls," they are also more open to learning from peers.

As discussed earlier, engineering problems are often called "ill-structured" because they tend to have multiple solutions. For example, there is more than one design strategy for building a bridge that can hold a specific amount of traffic or support a certain weight. Shin et al. (2003) suggest that to solve these problems, children need to not only understand the relevant content knowledge (e.g., types of bridge design) but also be able to employ metacognitive strategies such as planning, comparing alternatives, reflecting on outcomes, and monitoring one's own cognitive efforts.

Strong metacognition is built when students are actively engaged in their own learning, held responsible for it, and supported; including allowing them to express uncertainty about what they know (e.g., Darling-Hammond et al., 2020; Schraw & Moshman,1995; Watkins, et al., 2016). Through analysis of video interactions of elementary and college-aged students engaged in group science work, Watkins et al. (2016) found that students' expressions of uncertainty helped guide group processes by solidifying the work the group was already doing or leading the students to new discoveries. The researchers suggest that expressing uncertainty is integral to learning because it creates important discourse around understanding what one student knows versus what others know. Furthermore, Watkins et al. (2016) suggest that expressions of uncertainty help create more equity within the learning process by allowing all students to fully participate and by reminding them that there may be more than one way to do something. For younger children, adult intervention may be necessary to facilitate building these metacognitive skills. For example, adults might ask children to theorize about their own thinking or model their own thinking or metacognitive processing by narrating their process. Adults can also prompt children to practice these skills as they are observing children's communication with peers.

The use of drawings or journaling is a common part of the engineering design process (Hertel, et al., 2016), and Sadler et al. (2000) recommend that students keep purposeful records that track all trials and attempts. Engineering notebooks or journals provide a place to record ideas, data, and results. They can facilitate metacognition by providing a reference to prior thinking, planning, and designing, which can be used to improve problem solutions and help children with explanations of how and why they ended on their final design. Hertel et al. (2016) found that children in third through fifth grade successfully used engineering notebooks to record their design iterations and collaborate with their peers.

Theory of Mind

As children develop, they learn that people have goals, intentions, and expectations. Psychologists use a construct known as theory of mind to describe the awareness and understanding that mental processes such as thoughts, beliefs, and desires guide people's behavior (Wellman, 1992). Research shows that even very young children have this understanding and use it to explain the behavior of others (see Figure 1). Specifically, children as young as 3 understand the link between the mental states of a person and their actions as well as the distinction between thoughts in the mind and occurrences in the physical world (Wellman, 1992).

Theory of mind connects to engineering in several ways. First, engineers must think about and understand others' goals or beliefs in order to understand what is needed from the end product. They also need to think about how the materials and product will ultimately be utilized by the users, who may have different knowledge or expectations (Letourneau et al., 2021). And, finally, they need to consider others' knowledge when they are collaborating with a team to solve problems. For example, an automotive engineer works with a team to design, test, and alter components of a vehicle. The engineers must keep in mind the usability and the safety of the design, and then test these designs in ways that may be different from how they would operate the vehicle. Through this process, the engineers are ultimately predicting and interpreting the behavior of others in order to adapt and refine the product so that it both meets safety guidelines and can be used for everyday purposes.

A number of different tasks have been developed to assess children's developing theory of mind. In the location change false-belief task, children are asked to distinguish between a person's "true" belief and their awareness of another person's "false" belief (Dennett, 1978). In a seminal false-belief task called the Sally-Anne task, children are presented with a story about two girls, Sally and Anne, who have a box, a basket, and a marble (Baron-Cohen et al., 1985). While both Sally and

Figure 1

THEORY OF MIND

Theory of mind is the understanding of one's own and others' mental states (e.g., thoughts [***wonder***], emotions, beliefs, desires [***want***]).

Anne are in the same room, Sally places the marble into the basket and then leaves. While Sally is out of the room, Anne moves the marble into the box. When Sally comes back, the child research participant is asked, "Where will Sally look?" To answer correctly and identify the basket, children need to understand that their own beliefs are not the same as others, in this case, Sally's. If they are unable to take an alternate perspective, they will think that Sally's beliefs are the same as their own and will select the box.

During problem solving, children may assess their own knowledge and determine that they have an answer or solution (i.e., metacognition) and need to ask others for help. Theory of mind may be one mechanism children use to discern whom to ask questions. Another mechanism is identifying persons who are willing to take the time to answer questions thoughtfully (Fusaro & Smith, 2018). One study found that even children as young as 2 were more likely to seek help from "good helpers" – those who had previously demonstrated being able to solve a problem of retrieving a toy – rather than "bad helpers" who could not help (Cluver, et al., 2013).

Fusaro and Smith (2018) found that children who asked questions during one problem-solving task were more successful at solving subsequent problems. In their study, children were shown pictures of scenarios, such as a cat in a tree, and asked how they could solve that problem. The researchers found a correlation between children who asked the most questions and those who generated the most solutions, with the older children being better able to construct solutions to more scenarios than the younger preschoolers. Thus, actively encouraging young children's questions and curiosity may help them build problem-solving abilities.

In a series of experiments, Aguiar et al. (2012) examined preschoolers' ability to recognize gaps in their own knowledge and ask an expert – in this case, three puppets dressed as a doctor, firefighter, and farmer – for help. Children were told they were playing a game. The experts were part of their team and together they should try to answer as many questions correctly as possible (a prior study had determined that children understood the professions of the three experts). For each question, children chose whether they wanted to answer themselves or assign the question to one of the experts. Questions varied in difficulty (i.e., easy and hard) and format (i.e., open ended and forced choice). The researchers found that 4- and 5-year-olds were inconsistent in their ability to recognize when they needed help with a question (i.e., they overestimated their own knowledge) and that this judgment impacted their ability to select the correct domain expert. By contrast, 6-year-olds correctly selected the appropriate domain expert once they decided not to answer the questions themselves.

In another study, researchers used a version of the Knights and Knaves logic puzzle (knights always tell the truth and knaves always tell lies) to study the ability of 3- to 5-year-old children to ask the best questions of the right puppet to determine what was in a box (e.g., a blue shoe or a red shoe; Mills et al., 2011). In each trial, two puppets were available to question. There was always one knowledgeable puppet (who always spoke the truth), as well as one of two other puppets: one who always lied (the inaccurate condition) or one who did not know the answers but did not mislead with false statements (the ignorant condition). The researchers evaluated children's questions based on which puppet they were directed to as well as their general effectiveness. Results showed that older preschoolers (5-year-olds) were better than younger preschoolers (3- and 4-year-olds) at figuring out who the knowledgeable puppet was and asking effective questions. However, these abilities did not correlate to a higher rate of correct guesses of the object in the box. Older children were more sensitive to uncertainty in the inaccurate puppet when it provided a response but indicated that it was unsure about its answer (by stating that it was "guessing" or "not sure"; p. 549). This indicates that as children age, they add to their understanding of communication by listening to or paying attention to other cues from the speaker. A shrug of the shoulders imparts doubt to the listener, who may ask better questions to discern the truth.

Executive Functions

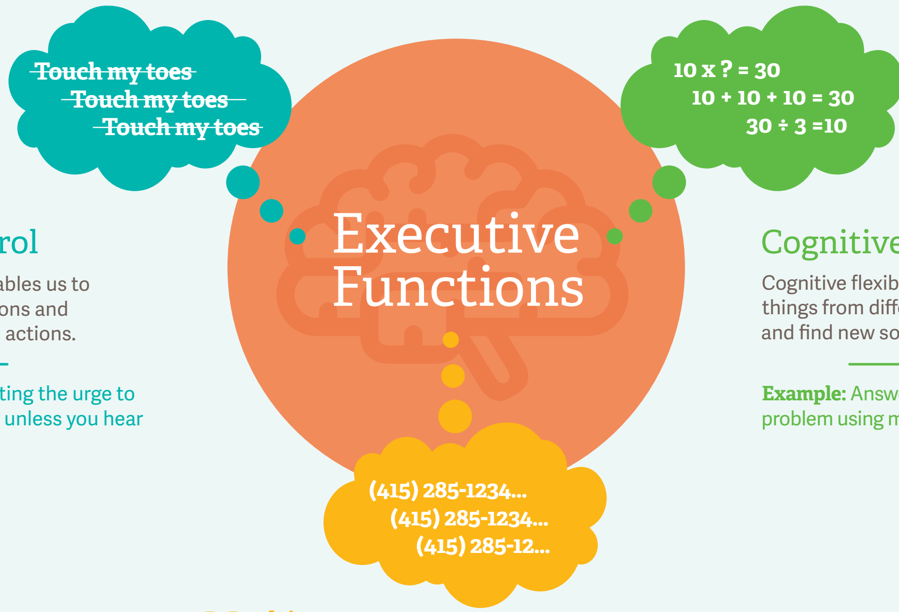
Executive functions are generally described as a group of higher-order cognitive processes responsible for directing the brain's power and attention. The key components include working memory, inhibitory control, and cognitive flexibility (Zelazo, 2015; see Figure 2). These components are interconnected and critical to successful cognitive development and problem solving (Zelazo et al., 1997; Diamond et al., 2007).

The development of executive functions begins in infancy and continues throughout early childhood. Executive functions are linked to a neural circuit which centers around the prefrontal cortex, a region that modulates cognitive processes like decision making. This region develops rapidly in early childhood and continues developing through adulthood. There is a great deal of interest in executive functions given the important role they play in social competence (Hughes, 1998) and academic outcomes (Darling-Hammond et al., 2020). Executive function skills have predicted academic success in elementary and middle school (Blair & Razza, 2007; Darling-Hammond et al., 2020; Diamond, 2013; Duckworth & Seligman, 2005; McClelland & Cameron, 2011). In one study, researchers found that executive function skills in kindergarteners accounted for individual variation and were predictors of success on scientific reasoning tasks such as experimentation and evidence evaluation (van der Graaf et al., 2018).

Executive functions are related to what some researchers call "engineering habits of mind," which include skills such as systems thinking (see TRY below), creativity, collaboration, and communication (English & Moore, 2018). Therefore, teaching that promotes executive function skills also promotes engineering skills (Bustamante et al., 2018; Van Meeteren, 2018). For example, as compared to direct instruction where the teacher outlines a lesson and the way to find the solution, open-ended teaching that allows and facilitates students to ask their own questions and come up with ideas for solving problems, requires inhibitory control and cognitive flexibility.

Figure 2

EXECUTIVE FUNCTIONS



Self-control

Self-control enables us to ignore distractions and resist impulsive actions.

Example: Resisting the urge to touch your toes unless you hear "Simon says..."

Cognitive flexibility

Cognitive flexibility helps us to see things from different perspectives and find new solutions to problems.

Example: Answering a math problem using multiple strategies

Working memory

Working memory allows us to hold and manipulate information in our mind to complete a task.

Example: Repeating a phone number until you can write it down

MAKE

Make a physical model of a possible solution

After children have begun their engineering journey to solve a problem by THINKing about it, they engage in the MAKE stage. During this stage, children brainstorm possible solutions and make a physical model, or prototype, of a possible solution. As children transition from thinking to making, they have the opportunity to engage in hands-on construction. Their understanding of *dual representation* will come into play as diagrams or pictures of solutions are created and expanded into models. Children will also utilize *spatial reasoning* and *sequencing* to decide where to put pieces of their design and in what order.

Dual Representation

Dual representation is the understanding of the relation between a symbol and its referent, for example, a map is both an object itself as well as a representation of a place. Representational understanding develops over time in young children; however, even very young children understand that some objects are representations of other objects and are able to use those representations to solve problems (e.g., DeLoache, 1987; Uttal et al., 2009). Children exhibit some evidence of understanding representation during pretend play when they use an object to stand for something else, such as a telephone, or pretend to have a tea party in the sandbox.

Representations can take many forms and can be both two-dimensional (2D), like drawings or photographs, or three-dimensional (3D), like models of objects. Children's understanding of representations is important as they work through engineering problems. Not only might children need to move from drawings to 3D versions, they also might build prototypes of designs rather than "real" products for use. For example, if children create a bridge, they will need to understand that while their creation is a bridge, it is a model or representation of what might be a "real" (i.e., larger) bridge that people, animals, or vehicles could cross. Furthermore, many engineering design activities for children will have them use art supplies or recycled materials rather than the "real" materials a professional might use (e.g., recycled paper towel tubes rather than steel for a bridge beam).

Thus, in order to successfully use representations, children need to understand that the symbol is both its own thing as well as reference to something else (DeLoache, 2002). In seminal research by Judy DeLoache (1987), 2½- and 3-year-olds participated in studies in which they were shown either a small-scale model or a photograph of a room. In both the model and the photograph, an attractive stuffed toy was hidden behind the sofa. DeLoache found that 2½-year-olds understood they could use information from the photograph to find the analogous toy in the real room while the 3-year-olds could use both the photograph and the model. Although young children understand the nature of representation, they have difficulty when the representation has salient features and they are allowed to engage with it (e.g., playing with the model room). In those cases, they tend to focus on those interesting features of the representation and have trouble connecting the representation with the actual object (Uttal et al., 2009).

Brooks and Wangmo (2011) studied 6- and 7-year-olds' emerging understanding of representation through drawings and modeling with clay. The researchers introduced students in Bhutan to new art materials like pastels and charcoal to draw local flowers and vegetables. After this 2D lesson, students were taught how to model with clay, which was a new experience for them. Teams of students were then tasked with documenting their village: drawing, measuring, and photographing well-traveled sites and then creating 3D models using cardboard, clay, paper, and other craft materials. Student level of engagement was high as they worked collaboratively to accurately represent buildings or sites, even creating additional details like furniture and landscaping without prompting. They shared their 3D representations of the village, along with their written work, with the school community. This project reinforced many aspects of STEM inquiry, challenging students to practice the skills of questioning, expressing doubt and confidence, and collaborating with peers all while trying to solve this problem. Brooks and Wangmo (2011) found that translating what is seen into a visual representation helped students with recall and understanding of objects.

Representation is not only apparent in mapping and visual arts but in all the STEM fields. For example, in math, dual representation is essential in creating the link between the abstract and the real world. Children must progress from physically manipulating items in order to group and count to utilizing the abstract concepts of numbers and symbols (e.g., "+" and "-") to indicate how groups change without actually seeing any items grouped. Because children do not spontaneously link objects and symbols, the challenge of math is to help children understand and manipulate symbols (Uttal et al., 2009). Physical, external representations, such as counting bears or base 10 blocks, help children move from the concrete to abstract. Allowing students to discover mathematics concepts using the many representations available encourages them to make connections in ways that are personally meaningful (Jao, 2013).

Spatial Reasoning

Spatial reasoning encompasses three elements: concepts of space, ability to work with representations, and reasoning or thinking about concepts (NRC, 2006). It is an integral part of our everyday lives; we use spatial reasoning when we visualize and navigate the world around us – reading a map or putting together furniture from a diagram –and when we construct images in our mind and mentally manipulate them.

Spatial reasoning is a key component in all disciplines, but it manifests differently across diverse fields like astronomy, math, geography, or art (NRC, 2006). Engineers specifically use spatial reasoning to visualize components and imagine what they look like from different perspectives, and as they move between 2D graphics and 3D representations (McGarvey et al., 2018), for example, when designing bridges or biomedical apparatuses.

Spatial reasoning is explicitly associated with success in STEM subjects and the likelihood of pursuing STEM careers (Cheng & Mix, 2014; Lowrie et al., 2019; Wai & Uttal, 2018). In one longitudinal study, high schoolers took four spatial tests, and 11 years later, researchers linked their performance on these tests with their occupations. They found that students who pursued careers in engineering, computer science, and other STEM occupations had better spatial skills in high school than those who pursued non-STEM occupations (Wai et al., 2009).

Very young children already use spatial reasoning as they play with blocks and puzzles, and research shows that even infants can recognize when objects have been rotated (Shutts et al., 2009). Research also shows that children's spatial abilities grow throughout childhood and importantly, spatial skills can be taught and learned (Bower et al., 2020; Lowrie et al., 2019; McGarvey et al., 2018; NRC, 2006; Tzuriel & Egozi 2010; Uttal et al., 2013). In fact, a meta-analysis of 207 studies with children, adolescents, and adults found that participants who received spatial skills training improved from pre- to post-tests, that their learning held up over time, and that these skills transferred to new tasks.

Spatial thinking can be facilitated through early language exposure to spatial language such as *above, below, far, on,* and *next to* (Loewenstein & Getner, 1998; Pruden et al., 2011). Pruden et al., (2011) found that 14-month-olds who heard more spatial language produced more such language themselves and later, at age 4, performed significantly better on spatial tasks that involve spatial reasoning.

Studies that demonstrate that spatial skills can be taught to children span a range of ages and use a variety of methods (e.g., Bower et al., 2020; Lowrie et al., 2019; Lowrie et al., 2017; Shumway, 2013; Tzuriel & Egozi, 2010). In one intervention study, Bower and colleagues (2020) randomly assigned 3-year-olds to either a control group or a training group in which children were asked to perform a spatial task called the 2-Dimensional Test of Spatial Assembly (2D TOSA). Using a tangram-like puzzle, the task challenged children to construct their pieces to match a target formation. Even a brief spatial training once per week over the course of five weeks improved children's performance on the puzzle task, with lower-SES children showing the greatest gains.

In another intervention study with first graders, Tzuriel and Egozi (2010) administered baseline mental rotation tests before placing students in either a control group or experimental group. Meeting weekly for three months, students had opportunities to practice mental rotation and representation tasks by viewing flashcards and drawing what they saw. Students in the experimental group worked with peers and were guided by their instructor to look at the drawings from multiple perspectives, while students in the control group worked more independently and did not receive guidance. The researchers found that the first graders in the experimental group improved significantly on post-tests of spatial performance, and moreover, the initial gap in performance between boys and girls was eliminated.

Using a bridge design challenge, Shumway (2013) found that second grade students who participated in lessons on spatial reasoning showed more strategic progress than students who received no lessons. In the study, students participated in three days of coaching sessions designed to strengthen their abilities to form and manipulate mental images, visualize moving the blocks, and then construct transformations before making changes to their designs. During the sessions, students freely built with standard wooden blocks while being queried individually about their thinking. The researcher used small group time to discuss any new discoveries. To demonstrate their learning, children were asked to recreate block structures shown in pictures, which was challenging because the interior blocks were not visible. Asking questions about block design and bridge construction helped guide student learning, and children were also able to learn from watching and talking with each other. By the end of the sessions, most students were performing more mental transformations than on the first day, and they used more transformations, reflections, and rotations in their final builds than in the free builds. Some students were able to do these mentally while others had to manually manipulate the blocks.

Interventions with older children in grades 5 and 6 show that students not only saw significant improvement in general spatial reasoning (on both spatial visualization and spatial orientation), but they also show improved performance in math (on geometry problems and word problems) (Lowrie et al., 2017; Lowrie, Logan, & Hegarty, 2019). Interestingly, Ramey et al. (2020) found that even without a specific spatial intervention, fifth and sixth graders who worked collaboratively on STEAM-based challenge projects naturally engaged in a variety of types of spatial reasoning and their skills developed over time. The researchers suggest that this gain was partly due to the hands-on, iterative nature of the challenge projects – in other words, students' spatial skills improved during the course of revising their projects as they observed how their designs worked and experimented to make improvements.

One component of spatial reasoning that is especially important in engineering is visual literacy, and both the Common Core English Language Arts Curriculum and the NGSS include related standards. For the Common Core, students should be able to "interpret, recognize, appreciate, and understand information presented through visible actions, objects, and symbols, natural and man-made" (Finley, 2014), while the NGSS requires "Analyzing and Interpreting Data and Obtaining, Evaluating and Communicating Information" (NRC, 2013). Together, these standards point to the importance of children being able to communicate and interpret ideas presented in prototypes, sketches, charts, and graphs.

Accurate drawings and detailed sketches are an important part of creating well-designed products. Song and Agogino (2004) found that undergraduate engineering students who produced multiple sketches and a greater variety of sketches developed better designs. Research with younger students showed that even fourth graders can create sophisticated design sketches that include all design features and perspectives (English & King, 2017). Further, children in third through fifth grade successfully used data tables in engineering notebooks to record design data, reflect on results of their designs, develop conclusions, and plan for next steps (Hertel et al., 2016).

Practice with drawing and sketching skills from a young age can help children with initial creations as well as iterations of design. As discussed earlier with metacognition, researchers suggest that these skills are useful for planning and reflecting on one's design. These skills also help children communicate their experiences on a specific topic, stimulate discussion, and facilitate questions from peers about their experiences and the subject matter (Darling-McQuistan, 2017; English & King, 2017; Hertel et al., 2017; Lieu & Sorby, 2015).

Sequencing

Sequencing refers to the logical ordering of a series of objects or events. This cross-disciplinary skill is used to teach and understand many subjects such as history, language arts, chemistry, and math. In engineering, sequencing is important both in planning how an object or design might work but also in evaluating where a failed design may result from a step being out of order.

Sequencing, sometimes referred to as patterning, is taught at the youngest ages and is included in early math curricula. Research has indicated that repeating patterns, or predictable sequences that follow a specific rule, are crucially important for math development (Gadzichowski et al., 2018; Zippert et al., 2020). One study with 65 preschool children found that preschool patterning knowledge was a significant predictor of several types of math knowledge by the end of kindergarten, even when controlling for verbal and visual-spatial working memory (Zippert et al., 2020).

Children as young as kindergarteners can be taught sequencing in the context of computer programming (Kazakoff & Bers, 2012; Kazakoff et al., 2013; Bers et al., 2014). Kazakoff et al. (2013) conducted a one-week robotics workshop in a PreK and kindergarten classroom. They examined children's sequencing skills using a picture sequencing assessment before and after the workshop relative to a control group of children that did not participate. Although the study had a small sample size, researchers observed a significant difference in sequencing ability among the students who participated in the robotics workshop, but no increased sequencing ability among those of the control group.

In another study, Bers et al. (2014) observed kindergarteners working on a series of lessons focused on programming, robotics, and computational thinking. The researchers found that the kindergarteners' scores on sequencing improved during the study such that scores on their final projects were higher than on previous lessons. They also suggest that students' improvement led children to be more motivated to engage in programming.

Sequencing is also an important skill for comprehension of narrative texts. In one study, 64 children between ages 8 and 11 read short stories that either shifted forward or backward in time (Gouldthorp et al., 2017). They were then asked to place cards that depicted the story in the correct chronological order. Children who had high story comprehension produced more accurate sequences of the cards, which suggested preliminarily that sequencing is an important skill as children develop reading skills.

Given the importance of sequencing in both early math and early literacy, the results of these studies suggest that even brief interventions using developmental approaches can be impactful in improving children's sequencing skills. Researchers suggest that children may only need these brief interventions because children have experience with storytelling and use similar cognitive structures in sequential storytelling as when they are programming robots with a sequence of commands (Bers et al., 2014).

TRY

Try out the physical model of the solution to see how it works (and then improve upon that solution by going through the process again)

Once children have MADE their solution to a problem, they need to TRY out their design to see how it works. During this stage, they should iterate as many times as needed to continue improving their designs, even if their designs "succeed" on their first try. Using *systems thinking,* children can assess how the parts of the system work together for their design to function. Sometimes designs might not work as expected or sometimes they do work, but during observation, the designer gets an idea for improvement. Applying *causal reasoning* is an important step to finding a better solution. To that end, it is helpful for children to use *counterfactual reasoning* to think about how the design might work if they try "this instead of that." With the inherent "failure" in engineering design, the development of a *growth mindset* is critical to student perseverance and success throughout the process, especially during the TRY phase. In fact, multiple iterations need not be recorded as failures but instead as learnings about when things do and do not work or how they might work better.

Systems Thinking

Systems thinking is the understanding of how individual parts function, relate to each other, and contribute to the system as a whole (Akcaoglu & Green, 2019; Jonassen, 2000). It is an important skill across STEM fields (Akcaoglu & Green, 2019) and within the NGSS in which understanding the interrelationships between all aspects of a broad system is a component of "Crosscutting Concept: Systems and Systems Modeling" (NRC, 2013).

While limited research focuses on systems thinking in young children, Camelia et al. (2020) found that even college undergraduates could benefit from explicit teaching of systems thinking. Students enrolled in systems engineering classes were taught how systems are designed and developed by engineers, and then systems thinking was used to teach them how to break down complex systems to complete challenges in design, comprehension, and development of engineering systems. Results from pre- and post-test scores showed that students made significant gains in systems thinking domains such as assessing systems boundaries, taking multiple perspectives, understanding dynamic characteristics, and incorporating whole picture and systems thinking tools.

Younger students can also learn to use systems thinking to try to understand the design problem and to create order out of what may seem an overwhelming task (Akcaoglu & Green, 2019; Ben-Zvi Assaraf & Orion, 2010). Game design is an engaging task for children — creating computer games can weave interdisciplinary lessons into systems thinking since character development and story writing are combined with coding and computer science skills. Akcaoglu and Green (2019) looked at whether participation in a game design course improved systems thinking in sixth graders. During a weekly game design course, students learned about basic game design and created flowcharts showing connections between objects in their games, while a control group of students did not participate in any game design sessions. Both groups completed the same pre- and post-tests, and results showed that students in the game design course showed significant increase in systems thinking as well as improvement in their general problem-solving skills.

Mambrey et al. (2022) found that 9- to 12-year-olds' systems thinking about ecological systems was impacted by their preexisting knowledge and assumptions. This finding is consistent with a preschool study that involved individual readings of a children's book (*The Water Hole* by Graeme Base) followed by structured interviews about children's knowledge and understanding of systems thinking through the context of the ecosystem (Feriver et al., 2019). The researchers found that while some preschoolers showed signs of systems thinking, their understanding was limited to features of the system that were most perceptible. They suggest that in addition to developing communication abilities, young children are still developing content knowledge and understanding of time and space, both of which impact their ability to reason about systems.

Similarly, Ben-Zvi Assaraf et al. (2010) looked at the systems thinking abilities and development of fourth graders through the examination of an earth systems–based unit looking at the hydro-cycle, or the process of water transportation through Earth's systems. Pre-test measures showed that students initially presented fragmented views of the water cycle. Following 30 hours of content-related activities plus three field trips, however, students showed a significant increase in their ability to analyze the hydro-cycle, which allowed them to see connections between the components of the system. The researchers noted that while students still lacked the ability to identify some of the more complex processes (such as the cyclical nature of the process), results lend support to the idea that younger children can be taught processes for abstract systems thinking.

Causal Reasoning

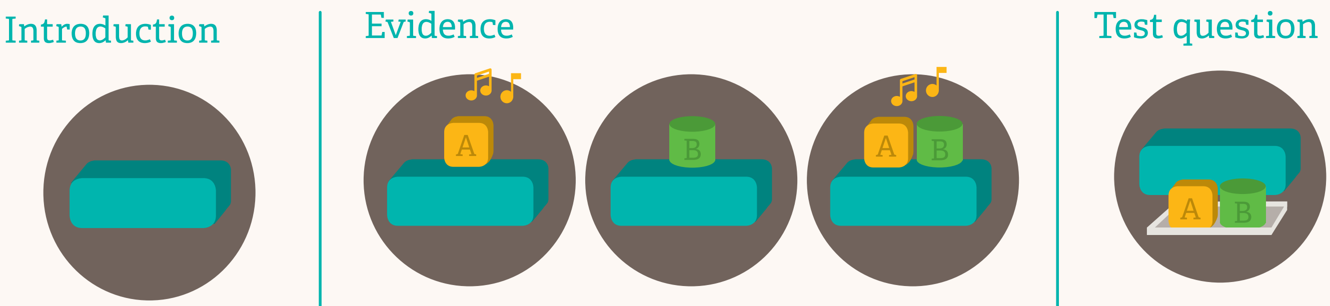
Causal reasoning is the ability to recognize that one thing leads to the next and that events have causes that can be discerned through observation and reasoning. Causal reasoning allows us to make predictions about what will happen and interpret what has already happened. Looking for causes and interpreting actions and events as causal helps us make sense of the world. Causal patterns have their own category in the NGSS's "Crosscutting Concepts: Cause and Effect" (NRC, 2013).

Evidence exists that even young infants interpret perceived events as causal (Leslie & Keeble,1987), and researchers suggest that toddlers first look for linear cause-and-effect relationships and then progress in their understanding of complexity to an interactive one involving many relationships with varying degrees of causal influence (Bullock et al., 1982; Gopnik & Sobel, 2000; Hokayem & Gotwals, 2016; Solis & Grotzer, 2016). Gopnik and Sobel (2000) created a machine called a "blicket detector" to look at young children's causal inferences. The blicket detector lights up when certain objects (i.e., blickets) are placed on top (see Figure 3). The researchers showed children several sets of blocks varying in shape and color. They found that children as young as 2½ were able to use information from the blicket machine to make inferences about the properties of the blocks and could name and categorize the objects that lit up the machine as blickets. In other studies, Gopnik and colleagues found that young children use patterns of evidence about blocks to learn causal structures of the blicket events (Gopnik et al., 2001), and that children's free play with materials provides extra support to their causal learning (Schulz et al., 2007). Even toddlers who observe others' actions with objects can learn about the causal structure of events, for example,

Figure 3

EXAMINING CAUSAL LEARNING

Many researchers investigate causal learning by showing children a novel machine (a "blicket detector") that plays music when certain objects are placed on top. Children have to reason about things they cannot see and make predictions about which objects will activate the toy and which objects will not.



Introduction: First, children are introduced to the machine and told that some objects make the machine play music while other objects do not. Their job is to determine which objects make the machine "go."

Evidence: Next, children watch an experimenter place different objects on the machine.

Test question: Finally, based on their observations, children are asked to deduce which object(s) make the machine "go."

Adapted from Gopnik (2012)

that they can act on the objects to bring about the same effect (Waismeyer et al., 2015).

Research also finds that children can reason about causality when multiple features are involved (Dejonckheere et al., 2016; Klahr et al., 2007). In one study, researchers looked at preschoolers' (4- to 6-year-olds) causal exploration of 15 science concepts such as magnets, optics and mirrors, balances, and gears (Dejonckheere et al., 2016). Children were divided into experimental and control groups and completed pre- and post-tests, but only those in the experimental group had the opportunity to play and explore with the materials between testing periods. For this group, the classroom teacher described the science stations using guiding questions, encouraged children to let their curiosity drive them, challenged children to record data in a meaningful way, and emphasized the need to rethink. The researchers found that children in the experimental group, who were allowed to play and explore at the stations, were more likely to conduct their own experiments to gather additional information. Further, these children spent less time on uninformative experiments. The researchers suggest that children learned to control events in order to gain information about causal relationships while not necessarily always using scientific reasoning.

Interactive Causality

Not all causal events are deterministic or unidirectional – in some cases, features interact with one another to cause an outcome. This concept, sometimes called interactive causality, is important in science when chemicals are combined to form a reaction. For example, in a popular children's science experiment, baking soda and vinegar are combined to simulate a volcanic eruption. While the vinegar is typically added to the baking soda, it is important for children to understand that vinegar does not *cause* the eruption but rather, the interaction between the chemicals causes the reaction. Interactive causality is also important in engineering design, where on the surface, it may look like one thing causes another, but in reality, the features work together to produce a reaction. For example, we might think that setting a thermostat turns on the heat, but complex design features and interactions among the parts actually cause the heater to function.

Solis and Grotzter (2016) looked at kindergartners' understanding of interactive causality through a design similar to the blicket studies. In their study, children engaged with sound blocks that looked identical but when placed in a specific arrangement (by color) would produce a sound. The children were asked to determine what caused the sounds. Results showed that most children used interactive explanations or actions to play sound with the blocks; in other words, children thought that the blocks worked together to play sounds, not that one block caused the sound to play.

Hokayem and Gotwals (2016) assessed the causal reasoning of first through fourth grade students using a task about a forest ecosystem. Based on observations usually involving one factor (e.g., all of one species dying out), they determined that even the youngest children were able to engage in simple causal reasoning. They also found, however, that some children moved between levels of reasoning even within one explanation; depending on the type of question asked, these children would use both simple and complex causal reasoning (i.e., reasoning that accounts for more than one factor) to explain the same phenomenon. The researchers recommend that educators provide opportunities for engagement, discussion, and feedback about how systems work to facilitate complex reasoning skills. This recommendation is consistent with Lehrer and Schauble (1997) who found that fifth graders were more likely to further explore how gears worked when they were asked questions about function. They suggest that allowing children to search for explanations rather than providing direct instruction might be the best method for teaching how machines work.

In another study, Bolger et al. (2012) found that second and fifth grade students did not often consider multiple features when explaining simple mechanical devices. First, children were shown lever machines attached to a pivoting system that propelled a cutout paper person in one direction or another, then asked to predict and rationalize the direction of the output of the paper person, and lastly allowed to test the device and explain if their prediction was correct or not. The researchers found that when students included multiple mechanistic elements (e.g., information about rotation, direction, or lever

arms) in their explanations, they were more likely to accurately predict where the paper person would land. However, these explanations were less common – students frequently were only able to explain one simple aspect of the system. Bolger et al. (2012) suggest that children should be provided more opportunities to engage with simple machines and explain how they work, since this skill is useful for all STEM disciplines. This recommendation is consistent with other studies that giving young students the opportunity to explore uncertainty about how things work and feedback during the exploration are important to understanding complex causal systems (e.g., Grotzer et al., 2017; Kushner & Gopnik, 2005). This finding held true that even when the students did not initially consider multiple features or outcome possibilities.

Counterfactual Reasoning

Counterfactual reasoning is the ability to think of alternative outcomes to events. This type of thinking is important to explain past events and predict future events (Byrne, 2016). Counterfactual reasoning is a key part of the engineering process as it encourages children to redesign their creations. During that process, children must consider what might happen if they "try this instead of that."

Young children engage in counterfactual reasoning during game play when they ask for "do-overs" because they can see an alternative ending. During pretend play, children engage in counterfactual reasoning by imagining the world in ways they wish it was rather than how it actually is. Weisberg and Gopnik (2013) argue that engaging in pretend play allows children to practice counterfactual reasoning and helps them learn about the world.

But how do young children curtail their often fictional or magical thinking into reasonable outcomes? Research by Magid et al. (2015) found that young children (4- to 6-year-olds) can use abstract representations of problems and solutions to constrain their hypotheses and explain why events occurred. They suggest that children run through a series of possibilities in their heads and then discard the least plausible ones. Children use their current understanding of constraints and parameters regarding the activity to mentally identify those goals that could be feasibly achieved.

In a series of studies with 3-year-olds, Harris et al. (1996) found that young children easily considered counterfactual information in determining what had caused an event or what might have prevented it. For example, in one of their studies, children heard a story about a puppet named Teddy who used a brush to paint red on a white floor. They found that the young children knew that the floor would have been "clean" (i.e., unpainted) if Teddy had not painted it. Children further responded that the floor would likewise still be "dirty" even if Teddy had used his fingers to paint instead of a brush.

However, while young children are quite good at considering and answering questions about straightforward alternatives (Guajardo et al., 2009; Harris et al., 1996), some researchers suggest they are not as successful at tasks that require them to imagine multiple possibilities (Beck et al., 2006; Byrne, 2016; Rafetseder et al., 2013). In one series of studies, children aged 3 to 5 played a game requiring them to prepare for a mouse or a ball going down one of two slides. Children were asked to place cotton wool mats at the bottom of one or both slides so that the mouse would not get hurt (Beck et al., 2006). The children were quite successful in preparing for events where they knew the mouse would come down one specific slide, and they could make accurate predictions about the future when asked “What if next time it goes the other way?” However, even with extra prompting (e.g., “Could it go elsewhere?”), children were not as likely to put mats at the end of both slides when the route was uncertain.

Rafetseder and colleagues (Rafetseder et al., 2010; Rafetseder et al., 2013) argue that very young children (around age 3) have a reality bias in talking about or explaining events and suggest that it is not until about age 5 or 6 that children start to use actual counterfactual reasoning. They further argue that this skill continues to develop until reaching adult-like reasoning between ages 10 and 12. Rafetseder and colleagues hypothesize that the challenge for young children centers around the ability to change only one real-world constraint that is logically dependent on the causal outcome while leaving everything else the same. Nyhout and Ganea (2019) used a version of the blicket detector study to examine this suggestion that children might not be able to only change one feature to reason counterfactually. After learning which blocks were causally related to turning the light on, 3- to 5-year-olds were asked what would have happened if one of the blocks was not put on the machine. Their findings suggest that while 3-year-olds had difficulty with counterfactual reasoning, the 4- and 5-year-olds displayed what they called “mature counterfactual thinking” (Nyhout & Ganea, 2019, p. 63).

Some of the discussion around the varied findings about children’s ability to think counterfactually has looked at the connection between counterfactual reasoning and other skills discussed earlier – for example, executive function (specifically working memory to hold information in mind), dual representation (to imagine another possible outcome), and false-belief (to imagine something that did not actually happen; for example, see Byrne, 2016). Research findings are not fully conclusive about the extent of the relationship between this group of skills and counterfactual reasoning, nevertheless, they suggest that children having more experience with those foundational skills and engaging in play or activities that encourage imagining other possible outcomes or predicting future outcomes could support the development of counterfactual reasoning (Guajardo et al., 2009; Weisberg & Gopnik, 2013).

Growth Mindset

The idea that mindset impacts performance, first proposed by Carol Dweck in 1986, suggests that a person’s motivation is impacted by their belief about whether intelligence is stable (fixed mindset) or can be developed (growth mindset) (Dweck, 2008). A person with a growth mindset believes that intelligence is malleable and can be developed with hard work and persistence. Having a fixed mindset or growth mindset can lead people to different behaviors when solving engineering problems as well as in school and all aspects of life.

There are numerous benefits to having a growth versus fixed mindset. More than two decades of research conducted and inspired by Dweck suggests that people with a growth mindset outperform those with a fixed mindset (e.g., Dweck, 2006; Dweck, 2015). Further, students who believe intelligence is fixed may sacrifice important opportunities to learn if there is a risk they might perform poorly or be forced to acknowledge their own deficiencies, whereas students with a growth mindset view challenging tasks as a chance to learn and grow (Dweck, 2010).

Research has shown that perceptions of learning and intelligence impact students’ performance in STEM, so it is essential to develop a growth mindset and refute the idea that STEM ability is innate rather than something that can be learned through hard work. For example, researchers observed that seventh grade students with a growth mindset focused more on learning goals and achieved significantly higher grades in math as compared to those students with a fixed mindset (Blackwell et al., 2007).

Engagement in the engineering design process exposes children to repeated failures since they are working to create the best solution to a problem (Lottero-Perdue & Parry, 2017). These encounters with failure, along with the iterative nature of the engineering design process, highlight the importance of children having a growth mindset during engineering challenges (Lottero-Perdue & Parry, 2017; Lottero-Perdue & Lachapelle, 2019). It is possible that children with a fixed mindset may feel that they are not the "engineering type" if success does not come naturally or easily.

Gathering information about what causes failure is an essential component of the engineering design process and can be used by children to increase resilience (Lottero-Perdue & Parry, 2017). During a bridge-building design project with kindergarteners, Shumway (2013) noted that a student with less experience with block building and spatial reasoning relied on a method of concrete trial and error. Students' ability to use information gathered from successes and failures (errors) helped develop skills that facilitated their ability to make design plans in advance.

Linda Darling-Hammond and colleagues suggest that when children are provided with feedback and opportunities to revise their work, they develop more confidence and competence, which enhances development of growth mindset (Darling-Hammond et al., 2020). Many people have heard about the importance of using process or effort praise ("You tried really hard.") rather than person praise ("You are really smart.") (Mueller & Dweck, 1998). Research by Dweck and others shows the importance of taking that praise to the next level by helping children focus on the process that leads to learning and improvement and letting them know that learning happens over time; for example, by using phrases such as "Let's talk about what you tried and what you can try next" (Dweck, 2015).

Additionally, cooperative learning models, as opposed to settings that focus on performance goals like grades, generate students who are less likely to give up when the science or math gets difficult (Lottero-Perdue et al. 2016; Wang & Degol, 2017). For example, Lottero-Perdue et al. (2016) describe teaching engineering design to kindergarteners performing an egg-drop challenge by using failure as a learning experience. After children initially designed contraptions to protect an egg from a fall, teachers facilitated group conversations about what worked and what did not, and then children were required to redesign their contraptions. By redesigning a failure, children were able to push past their feelings so that they did not get stuck on their unsuccessful last attempt.

Another way children may be encouraged to persist through failure is by hearing stories about others in STEM disciplines. Researchers examined the potential association between hearing a story about success and children's subsequent persistence on a challenging STEM task (Haber et al., 2021). Four- and five-year-olds were randomly assigned to four storybook conditions about Marie Curie or Albert Einstein before engaging in a STEM task: 1) achievement without failure ("Marie Curie won many awards in her life."), 2) intellectual struggles ("Even though she did not always succeed right away, she knew that she needed to keep trying to learn something new."),

3) life struggles ("She also struggled because she did not have enough money to pay for food."), or 4) no story (i.e., control condition). Results showed that children's persistence on a challenging STEM task was impacted by the type of story they heard; specifically, children who heard stories describing intellectual struggles and life struggles persisted longer than the children who read only about successes and children in the control group.

For more information on how the research discussed here can be translated into action, please refer to *Early Engineering with Think, Make, Try®: A Guide for Educators* at BayAreaDiscoveryMuseum.org/ThinkMakeTry

MAJOR BRANCHES OF ENGINEERING AND LINKS TO OUR EVERYDAY LIVES

Table 1

Main Branches of Engineering	Description of Work	Link to Everyday Lives	Select Engineers
Chemical Engineering	Chemical engineers apply chemical, physical, and biological sciences to the conversion process of chemicals or raw materials into more useful forms. Subdisciplines include molecular, metallurgical, and materials engineers.	The work of chemical engineers helps create products such as textiles, household products, and medications (e.g., penicillin and insulin) and vaccines (e.g., COVID-19).	**George E. Davis (1850-1906)** Sometimes called the "founding father" of chemical engineering. He wrote the first handbook of chemical engineering. **Ann L. Lee (b. 1961)** Innovated and developed large-scale, cost-effective methods of production of vaccines (e.g., HIB and HPV) as well as breakthrough therapies for cancer treatment. **Frances Arnold (b. 1956)** Developed a process for creating new proteins that led to cleaner, cheaper processing for a variety of products such as drugs, fuels, and detergents. In 2018, she won a Nobel Prize in Chemistry.
Civil Engineering	Civil engineers design, construct, and maintain the physical and naturally built environment. Subdisciplines include environmental, structural, and transport engineers.	Civil engineers design a variety of structures including roads, bridges, buildings, canals, and sewage systems. They also help make our world safer by protecting the air, water, and soil from harmful pollution, as well as from flooding and erosion.	**George Stephenson (1781-1848)** Pioneered rail transport for cargo and people. **Maj. Gen. Hugh G. Robinson (1932-2010)** Army engineer and first African American to serve as military aide to a US president (under Lyndon B. Johnson). He was also the first African American general officer in the Corps of Engineers. **Áine O'Dwyer (b. 1986)** Principal and CEO at Enovate Engineering which performs construction management, transportation engineering, surveying, and safety engineering.

Main Branches of Engineering	Description of Work	Link to Everyday Lives	Select Engineers
Electrical Engineering	Electrical engineers work on both macro-projects (such as power grids that support our cities) and micro-projects (such as tiny devices that control airbags in cars). Computer engineers, who work within a subdiscipline of electrical engineering, design and develop computer equipment and software.	The work of electrical engineers helps us use computer networks, wireless communication, medical imaging, and robots	**Alexander Graham Bell (1847-1922)** Received a patent for the first practical telephone. **Lynn Conway (b. 1938)** Multiple groundbreaking contributions and inventions in the field of circuits and chip design. She is also an activist for transgender rights and opportunities in engineering and technology. **Teresa H. Meng (b. 1961)** Pioneered development of distributed wireless network technology and founded Atheros Communications which partnered to create integrated cellular and WiFi solutions initially used in smartphones.
Mechanical Engineering	Mechanical engineers are called "general practitioners of engineering" because they are involved with any area related to machines and technology, including aerospace, automotive, and computers. Subdisciplines include vehicle, sports, and energy engineering.	Mechanical engineers help design and create a variety of devices we use daily such as bikes, cars, trains, planes, elevators, and wheelchairs, as well as develop systems for energy production and efficiency.	**Elijah J. McCoy (1844-1929)** Invented and patented many engine lubricators including the automatic lubricator used on steam engines on railroad and ship engines. **Anne McClain (b. 1979)** Senior army aviator. Served as engineer on the International Space Station. **Melonee Wise (b. 1982)** Designs, builds, and programs robotic hardware. She was a co-founder of Fetch Robotics which pioneered robots working in manufacturing and fulfillment centers.

Main Branches of Engineering	Description of Work	Link to Everyday Lives	Select Engineers
Inter-disciplinary engineering that combines two or more disciplines of engineering	There are many interdisciplinary engineers including biomedical, software, agricultural, systems, and textile engineers.	Due to their interdisciplinary nature, these engineers assist with design, creation, and maintenance of a wide range of products that we use in our lives. For example, software engineers are responsible for programs that help with writing, editing photos, and coding, and textile engineers design and create fabric and the equipment and tools necessary for processing the fabric.	**Michel Mirowski (1924-1990)** Developed the first miniaturized defibrillator (to regulate heart rate) that could be implanted into patients. **Wanda M. Austin (b. 1954)** Systems engineer instrumental in shaping the US space industry. She served as the first woman and first African American woman to hold the position of president and CEO of The Aerospace Corporation and served on the President's Council of Advisor on Science and Technology under President Barack Obama. **Diego Rejtman (b. about 1976)** Software engineer and longtime Microsoft employee who helped deliver hundreds of Windows and Xbox releases. In 2016, CNET named him one of the Top 20 most influential Latinos in Technology.

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