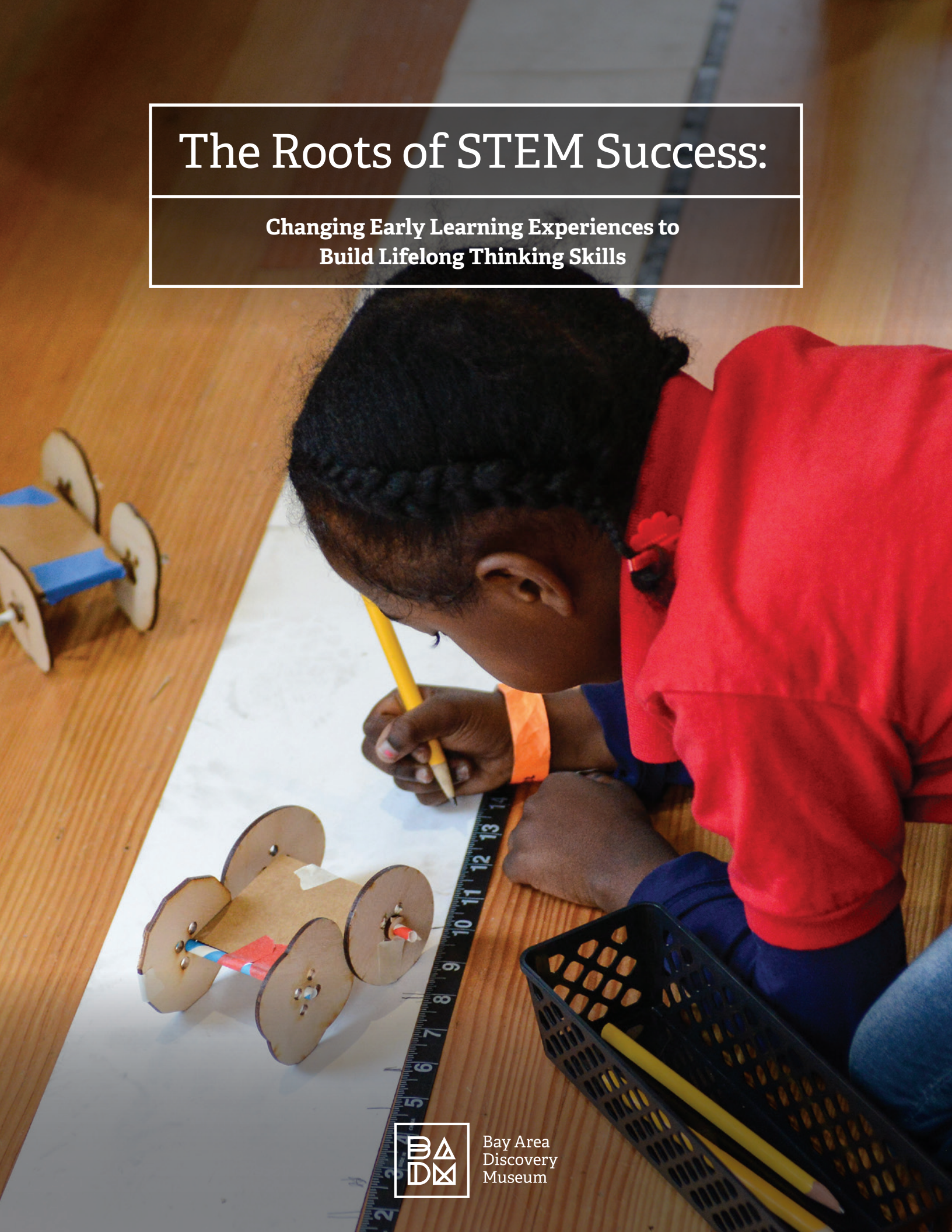


The Roots of STEM Success:

Changing Early Learning Experiences to
Build Lifelong Thinking Skills



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*This research was made possible by the generous support of:
Thomas P. Murphy Fund at the San Diego Foundation*



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Introduction

In recent years, STEM education—the teaching and learning of science, technology, engineering, and mathematics—has become a national priority.

This focus has, in part, been driven by concerns over international competitiveness, dating back to Sputnik and the space race. The focus is also fueled by data showing that young people are not graduating with the skills needed to succeed in a rapidly-evolving, technologically-driven workforce.

A third reason for the focus—one that is particularly important when considering the education of younger children—is the role of STEM in shaping our modern life.

From how food is grown and healthcare delivered, to the ways we get from place to place, save and spend money, consume and evaluate information, and connect to those we love, STEM is transforming our everyday lives. Innovations such as robotics, artificial intelligence, and big data are so dramatically evolving the economy, some leaders believe we are in the midst of the Fourth Industrial Revolution (Schwab, 2016).

Additionally, the “grand challenges” of our time—such as providing clean water, controlling carbon emissions, designing new medicines, and securing cyberspace—all require STEM-based solutions (National Academy of Engineering, 2016). STEM understanding can no longer be held by a select few; all children need the underlying thinking dispositions and knowledge to succeed in a STEM-driven economy and world.

There is a growing recognition that STEM educational experiences—particularly, when designed to foster creativity, collaboration, and persistence—lead to greater problem-solving skills and better equip young people for the dynamic world they will face after graduation. This recognition is precipitating big shifts

in education. Across the nation, a majority of states are rolling out new science standards that dramatically change how teachers approach science education. Children will be expected to “do” science with much more hands-on, experiential, and collaborative learning, and K-12 standards will include engineering as part of the science curriculum, with a strong focus on creating solutions to problems. Additionally, some school districts are pioneering computer science standards, and STEM-aligned makerspaces—where children can tinker and take things apart, design and create, and play with code and electronics—are increasingly common in both schools and community-based organizations.

Most of the current work in STEM education has focused on older children, however, generally beginning in late elementary or middle school. Developmentally-appropriate, rigorous STEM learning remains a missing link in most children’s early educational experiences, even though research shows that brain development is most robust in a child’s first years of life.

Why an Early Focus Matters

Research tells us that children’s early experience builds brain architecture and lays the foundation for one’s lifelong thinking skills and approach to learning, both critical roots of STEM success. After all, the STEM disciplines require not only content knowledge but also robust thinking dispositions—such as curiosity and inquiry, questioning and skepticism, assessment and analysis—as well as a strong learning mindset and confidence when encountering new information or challenges. These need to be developed in a child’s early education, beginning in infancy and continuing through third grade to lay the roots for STEM success (McClure et al., 2017).

Formal STEM Education

In the school context, literacy development remains the primary focus through third grade. While learning to read is, of course, a key foundation for academic success, educational experiences that teach children to question, to think, and to effectively communicate ideas matter even more to one's lifelong success. These are the skills that hands-on, active STEM education can cultivate. Fortunately, research indicates that we need not see this as a zero sum game of either teaching literacy or STEM; in fact, STEM education boosts literacy development by providing opportunity for children to expand vocabulary and practice using language to describe and explain ideas and phenomena.

Mathematics is also emphasized in our schools. And while new mathematics standards expect more creative problem solving and more exploratory thinking, in many classrooms, mathematics remains a performance, rather than a rigorous process of thinking, creating, or analyzing. Additionally, few classroom teachers are equipped with the skills or knowledge to help children apply math learning to the world around them or connect it meaningfully to other STEM disciplines. The teaching of mathematics rarely helps children

appreciate it as a universal tool of scientific discovery and engineered innovation.

Science—let alone engineering or computer science—is rarely introduced in a meaningful, consistent way until late in the elementary years. In fact, whether a child receives any science education in the elementary years depends, at present in most districts, on luck of assignment to a class whose teacher chooses to include science lessons and experiences. New science-based assessments, aligned to the Next Generation Science Standards, are beginning to be implemented in elementary schools. However, science-based standardized testing for elementary students occurs only in the fourth grade¹, while assessments in literacy and mathematics begin in third grade and continue each year through a child's academic life. Because teachers are measured by these assessments, they feel pressure to focus their precious instructional time on literacy and mathematics. Moreover, most teachers struggle to know how to build either language or mathematical skills through interdisciplinary approaches.

Additionally, adults struggle to reimagine science and mathematics as a flexible or collaborative problem-solving process. While new school-based standards demand a shift in approach, with less rote memorization and more opportunity for creative, team-based, and iterative problem solving (such as we see in the modern workplace), teachers and parents alike tend to hold on to preconceived ideas of what makes for good learning, often reverting back to their own experiences of math and science instruction and asking children to recall information, rather than do challenging thinking and questioning. This is compounded by the fact that outdated understandings of learning and intelligence persist, particularly in regards to STEM capability. Teachers and parents regularly and unwittingly communicate to children that some people “just aren’t” math or science people. While most teachers and parents would find it unthinkable to say to their children, “I’m a terrible reader,” it is all too common to hear adults declare that they, “have never been good at math.” Research demonstrates that these messages shape children’s mindsets significantly and have particularly



¹ Testing content and grade-levels vary across states; these represent the expectations of California public schools.

negative effects on groups underrepresented in STEM fields, including girls and children of color (Aronson, 2007; Dar-Nimrod & Heine, 2006).

Informal STEM Education

Increasingly, communities are seeking to bridge children's learning inside and outside the school walls and are considering how informal learning spaces (including museums, libraries, educational technology, and community-based organizations offering afterschool and summer programs) along with strengthened family learning can complement and deepen children's school-based STEM education. This is particularly important in the early years of formal schooling, from kindergarten through third grade, when children spend only 15 percent of their waking time in class. Given that many children do not have access to formal school until age five, and that nearly all children spend the first three years of their lives in informal environments (e.g., in childcare or with family), this overall percentage is even lower when considering the amount of time children spend learning in school-based classrooms over their first eight years.

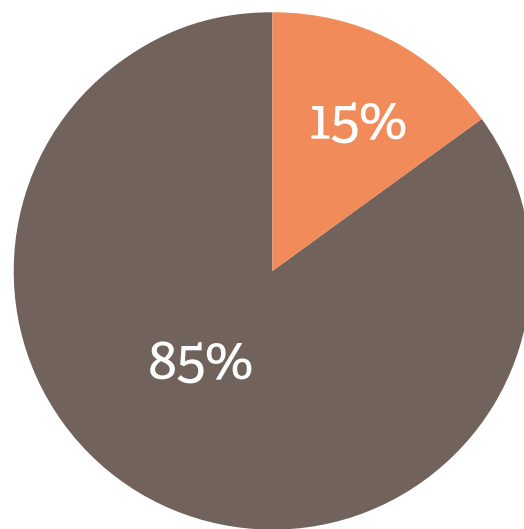
In many cities and regions, community-based organizations and education institutions (like museums) are partnering with school districts and employers to develop "badging" systems through which youth's out-of-school time learning can be credited and recognized as preparation for adult life and work. This blurring of boundaries between learning environments represents a significant shift in how we think about educating our children. Their needs are now far broader—and more complex—than the basic school outcomes of reading, writing, and arithmetic. Community resources and out-of-school time learning are needed to provide the holistic STEM education children need for their futures. Yet, the majority of badging programs and STEM learning spaces target middle and high schoolers, and most funding for STEM education is tied to "workforce development" and the latter years of schooling.

STEM Learning at Home

Currently, parents and caregivers are far more comfortable supporting their children's literacy development—reading with and to their young children—than they are incorporating STEM learning at home. Families do not yet recognize the potential of home-based activities such as building, fixing, crafting, shopping, cooking, gardening, self-care, watching sports, and cleaning to inspire children's STEM-based questions and build their STEM content knowledge.

Additionally, while families increasingly look to apps to engage their children, most families struggle to know how to find apps—from the dizzying array of choices—that have meaningful educational value. Few apps with math, science, or engineering content are designed in a way to build children's creative problem-solving skills.

K-3 Time Spent in the Classroom



Time spent in classroom-based instruction in a California public school, K-3

Time spent outside the classroom, assuming child is awake 14 hours per day

And while children use technological devices as the medium for playing with apps, there is minimal learning *about* technology embedded in most apps. Additionally, research shows that technology-based learning is most effective for children in preschool and early elementary school when it is coupled with interaction, conversation, and support from adults (Donohue & Schomburg, 2017). Yet families are largely unaware of this research-based best practice, and few apps are designed to be used with adults and children together.

The lack of developmentally-appropriate, strong STEM learning opportunities for families with young children represents a great opportunity for informal education providers to better serve the needs of the community. To leverage families' learning time, informal educators—including librarians, museum professionals, afterschool and childcare providers, camp counselors, and toy and media designers—need support in bringing STEM education to children zero through eight. Some informal educators have strong science, engineering, or math content knowledge but little understanding of children's development or learning needs; others are strong with young children but lack the content expertise or confidence to infuse STEM learning into activities. Some

struggle to know how to design STEM experiences that are open-ended enough to allow for creative thinking; others struggle to know how to present abstract ideas and phenomena in ways that are approachable and developmentally appropriate for younger children. At present, there is great need and opportunity to strengthen informal learning experiences to bring age-appropriate, challenging, creative, and content-rich STEM learning to young children.

This paper was authored to support classroom teachers, informal educators, experience designers, and families seeking an evidence-based approach to STEM learning for young children.





Key findings

Based on the review of more than 150 empirical studies from cognitive and developmental psychology and education, the Bay Area Discovery Museum finds that children are capable of remarkable problem solving from the earliest of years. At the same time, adult guidance, support, and awareness are critical to harnessing our intrinsic STEM capacity and transforming it into lifelong STEM intelligence, knowledge, and capability. Specifically, we offer these six research-backed findings:

1. STEM thinking begins in infancy

Counter to long-held assumptions about babies and toddlers' cognitive capacity, we now know that STEM thinking starts in infancy. Even before a child's first birthday, she is capable of making inferences, drawing conclusions about cause and effect, and reasoning about the probability of events. These roots, which lay the groundwork for later abstract reasoning, must be encouraged through engagement and play in order for inherent tendencies to develop into lifelong STEM thinking skills.

2. To become strong STEM thinkers, children need more play

Play is not frivolity and fluff; it is the brain's wired-in process for learning. Through play of all sorts—from building to board games, from make-believe to magic tricks—children are testing theories about how the world works and developing the brain plasticity for lifelong learning. Guided play, where adults follow the child's lead and shape the learning experience through thoughtful questions and interaction, has been shown to be particularly effective for teaching

STEM content. STEM education should include robust, frequent, and varied opportunities for play through the third grade.

3. STEM amplifies language development; language enables STEM thinking

As children engage in STEM experiences, they hear and practice new words. Growing vocabularies allow children to make sense of increasingly complex ideas and phenomena, and early exposure to vocabulary used for concepts can support children later on to master higher order thinking. Questions are particularly important—for adults to ask of children and for children to learn to ask themselves—in order to guide problem-solving and thinking strategies. Spatial reasoning—the capacity to envision and mentally manipulate objects in space, which is particularly key in engineering and mathematics—can be developed through language exchange.

4. Active, self-directed learning builds STEM skills and interest

Hands-on STEM learning is not only more fun, it is also more effective at helping children make sense of information that is complex or abstract. Museums and community-based organizations complement children's in-school STEM education by providing families with guided, hands-on learning and by giving children the opportunity to self-direct exploration and inquiry, which correlates to long-term interest in STEM. Technology is increasingly seen as another avenue for self-directed learning, though further work and scholarship are needed in this area.

5. Mindset matters to STEM success

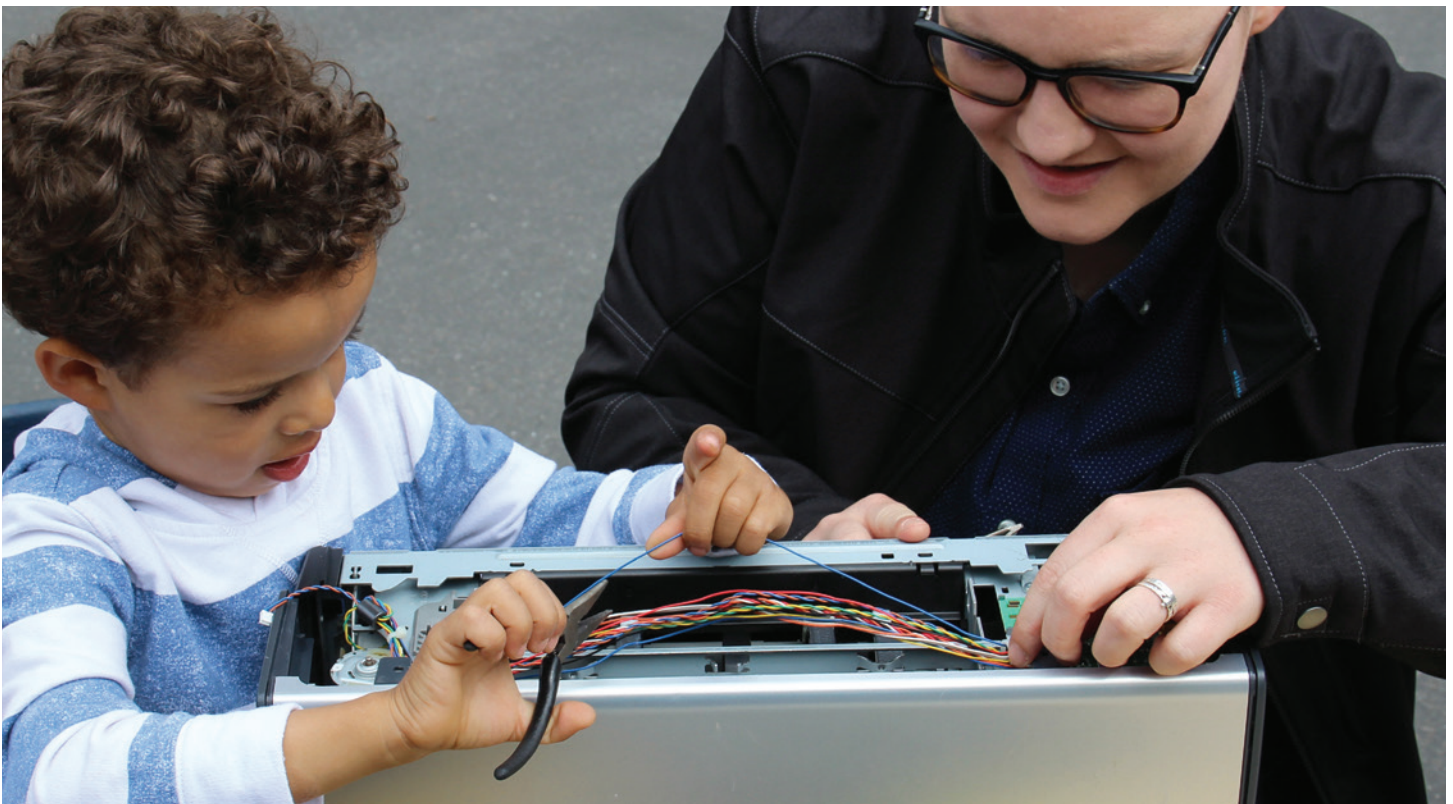
Developing what psychologists call a “growth” mindset—believing that learning and improvement will follow hard work and intentional effort—is particularly important in STEM learning, especially as children move from early to middle childhood. Adults need to support children, particularly girls and children of color, to develop a growth mindset with the STEM disciplines.

6. Children’s abstract thinking potential can be unlocked through both adult support and executive function skill development

Modern research debunks the myth that children are concrete thinkers, only capable of making sense of what they can directly see and experience. Instead, we now understand that children can grapple with abstract ideas and phenomena, when challenged and supported to do so. Children with more developed executive function skills (EFs) show greater ease incorporating new information and ignoring irrelevant information during abstract problem solving, so

experiences that strengthen EFs are critical to long-term STEM success.

These findings demonstrate the promise and importance of prioritizing STEM learning for children from infancy through third grade, in both schools and through education opportunities outside of school. They also highlight the critical role that adults play during these early years and the need for well-designed STEM experiences that support and challenge children in age-appropriate ways. By focusing on children’s STEM learning during the preschool and earlier elementary years, we can prepare them with the underlying dispositions for STEM thinking, equip them to meet school-based outcomes, and ready them for success in a STEM-rich economy and world.



1

FINDING ONE: STEM thinking begins in infancy

Recognizing that events have causes that we can discern through reasoning and hypothesis testing is at the core of STEM discovery and foundational to problem solving. Whether an engineer is trying to understand why her design is failing, a mechanic is fixing a faulty engine, or an artist is figuring out how to mix paints so that the color does not fade over time, causal reasoning powers our problem solving. Given this, it is no wonder that babies enter the world exploring, testing, and evaluating cause and effect.

Children's fascination with cause and effect relationships is evident in their seemingly endless stream of "why" questions. In fact, researchers estimate that preschoolers ask an average of 76 information-seeking questions per hour (Chouinard, Harris, & Maratsos, 2007)! Once infants can grasp objects, they may experiment with dropping a spoon from their high chair or shaking a toy to see if it makes noise. Not so long ago, psychologists believed that young children were "pre-causal," that is, not logical in their thinking and challenged to reason about cause and effect—a theory of cognitive development proposed by the famous developmental psychologist Jean Piaget (1929). However, a robust body of empirical research over the past 30 years demonstrates that starting in infancy, children develop and test intuitive theories about the world around them, much like scientists do (Gopnik, 2012; Gopnik, Schulz, & Schulz, 2007; Gopnik & Wellman, 2012).

In fact, research indicates that—counterintuitively—younger learners can be more flexible in their thinking than older children and adults trying to infer cause and effect from a pattern of evidence and, as a result, sometimes outperform those with more life experience

(Gopnik et al., 2017). To capitalize on this early period of cognitive flexibility, even very young children should be given interesting and challenging opportunities to explore what causes what in the world around them.



Early causal learning

One way that researchers investigate how young children reason about cause and effect is to conduct studies that involve a “blicket detector,” a machine that will play music or light up when certain objects (referred to as “blickets”) are placed on top of it (Gopnik & Sobel, 2000; Nazzi & Gopnik, 2000). Children performing the blicket detector task are shown a set of blocks, along with different patterns of evidence

revealing which blocks—the “blickets”—have the causal power to activate the machine (see Figure 1). By observing children interacting with the blickets and other blocks, psychologists track how children develop theories, make predictions, test their hypothesis, and revise their theories.

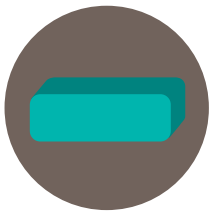
For example, Gopnik, Sobel, Schulz, and Glymour (2001) used this task to examine how children use statistical patterns to infer causation. These researchers introduced 2-, 3-, and 4-year-olds to a blicket detector and a set of blocks and explained to children that “blickets make the machine go.” The children were then shown a series of actions providing evidence that Block A (but not Block B) was a blicket. After observing the researchers put the blocks on the blicket detector in different patterns, children as young as 2 were able to determine which block was the blicket. This study highlights young children’s impressive ability to understand direct causal relationships (i.e., “Block A makes the machine go, so Block A must be the blicket.”). Subsequent research demonstrates that by the age of 4, children are capable of reasoning about more complicated causal relationships, such as causal chain structures (i.e., A causes B which, in turn, causes C) and common cause structures (i.e., A causes both B and C) (Schulz, Gopnik, & Glymour, 2007).

Figure 1.

Examining causal learning

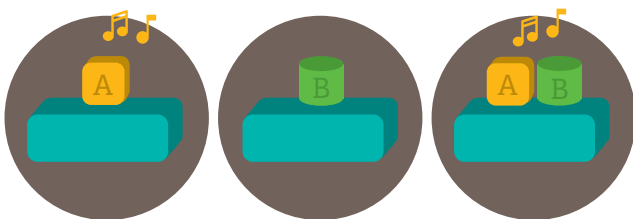
Many researchers investigate causal learning by showing children a novel machine (a “blicket detector”) that plays music when certain objects are placed on top. Children have to reason about things they cannot see and make predictions about which objects will activate the toy and which objects will not.

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)

Social cues and causal thinking

Though a growing body of evidence demonstrates young children are wired to explore and reason about cause and effect from an early age, it is important to understand the role of the social environment in influencing children’s understanding and development. For example, research indicates that preschoolers can learn about causal relationships by observing the actions of others and using this information to guide their choice of which actions to imitate (Buchsbaum, Gopnik, Griffiths, & Shafto, 2011). In one such study, 4-year-olds watched an experimenter perform five different sequences of three actions on a toy, where some sequences resulted in the toy playing music, and other sequences did not. By carefully examining each sequence of actions, children were able to infer

that only the last two actions of each sequence were necessary to activate the toy. When asked to activate the toy themselves, children regularly produced only the last two actions.

To study the role of social cues in causal reasoning, the researchers then used the same procedure in a second experiment, with one important change: before beginning, the researcher told the child, “See this toy? This is my toy and it plays music. I’m going to show you how it works.” This time, children were more likely to imitate all the actions, even those with no impact. They would over-imitate, following the social cue of the “authority” on the toy. This finding has important implications for educators and parents, who by their very nature, are going to be seen by children as authorities. When it comes to the teaching and learning of STEM—where the vast majority of adults in a child’s life are not, in fact, authorities on the topics being explored—it becomes particularly important for adults to support more open-ended exploration and to communicate to children that they are also learners. A child playing in the bath may ask why a plastic boat doesn’t stay afloat. The father might explain that it’s too heavy. (When in fact the child’s toy wooden boat is heavier but stays afloat.) By refraining from providing answers, and instead using the child’s piqued curiosity to bring lots of materials and shapes into the water to play, the father could boost the child’s causal reasoning and avoid giving information that might lead to wrong understandings.

Explanation and exploration

Further evidence of how adults can support children’s STEM thinking is provided by recent empirical work highlighting how simply asking children to explain what they observed can promote causal learning (Legare & Lombrozo, 2014; Walker, Lombrozo, Legare, & Gopnik 2014). Using the blinket paradigm with 3- to 5-year-olds, Walker and colleagues (2014) found that prompting preschoolers to *explain* what they observed after each block was placed on the toy (i.e., talking about *why* the block made the toy play music rather than merely reporting whether it did or not) led children to focus on



CASE STUDY

PUTTING RESEARCH INTO PRACTICE: Learning through hands-on exploration

Designed for Pre-K to third grade students, STEM Workshops at BADM invite local schools to the museum for a hands-on, multisensory exploration of a diverse set of STEM topics. In *Push, Pull, Crash*, students experiment with the powers of force and friction to create art, cause and avoid toy collisions, and test hypotheses about the properties of different materials. Through these activities, children explore cause and effect relationships, which are foundational to the processes of scientific inquiry.

Our museum educators elicit deeper conceptual learning by encouraging children to “act like a scientist,” and explicitly instructing them to use their eyes and ears to find out more about things, their hands to try things out to see what happens, and their brains to think about why things happened or guess what will happen next. The educator then introduces the concept of *force* in a playful demonstration with a toy truck, and asks children for ideas on how to make the truck move. Next, *friction* is introduced as a special force that makes things slow down or stop completely. Later in the program, students freely explore a variety of stations, including one with cars and ramps covered with different materials (e.g., duct tape, LEGO blocks), as pictured in the photo. Children are then asked to make predictions about which material provides the most friction, and consequently, which cars will go the fastest and slowest down the ramp. Asking children to make predictions or reflect on what causes things to happen during a fun, hands-on activity like the one described here, encourages children to engage in causal reasoning and build on their STEM knowledge.

the causal (internal) properties of the blocks instead of the appearance (i.e., color or shape) of the blocks.

Relatedly, Legare and Lombrozo (2014) explored how explanation influences learning in preschoolers by observing children's interactions with a novel mechanical toy with gears of different colors and configurations. They found that children prompted to explain how the toy worked performed significantly better on measures of cause and effect than children who explored the toy but were not asked to explain how it worked. Interestingly, those who explored without direction did a better job remembering perceptual information (i.e., which color gears were in which location), indicating that when left to their own exploration, young children's brains may be inclined to pay most attention to surface-level perceptual details and ignore function. As will be described more in Finding Six, adults should be aware that young children need support from adults to focus their attention on the most important information and to ignore less relevant information that is highly visible, such as color or size.

Reasoning through statistical inference

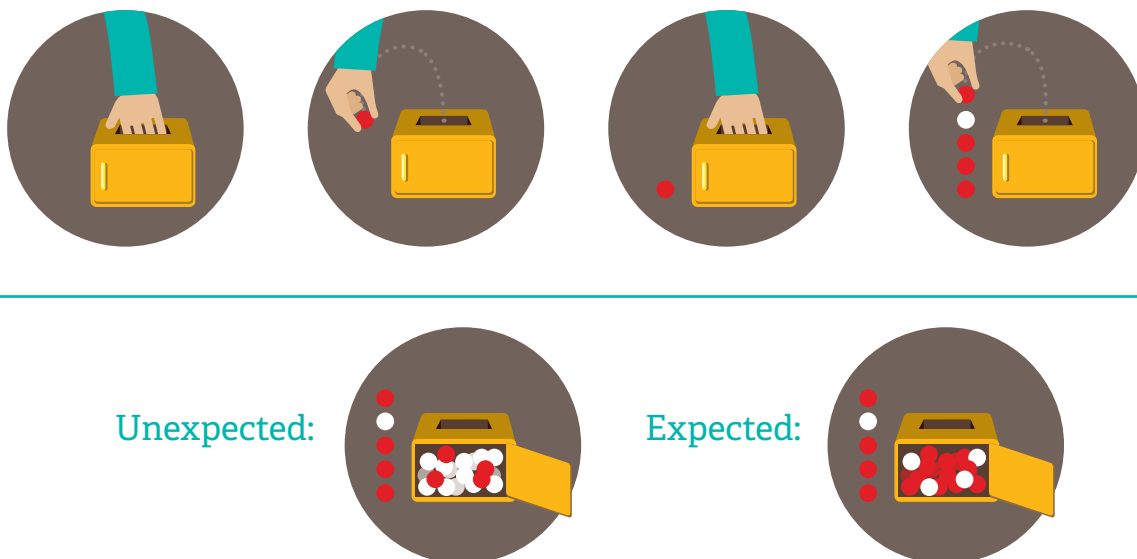
While causal reasoning skills are the precursors to scientific inquiry, children also have the ability to reason using *statistical inference* (e.g., generalizing from samples to populations and vice versa). Research indicates that the ability to reason using statistical inference is present very early in development and may be at the roots of understanding scientific inquiry and probabilistic reasoning (Denison & Xu, 2010; Kushnir, Xu, & Wellman, 2010; Xu & Garcia, 2008).

In order to test the origins of this capacity, Xu and Garcia (2008) designed a simple procedure capitalizing on infants' tendency to look longer at stimuli that violate their expectations. In one of their experiments, 8-month-old infants were shown a large box containing either mostly white or mostly red balls. They then saw an experimenter repeatedly pull five balls (the sample) from the box (the population). Each sample consisted of either four white/one red or four red/one white, and the researchers measured how long the infants spent looking at the five-ball sample. If infants, upon seeing the

Figure 2.

Intuitive statistics in infants

Xu & Garcia (2008) used the fact that infants tend to look longer at unexpected events to test 8-month-olds' sensitivity to the relationship between samples and populations. For example, infants were surprised (and looked longer) at a sample of mostly-red balls pulled from a mostly-white box.



Adapted from Xu & Garcia (2008)

ratio of red to white balls in the large box, had formed an expectation about which color would be more likely to get drawn, they should be surprised and look longer at the improbable sample (e.g., four red/one white pulled from the mostly white box) (See Figure 2). Indeed, this is what the authors found, suggesting a remarkably early intuitive foundation for the type of inference and prediction that scientific inquiry relies on. Another experiment using a similar design also revealed infants' capacity to make predictions in the opposite direction: *from* a sample to a population (e.g., looking longer at a mostly-red box as the origin of a mostly-white sample).

Researchers theorize that these early intuitive statistics and inference mechanisms allow children to quickly acquire knowledge, guiding their reasoning across domains and social situations. In other words, starting in infancy, children's sensitivity to statistical information in the environment appears to undergird their learning about everything from the probability of events to the workings of others' minds.

Given how important causal reasoning is for the development of all types of science learning, it seems only fitting that attention to cause and effect relationships should emerge at such a young age. The findings reviewed thus far indicate that causal reasoning and statistical learning develop without explicit training, and that adults play an important role in developing these skills to bolster children's scientific inquiry and STEM learning.

Practical Tips

- Choose toys and experiences that have manipulative elements (e.g., rattles, blocks, balls and ramps). Ask children to change the outcomes of these toys (e.g., make the rattle softer, build the block tower higher, make the ball go faster).
- Invite children to investigate the simple machines and functional tools around your house (e.g., kitchen tools like can openers; parts of your home that move or have variable functions like doors/hinges and adjustable shower heads; everyday tools like scissors and pencils). Ask them to explain to you how these objects work.
- Encourage children to notice patterns and changes to patterns. For example, point out the recurring sequence of day to night and season to season, and highlight how seasonal changes affect daily routines. "Even though it's still light out, it is time for bed. In summer, it gets dark later than in winter."
- Be patient with repetitive play: when your baby drops each clean spoon immediately after you give it to him, remember that he is testing out an emerging theory about how gravity works.

2

FINDING TWO: To become strong STEM thinkers, children need more play

Play is at the heart of children's learning, as developmental psychology demonstrates over and over again. And yet, in today's day and age, time for play is jeopardized as parents and educators worry increasingly about academic readiness. This, however, is in opposition to a large body of research indicating that play supports children's conceptual thinking and scientific inquiry. In a recent article for The Atlantic, developmental psychologist and author Alison Gopnik (2016) argues that "play lets the young learn by randomly and variably trying out a range of actions and ideas and then working out the consequences...The gift of play is the way it teaches us how to deal with the unexpected."

What is Play?

Researchers define play as an activity that appears to have no purpose or function for the individual; is voluntary and intrinsically engaging; immerses the individual in the moment; and opens the individual up to improvisation and imagination (Brown, 2009). Research demonstrates that play boosts thinking and learning by promoting brain plasticity, or the ability of the brain to mold and rewire itself in response to new information and experience. Within the broad definition of play, researchers look at the benefits of different types of play, both in terms of their content and in terms of who is involved. The most relevant for the development of STEM thinking, learning, and reasoning include the following:

- When engaged in "pretend" play, children use their imaginations to make up, narrate, or enact stories.

- In "exploratory" play, children engage in building, tinkering, taking things apart, or creating little experiments (e.g., spraying shaving cream all over the wall) to figure out how the physical world works.
- During "guided" play, adults play alongside children, taking cues from children about what to do and explore while adding questions, challenges, and interactions that make the play more robust.
- "Free" play is entirely directed by children without adult involvement. This type of play is often compared to guided play.

To develop strong STEM skills, children should have a strong balance of all these types of play.

Play provides real opportunities for scientific reasoning

Research indicates that pretend play, in particular, is related to counterfactual reasoning—an important type of thinking that supports scientific inquiry. When people engage in counterfactual reasoning, they ask questions like, "What would have happened if I had done X?" which is similar to the thinking children do during pretend play, when they construct unreal scenarios about possible worlds. *If I were the mom, and the teddy bear snuck a cookie before dinner, how would I respond?* Buchsbaum, Bridgers, Weisberg and Gopnik (2012) found that children who engage in pretend play do better on measures of counterfactual reasoning. Specifically, these researchers used the blinket detector, allowing some children to engage in pretend play with it before beginning a counterfactual reasoning task (e.g., reasoning about what *could* have



happened if a block had been a blicket). They found that, the longer children engaged in pretend play, the better they were at making counterfactual inferences about the machine.

Relatedly, research demonstrates that exploratory play in early childhood supports children's understanding of causal models. In one such study, Schulz and Bonawitz (2007) introduced preschoolers to a novel toy box with two levers—one that made a duck pop out, and one that made a puppet pop up. Some children were shown a clear demonstration of which lever made which toy pop up, and other children were shown an ambiguous demonstration that failed to distinguish which lever controlled which toy. After seeing either the clear or ambiguous demonstration, children were given time to play with the familiar toy box, as well as a similar toy box. As predicted, children who were presented with the ambiguous evidence were more likely to reach for the familiar box first in order to figure out which lever did what. This suggests that children are motivated to engage in exploratory play when there is *something to be learned*. Recalling our discussion of how asking

children to provide explanations can prompt deeper causal learning from Finding One, how might the process of explanation—specifically, explaining inconsistency—inform children's exploratory play?

Explanation leads to exploration, which leads to learning

Research indicates that *explanatory* and *exploratory* processes support and enhance each other: asking children for explanations directs their attention to information related to underlying causal mechanisms, and exploration, in turn, enables children to test the hypotheses generated via explanation (Legare, 2012). Thus, when coupled together, explanation leads to more exploration and exploration leads to a stronger explanation. For example, in a study with 2- to 6-year-olds, Legare (2012) investigated the relationship between explanation and exploratory play when children observed consistent versus inconsistent outcomes. After being introduced to two experimenter-controlled "light boxes" and a set of objects, children were taught about the different categories of objects (i.e., some objects lit the boxes, while others did not). After this training phase, researchers gave a demonstration that was either consistent or inconsistent with what they had previously shown children. They then asked the children, "Why did that happen?" and gave children time to play with the objects and light boxes.

Legare hypothesized that if inconsistent evidence drives the process of causal learning, then the kind of explanations children give—as well as their subsequent exploratory play—should focus on figuring out causal relations. As predicted, Legare found children's explanations predicted their exploratory play patterns, but only if they had been given inconsistent outcomes. More specifically, explanations related to causal functions (e.g., "The blicket is not working anymore. It is broken.") were associated with longer play times and more variable play (e.g., playing with both light boxes, trying different combinations of objects). This pattern of findings suggests that when children are presented with information that conflicts with their prior knowledge, it increases their motivation to explain the

inconsistency, and this promotes exploratory play and discovery. Thus, inconsistency can be a powerful agent for learning when it elicits explanation and exploration.

To further investigate the relationship between uncertainty and exploration, van Schijndel, van Bers, and Raijmakers (2015) examined children's patterns of exploration in a situation where they observed conflicting evidence in forming shadows. Children ages 4 to 9 years old were introduced to a shadow machine that projected shadows of puppets varying in size according to the size and distance of the puppets from a light source. Children who were confronted with conflicting evidence performed more informative experiments during free play than those who observed evidence that confirmed their theory. More specifically, all of the children who watched a conflicting event performed an experiment in their play through which they varied one dimension (size or distance) while the other was kept constant.

Taken together, these findings indicate that presenting children with theory-violating evidence during play can evoke their curiosity, motivate them to explore, and lead them to engage in hypothesis testing behaviors to learn about the world around them. Toys, learning experiences, and digital media can capitalize on this intrinsic process for learning about the world by incorporating elements of surprise and discovery that are not apparent at first.

Guided play as effective teaching and learning

While evidence of the benefits of pretend and exploratory play continues to grow, developmental researchers have recently highlighted the important role of adults in scaffolding children's learning through *guided play* (Weisberg, Hirsh-Pasek, & Golinkoff, 2013). Guided play combines elements of direct instruction and free play, where adults support children's learning by defining the learning goals of an activity and scaffolding the environment while allowing children to maintain control over their learning. A steadily growing body of research suggests that the balance



CASE STUDY

PUTTING RESEARCH INTO PRACTICE: Learning about shapes through guided play

Given the many benefits of guided play for children's learning, BADM designs activities that allow children to engage in playful learning with the intentional support of an adult. As part of Connections, BADM's community partnership program with local subsidized preschools, children learn about triangles while working in the Early Childhood Fab Lab. In this makerspace, children actively explore triangles with a range of low- to high-tech tools that focus on building STEM skills with the guidance and support of museum educators, teachers, and parents.

Following an introductory group circle time facilitated by one of our museum educators, children are given the opportunity to actively explore triangles at a number of different stations. One station invites children to sort triangles of different sizes and types (e.g., equilateral, obtuse, scalene, and acute) into different categories. A nearby sign prompts adults to ask children to explain their thinking: "These are all triangles. What do you notice is different? What is the same?" At another station, museum educators invite children to manipulate triangles on digital tablets by rotating, stretching or re-sizing them, and then watch as their triangles are printed on a laser cutter. Teachers then take the laser-cut triangles back to their classroom so students can continue to play with the triangle blocks they helped create. These activities provide a clear illustration of the type of playful exploration that—when guided by the intentional support of an adult—can lead to deep and meaningful math learning.

between structure and freedom in guided play makes it a successful tool for a range of educational outcomes, which is often more effective than free play or direct instruction in isolation (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Fisher, Hirsh-Pasek, Newcombe, & Golinkoff, 2013; Weisberg, Kittredge, Hirsh-Pasek, Golinkoff, & Klahr, 2015).

For instance, Fisher, Hirsh-Pasek, Newcombe, and Golinkoff (2013) found that children who were introduced to properties of shapes through guided play enjoyed significantly better learning outcomes than children who learned about shapes through direct instruction or free play. Specifically, direct instruction and free play scenarios enabled children to learn the properties of shapes, while through guided play, children mastered a more conceptual understanding of triangles, such as being able to recognize atypical shapes, like triangles with large internal angles. In contrast, children in the direct instruction condition tended to display relatively concrete knowledge of shapes and often rejected the atypical triangles as

not being “real shapes.” Of note, the preschoolers learning through direct instruction did not typically define shapes based on rules (e.g., a triangle has three sides and three angles), but rather based on shape recognition. These findings suggest that guided play enables young children to identify shapes in a rule-based, conceptual manner earlier and more efficiently than other means of instruction, and that guided play prompts deeper learning by directing children’s attention to the defining features of shapes, rather than perceptual similarities.

Ferarra, Hirsh-Pasek, Newcombe, Golinkoff, and Lam (2011) provide additional support for the benefits of guided play in the context of a block building activity. These researchers observed parents and their preschool children playing with blocks in one of three conditions: (1) free play, (2) guided play, and (3) play with preassembled structures. In the free play scenario, parents and children played with a set of blocks without any guidance. In the guided play condition, the parent-child dyads were given a set of numbered



photographs to build a structure from (similar to instructions for IKEA furniture assembly). In the third condition—play with preassembled structures—the dyads were given an already completed model made of blocks. Examination of participants' use of spatial talk revealed a different pattern of results for children and parents in the different conditions. More specifically, it was determined that children in the free play condition produced the least amount of spatial language (rates of spatial language for children in the guided play and preassembled conditions did not differ), and parents in the guided play condition produced significantly greater spatial talk than parents in both the free play and preassembled conditions. Taken together, these results suggest that the context of play matters for both adults and children and, importantly, that exposing children to guided play impacts the amount of spatial vocabulary they hear and produce. As discussed in the next key finding, these increases in perceiving and producing spatial language can in turn increase children's spatial skills and STEM learning.



Practical Tips

- Provide time for pretend play and exploratory play, even into the elementary years. For pretend play, provide costumes, dolls or animals, intriguing environments like a bedroom fort or a forest, and playmates. For exploratory play, try saying “yes” as much as possible: allow your toddler to make a sound on a real guitar, your preschooler to paint his legs with mud, or your 7-year-old to attach 17 wheels onto her DIY car.
- When children’s explanations or theories are incorrect, try showing them a result that is inconsistent with their reasoning, then give them the chance for exploratory play to develop a new idea. For instance, a child who thinks a sturdy base must be the heaviest part of the building will be challenged to rethink their theory when shown a book suspended in the air with only a sheet of paper folded into the shape of a triangle.
- Guided play is a particularly rich way to support conceptual development in young children. Articulate a clear learning outcome for the children and play alongside them, asking questions and supporting their developing theories. For example, invite children to play in a water table to explore relative density. Ask open-ended questions such as, “What happens when you add oil to the water? Why do you think that happened?”

3

FINDING THREE: STEM amplifies language development; language enables STEM thinking

As will be discussed in Finding Six, success with STEM learning depends heavily on an individual's capacity to reason about ideas and phenomena that one cannot directly see or experience. In other words, STEM thinking requires higher-order, conceptual thinking skills. Research indicates that vocabulary development—and particularly experiences focused on modeling and encouraging use of vocabulary to describe ideas—is a significant part of the answer. Just consider the impressive range of everyday (but conceptually complex) STEM-related words that children encounter on a regular basis—from technology words like *on-demand TV* (versus *live*) or *wireless internet*; to household words like *baking* (versus *heating*) or *hand sanitizer*; to transportation words like *bus fare* or *hybrid vehicle*. Children will effortlessly assimilate these words into their vocabularies, but of course that is not the same as understanding the phenomena the words describe. (After all, most adults cannot explain what the Internet is or how an outgoing email is sent to a colleague.) Research indicates that there are some important ways that adults can engage in conversations with children that support them to understand the phenomena behind words. In particular, a steadily growing body of research demonstrates the important role that parent-child conversations have on STEM conceptual learning (see Callanan, 2012; Haden, 2010 for reviews).

Science talk promotes conceptual understanding

Like many developmental researchers looking at science talk, Crowley and colleagues (2001) used a museum setting to investigate the ways that parents support children's learning. They found that adults

could support children to learn about a new concept through a variety of *explanatory talk*, including explaining children's experience in causal terms and connecting the experience of an exhibit to children's prior knowledge. Relatedly, Benjamin, Haden, and Wilkerson (2010) investigated the role of *elaborative talk*—open-ended questions that promote critical thinking and connections to prior knowledge—on children's engagement and memory for exhibit information and found that children who participated in this type of dialogue gained the most from their exhibit experience. More specifically, Benjamin and colleagues (2010) provided families with children between the ages of 4 and 8 with different types of information before they interacted with an exhibit focusing on building and engineering concepts. First, parent-child dyads engaged in a pre-exhibit experience consisting of: (1) instruction to use elaborative questions (e.g., “Why would a workman wear these goggles?” “What is this called?”); (2) guidance for building structures (i.e., discussion of what makes structures strong and time to practice construction); or (3) a combination of both. The parent-child groups then completed a variety of construction tasks together, such as building a structure and evaluating the strength of other structures displayed in a series of photos.

The researchers found that parents who had been encouraged to use “WH questions” during the pre-exhibit activity also used more of that language in the activities that followed and had longer conversations with their children. Their children, in turn, showed better recollection of the activities than parents who were not encouraged to ask elaborative questions. Moreover, children who engaged in elaborative conversation with a caregiver subsequently demonstrated the most

success in creating and identifying successful building features. More recently, Callanan, Castañeda, Luce, and Martin (2017) investigated the impact of family science talk on children's conceptual engagement with a museum exhibit about mammoth bones. Consistent with findings for the supportive role of elaborative talk in children's learning (Benjamin et al., 2010), Callanan and colleagues found that the more parents asked questions that required critical thinking and connected the exhibit content to children's prior experiences, the more children used language indicating they were conceptually engaged with the subject matter. For example, children made comparisons from something in the exhibit to another event or object ("This is like the movie *Ice Age*").

While much of the reviewed research takes place in museums, it is worth noting that it was the *content* of parent-child conversations which guided children's science learning; thus these findings should extend beyond museum environments. Together, this robust and growing body of research provides convincing evidence that parent-child conversation in informal, real-world settings promotes children's causal and conceptual reasoning, and in turn, may inspire children's interest in STEM. This is discussed at more length in Finding Four.

Science learning and language learning develop in tandem

Recent work at the Institute for Inquiry (IFI) at the Exploratorium has taken a different approach to promoting science learning through rich language exchanges between children and adults (Institute for Inquiry, Exploratorium, 2015). More specifically, IFI's approach recognizes that science learning and language learning develop in tandem, and the integration of these seemingly distinct areas provides a rich context for hands-on, inquiry-based science. Recognizing these benefits, IFI facilitated a unique collaboration between the Exploratorium and the Sonoma Valley Unified School District to develop a program that helps accelerate the language development of English Language Learners in grades K-5 within the context of hands-on science.

Over five years, the program provided support and guidance to teachers through an integrated curriculum meeting both English Language Development and science standards, professional development, a professional learning community, and district support. Qualitative evaluations revealed several important outcomes with regard to student learning opportunities,



including an increase in the amount of science instruction; an increased level of engagement, interest, and motivation in science inquiry; and improved receptive and expressive language (Castori, Heenan, Ramage, & St. John, 2015). The success of this program provides a real-world example of the critical role of language in developing science inquiry skills—and importantly, how the two work synergistically to create authentic intellectual experiences for students.



CASE STUDY

PUTTING RESEARCH INTO PRACTICE: Building STEM knowledge with blocks and spatial talk

Kids become STEM Superheroes at BADM and use their creative “super-powers” to design, imagine, and test innovations for solving problems dealing with robots, food, health, and space. As a part of the special event series *STEM Superheroes: Building Big*, children are encouraged to use spatial language (e.g., in, on, under) while arranging color-coded blocks (representing different buildings) within a 2' x 2' frame (representing a city). This program, titled Square City, also focuses on math concepts like measurement, estimation, and geometry, while introducing children to vocabulary such as *area* and *perimeter*.

All this learning happens in the context of children using math and critical thinking skills to work towards solving a problem. For example, each work-station displays “challenge cards,” one of which explains “Citizens of your city want bike lanes! Make sure you have at least 3 inches *between* all your buildings.” A museum educator or adult might then ask, “Where will you place your ruler to measure where the bike lane should go?” and the child may say “*next to it!*” or “*behind*” or “*in front of*” the buildings they are trying to test against the new city restriction. Square City provides children with a fun opportunity to work collaboratively and communicate using spatial and domain-specific vocabulary shown to improve spatial reasoning and problem solving.

Importantly, empirical work in lab settings parallels these findings for language’s critical role in science learning. As discussed earlier in Finding One, research on preschoolers’ causal learning demonstrates that prompting children to explain what they observe can direct their attention to causal properties of novel objects (Legare & Lombrozo, 2014; Walker, Lombrozo, Legare, & Gopnik, 2014). That is, asking a simple question like, “Why did this block make my toy play music?” prompts scientific thinking and supports children to reason abstractly rather than focus on perceptual features.

Spatial language promotes spatial reasoning

Another area of research highlighting the role of language in STEM learning focuses on children’s ability to make sense of and describe objects in relation to each other, known in the literature as “spatial reasoning” (see Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017 for a review). An ever-growing body of literature speaks to the importance of early spatial skills—the ability to mentally manipulate objects and shapes in the environment—for later success in a range of STEM areas, including mathematics (Casey, Nuttall, & Pezaris, 1997), engineering (Peters, Chisholm, & Laeng, 1995), and physics (Kozhevnikov, Motes, & Hegarty, 2007). Importantly, research with toddlers and preschoolers indicates that spatial language (e.g., *next to*, *above*, *under*) can help improve spatial reasoning. In a study with 3-year-olds, Loewenstein and Gentner (1998) found that children who heard spatial language (e.g., “I’m putting the winner [in, on, or under] the box.”) to describe the location of a prize were more likely to find a target object than children who did not (e.g., “I’m putting the winner right here.”). Relatedly, Pruden, Levine, and Huttenlocher (2011) found that spatial language input from parents in the toddler years predicted children’s use of spatial language, and this in turn, was linked to better performance on spatial problem-solving tasks. Thus, current evidence suggests that exposure to and use of spatial language in early childhood can improve spatial skills, which are foundational to STEM achievement (Cheng & Mix, 2014).

Vocabulary and cognitive load

Researchers theorize that early and robust exposure to conceptual vocabulary supports children with reasoning skills because of what psychologists refer to as “cognitive load” and its impact on our efficiency with processing complex information (Kail, Lervåg, & Hulme, 2016). Like a computer, when the brain is busy working with lots of information at once—particularly lots of new information—it slows down. Slow cognitive processing, in turn, impedes higher order thinking. For example, imagine that you are—for the first time in your life—purchasing a home. Before you can make a sound decision about what sort of loan you need, you first need to wrap your brain around what amortization means, how deductions work, and what it means to hold title in different ways. At first, all these terms are dizzying and you do not have confidence you’ll make a good decision, but as the words and ideas become more familiar your brain becomes freed up to process the information and make a good decision.

Children live much of their lives bombarded by new information that the brain works tirelessly to assimilate. By giving children many opportunities to hear and practice using vocabulary, adults are making an investment in a child’s future cognitive processing power. So, while a 3-year-old may not understand the concept when his preschool teacher explains that the ball is rolling down the slide because of *gravity*, by introducing the word early in his learning career and helping him to associate it with things going down, the teacher is supporting the child to make sense of his mother’s later explanation that the earth is like a great big magnet pulling objects toward it with a force scientists call *gravity*. Because the word is familiar, the boy’s brain can dedicate its processing power on making sense of the abstract idea.

Practical Tips

- Ask open-ended “WH questions”, such as why, what, and how, that prompt children to explain their thinking (e.g., “Why does ice cream melt on a hot day?”, “What is a hammer used for?”) to facilitate children’s learning and remembering.
- Use conceptually rich vocabulary, even with very young children. Babies begin to learn language from birth and receptive language precedes expressive language. Try talking with your toddler about how “stable” their block tower is, identify the “matching” socks, or remind her to be gentle with a “fragile” object.
- Connect conceptual ideas to a child’s prior knowledge and experience. “You know how light switches turn the lights on or off, and then it stays on or off until you flip the switch again? Computers work the same way: lots of tiny switches called bits can be turned on or off to store information.”

4

FINDING FOUR: Active, self-directed learning builds STEM skills and interest

When people think of science and mathematics education, what often comes to mind is a traditional high school where science and mathematics are taught in separate class periods involving lectures and practice sets, but rarely any hands-on problem solving or student-directed inquiry. With the introduction of the Next Generation Science Standards (NGSS), there is great opportunity for children to be introduced to STEM in a much more hands-on way and in a way that taps into children's natural drive to understand how the world works. These standards describe not only grade-level content standards (e.g., first-graders will begin to explore the properties of waves by learning that sound can make matter vibrate). They also explain the ways that scientists and engineers approach their work (e.g., while scientists ask questions and engineers define problems to solve, both scientists and engineers carry out investigations and analyze data using mathematical thinking). Additionally, NGSS describes what it calls "crosscutting concepts;" these are the big interdisciplinary ideas that cut across all STEM fields—from neuroscience to electrical engineering—from the earliest days of school all the way through graduate studies. They include concepts like patterns; cause and effect; scale, proportion, and quantity; and structure and function. The biggest shift with NGSS, however, is the call to action to have children learn science and engineering by doing science and engineering.

The approach outlined with NGSS aligns with what developmental research tells us about children's learning: active education promotes retention of information, understanding of complex ideas, and language development. Additionally, active learning

provides a meaningful opportunity for children to self-direct their own inquiry and problem solving. This motivation to engage with STEM ideas and questions has long-lasting, positive effects.

The value of active learning

A wealth of research on the benefits of active, hands-on learning supports the widely held notion that children learn by doing. For instance, research supports that children have better recall when they engage in hands-on learning compared to more passive forms of learning. Hartman, Miller, and Nelson (2000), for example, asked some children to build a model of a volcano and other children to observe an adult build a model of a volcano. As predicted, the researchers found that children who engaged in building the volcano themselves retained more information.

Research on using manipulatives to teach math provides additional evidence for hands-on learning in children. Teachers have long advocated for the benefits of using objects in the classroom to allow children to concretely see and represent mathematical ideas, especially in preschool, kindergarten, and the early grade school years. Blocks, in particular, allow children to think mathematically as they compare, measure, count, and explore shapes and patterns when building (Kinzer, Gerhardt, & Coca, 2016). And research shows that block play experiences at a young age support academic learning and achievement across subject domains. Wolfgang, Stannard, and Jones (2001) found, for example, that experience playing with blocks in preschool predicted children's math grades and overall achievement scores in junior high and high school.

In addition, research focusing on parent-child interactions shows that engaging in block play elicits high levels of spatial language—that is, using terms like *above*, *below*, *behind*—especially when parents intentionally scaffold their child’s learning (see description of Ferrera, Hirsh-Pasek, Newcombe, Golinkoff, & Lam, 2011 in Finding Two). Importantly, strong spatial skills—the ability to mentally manipulate objects in our environment—are highly predictive of math skills and achievement (Grissmer et al., 2013; Cheng & Mix, 2014). For example, Grissmer and colleagues (2013) gave kindergarteners and first-graders Legos, Wikki Stiks, and pattern blocks and asked them to copy model designs. They found that this experience with visuospatial toys increased the children’s math skills. From a language development perspective, researchers have also found children who engage in block play experiences score higher on language acquisition assessments than peers without those experiences (Christakis, Zimmerman, & Garrison, 2007).

Hands-on, conceptual problem solving

Related to research on hands-on learning is a growing body of research that demonstrates that children are more successful with complex thinking when they are encouraged to use their hands and bodies during thinking tasks. In particular, studies examining children’s performance in STEM-related cognitive domains (e.g., spatial reasoning, mathematics, conceptual reasoning) indicate that gesturing with their hands during problem solving activates different areas of children’s brains, allowing them to tap into knowledge they cannot yet verbalize (Ping, Goldin-Meadow & Beilock, 2014; Pine, Lufkin, Kirk, & Messer, 2007; Goldin-Meadow et al., 2012). Encouraging children to use their hands; count on their fingers; and move, build, and tinker during learning experiences not only engages different neural networks relevant for problem solving (e.g., prefrontal and motor cortices), but also allows children to access and utilize conceptual understanding they cannot yet articulate.



For example, one study examined the effects of encouraging third- and fourth-graders who were struggling to solve math equivalence problems (e.g., $5 + 3 + 4 = _ + 4$) to gesture during problem solving. Broaders and her colleagues found that these children conveyed strategies in their gestures not found in their speech (for example, they demonstrated an *equalizer strategy* relaying that both sides of the equation needed to be equal by sweeping a palm under the left side of the problem and then under the right). Remarkably, the strategies conveyed through body language tended to be effective in solving the complex problems (Broaders, Cook, Mitchell, & Goldin-Meadow, 2007). That children expressed new (and often correct) strategies uniquely through their body movements suggests they were using gesture to “explore” certain strategies before integrating them into their verbal repertoire; their gestures helped reveal previously unexpressed, implicit ideas about problem solving.

Further consideration for the importance of hands-on learning in children’s early STEM experiences—and the supporting role adults play in children’s ability to learn from these experiences—comes from research examining gesture training in preschoolers and school-aged children (Goldin-Meadow et al., 2012; Jaeger, Jaeger, & Chen, 2017). In a study comparing the effects of *observing* versus *producing* gesture on children’s performance on a spatial transformation task, Goldin-Meadow and her colleagues (2012) found that 6-year-olds who were encouraged to produce a problem-solving strategy in gesture (i.e., using the hands to simulate the movement needed to bring two pieces of a shape together to create a whole) performed better on a post-test than children encouraged to produce a less informative, pointing gesture (i.e., simply pointing at the two halves and the whole shape). Relatedly, Jaeger, Jaeger, and Chen (2017) found that, similar to the older children tested previously, preschoolers who were encouraged to produce the gesture representing a problem-solving strategy performed significantly better on the post-test than children who were encouraged to produce a pointing gesture.



CASE STUDY

PUTTING RESEARCH INTO PRACTICE: Designing and refining airplanes

The Bay Area Discovery Museum is home to the world’s first *Early Childhood Fab Lab*—a high-tech maker space where children use digital tablets and fabrication technologies to engage in the design thinking process. That is, children are presented with a novel problem, and given the opportunity to design, test, and refine a solution.

For example, one program gives children the chance to design and test wings for airplanes. First, a museum educator guides a group discussion where children share information and learn about airplanes before sketching their own wing design for an airplane. When their paper sketches are ready, children re-draw their wing on a digital tablet, which is then “printed” on a laser cutter to create a physical, 3-D model. After assembling their airplane, children can experiment with pennies to determine the effect of added weight in various amounts and positions on the plane. Children then test their wing design by throwing their airplane and measuring how far it flies. Importantly, children are encouraged to improve upon their designs by analyzing test results, making changes to one or more variables (e.g., shape of wing, amount or position of pennies, type of throw), and comparing the strengths and weaknesses of each trial. Providing children with early exposure to the design thinking process and opportunities to engage with new and exciting high-tech tools can cultivate lifelong creativity, confidence using technology, and personal interest in STEM.

The results from these studies have important implications for children's STEM learning. Firstly, all of the studies demonstrated that getting children to engage their hands while doing complex problem solving enhances their ability to access and communicate their thinking, explore new strategies, and learn from the visual representation of their implicit knowledge. Secondly, these studies outline an effective way for adults to foster children's engagement with learning—by encouraging them to get their bodies involved. While the gesture research we reviewed took place in laboratory settings, there is nothing barring gesture's benefits for STEM learning from extending to real-world settings. Encouraging children to engage their bodies is a practical learning application that educators and parents can utilize in virtually any learning environment. Thirdly, the results from these studies indicate that children's developmental status should be considered when implementing hands-on learning experiences. Work with younger children should focus on gesture modeling and instruction to gesture, while work with older children can rely more on encouraging them to gesture.

Informal family learning boosts self-directed inquiry

Given the value of hands-on learning, it's no surprise that research shows that STEM learning outside of the classroom—in science museums, in parks, in the home—is critically important for young people (Dierking & Falk, 2003; Falk & Dierking, 2002; Falk & Dierking, 2010; Haden, 2010). After all, these environments afford great opportunity for hands-on learning. Additionally, research shows that these informal learning opportunities are beneficial because they are driven by an individual's inquiry and interest. John Falk and Lynn Dierking, two proponents of informal education, advocate for "[STEM] learning that is guided by learners' needs and interests—the learning that people engage in throughout their lives to find out more about what is useful, compelling, or just plain interesting to them" (Dierking & Falk, 2003, p. 77). In their article *The 95 Percent Solution* published in the *American Scientist* (2010), Falk and Dierking discuss

how average Americans spend less than five percent of their lives in classrooms, and contend that the best route to scientific literacy is through free-choice learning experiences, such as museums, national parks, community activities, and a vast array of digital resources and media.

Research indicates that parental involvement in free-choice learning experiences is an important component of STEM learning. Adelman, Dierking, and Adams (2000) conducted a five-year longitudinal study of participants in the Girls at the Center (GAC) program, which provides science experiences for girls and an adult partner in economically disadvantaged communities across the country. The GAC program invites participants to attend a series of Discovery Days at a local science center and enjoy a full day of other activities including watching an IMAX film and exploring at the museum. The program concludes with a Family ScienceFest, where the girls share their science experiences with friends and family.

Girls participating in the GAC program responded very favorably to the key science activities (i.e., observing, classifying, experimenting, and hypothesizing), and reported that the free-choice science learning experiences were personally meaningful to them. Of import, many went from holding negative attitudes towards science to describing GAC science as "fun because you get to build and create things, and you don't have to memorize lots of stuff that does not really make sense [to you personally]." (Dierking & Falk, 2003, p. 84). What's more, after participating in more than one GAC event, the number of girls contemplating a science-related career increased from 13 to 53 percent, and adults who participated learned how to support and facilitate science learning for girls, both inside and outside of the classroom. Other researchers (Fadigan & Hammrich, 2004) have looked longitudinally at the positive impact that long-term, informal science programs have on secondary students.

These studies demonstrate that OST science education programs positively influence youth's content knowledge and attitudes about science. Programs that emphasize personally meaningful, engaging, and fun

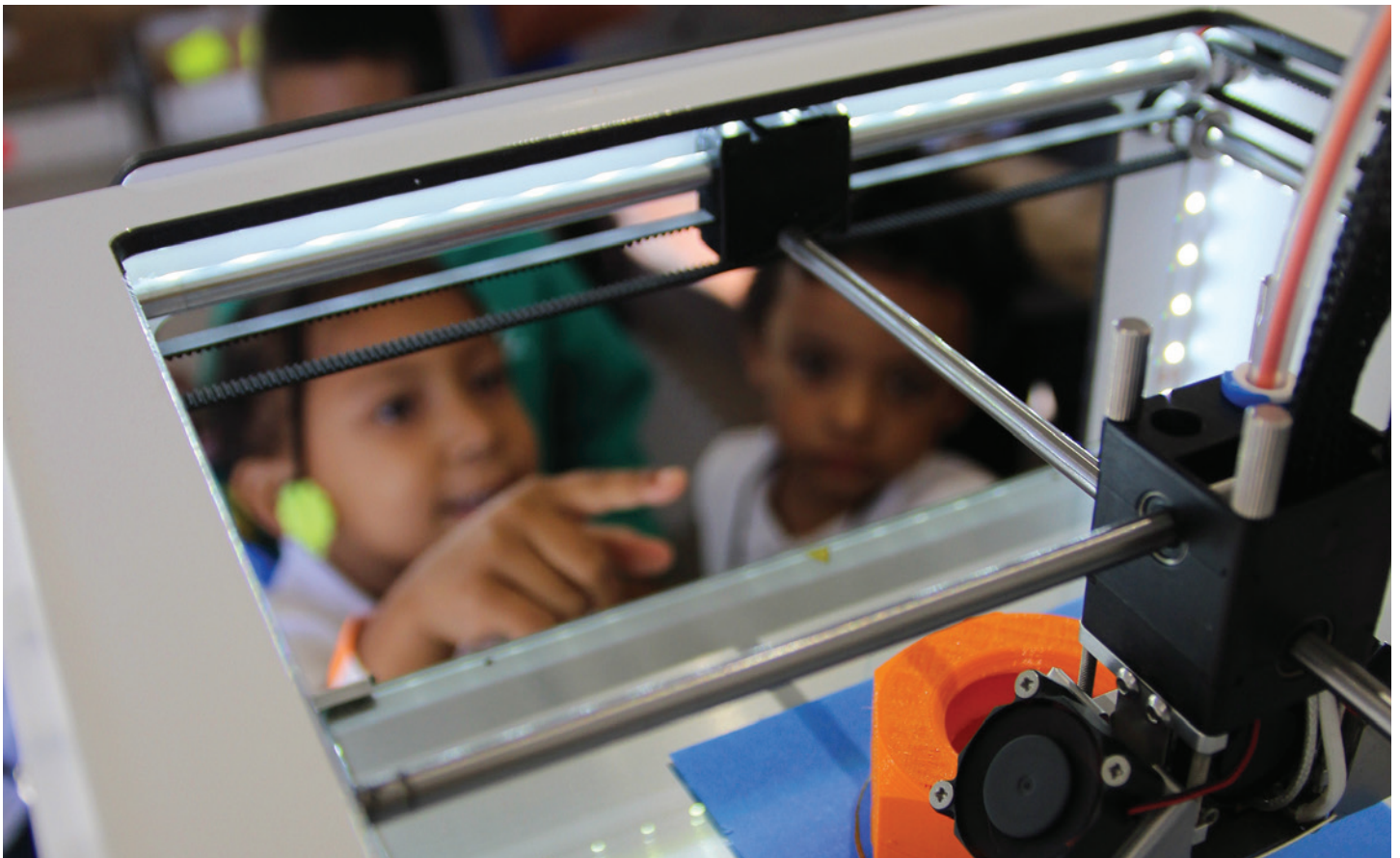
programming that breaks the mold of science learning as dull, irrelevant, or too taxing encourage children's interest in STEM fields. Falk and Dierking (2010) make the important point that "the inclusion of free-choice science learning experiences in the lives of children is essential because young children in particular learn through play." An essential quality of playful learning experiences is the *hands-on* learning that happens when children are active participants in an exploratory, inquiry-based learning process.

Technology-enabled informal learning

While many parents and educators express concern about the introduction of technology to young children, a growing body of research demonstrates that educationally strong content delivered through digital media can be beneficial to children's learning. In particular, well-designed computer programs and games can significantly increase children's math knowledge and skills starting as young as preschool (see Clements, 2002 for a review).

As technology disrupts all aspects of daily life, researchers are beginning to study how educational experiences delivered via technology influence children's learning. Importantly, when people use the word *technology* in relation to children, what they often mean is *digital media* (e.g., apps, games, videos). The American Academy of Pediatrics, the Fred Rogers Institute, and the National Association for the Education of Young Children all hold a similar position: digital media can be a useful vehicle for learning and a safe avenue for entertainment when families are intentional about what content they provide, how long children are permitted to watch or play, and how best to use the devices to prompt conversation, interaction, and shared exploration. The greatest risk of digital media is that families may use devices in lieu of talking and interacting directly with their children (American Academy of Pediatrics Council on Communication and Media, 2016; Paciga & Donohue, 2017).

How to create meaningful digital media experiences for children that are social by nature and lead to more—not less—exchanges between families remains a key area



of further needed study. Given the ubiquity of smart devices, there is terrific opportunity to leverage digital media to bring meaningful learning experiences to more children worldwide.

Additionally, more work is needed to identify ways to meaningfully teach children *about* technology rather than simply using technology as a vehicle for learning other content. Put another way, more research is needed to understand how to best move beyond consumption of technology for educational purposes. For instance, as coding robots become mass market toys, researchers are just beginning to look at computer science education for children in preschool and early elementary school. More work is needed to understand the value and best practices of young children learning these early computer science skills.

Taken together, these studies demonstrate that children learn best when they are able to build their knowledge and acquire new skills through active and engaging learning experiences. That these experiences often happen outside of the classroom—especially for young children—highlights the importance of informal learning environments, in which children can explore topics and engage in activities that are of personal interest to them. Digital media can further support these ideas by enhancing children’s learning of STEM concepts through exploration and active play.

Practical Tips

- Take advantage of everyday opportunities for STEM learning potential: in a nearby garden or park, in the bathtub or kitchen, at a museum or zoo, or even while waiting at a bus stop.
- Encourage children to use their hands and their whole bodies when problem solving. Allow them to count on their fingers and to move their bodies to aid their process and communication. Provide physical manipulatives like blocks or clay to support children’s thinking.
- Use technology or digital media alongside your child and talk with them through their experience to help them make meaning of it. Support children to use digital tools to enhance social interactions (e.g., video chatting with a classroom on the other side of the world) or to research areas of interest (e.g., investigating a topic that you are not an expert in).

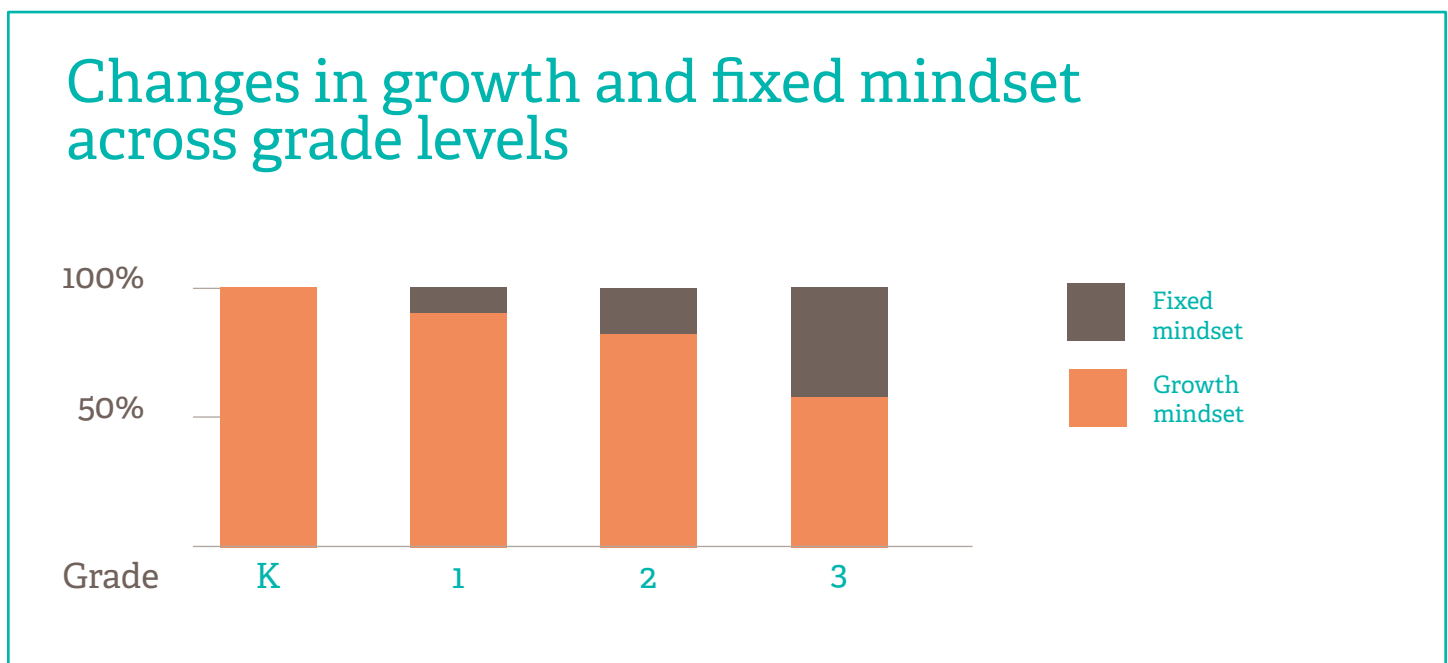
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FINDING FIVE: Mindset matters to STEM success

Research on *mindset*—an individual’s core beliefs about the nature of intelligence and intellectual growth—has had one of the biggest impacts on education in decades (Dweck, 2006). Some believe that intelligence is a malleable quality that can be cultivated and developed with hard work and persistence (a *growth mindset*), while others think of intelligence as unchangeable and static (a *fixed mindset*). The implications of these mindsets are profound—when faced with challenging situations, students with a growth mindset display resilience and use effort to overcome difficulty, whereas those with a fixed mindset give up easily and avoid future challenges. Moreover, students with a growth mindset focus more on learning goals (e.g., goals aimed at increasing ability) versus performance goals (e.g., goals aimed at documenting ability) (Dweck & Leggett, 1988).

Notably, while the majority of research on mindset has focused on children in middle school and older, a growing number of studies demonstrate the importance of mindset in young children and how parents and teachers can shape mindset from the earliest ages (Cimpian, Arce, Markman, & Dweck, 2007; Gunderson et al., 2013). In particular, children’s attitudes and behaviors regarding achievement and failure are already evident in the preschool years (Smiley & Dweck, 1994). Furthermore, survey data collected in elementary school classrooms suggests that the proportion of children with a growth versus fixed mindset decreases dramatically over the early elementary years, with the biggest jump between second and third grade (Ricci, 2013) (see Figure 3).

Figure 3.



Adapted from Ricci (2013)

Mindset influences STEM achievement

A continuing focus for researchers studying the impact of mindset on academic performance is the role of mindset in math and science achievement. Research finds that many students attribute failure to a lack of intelligence rather than effort (i.e., fixed mindset) when learning challenging subjects such as science, technology, engineering, and mathematics (Hong & Lin-Siegler, 2012), and that this mindset has implications for math and science achievement (Blackwell, Trzesniewski, & Dweck, 2007; Park, Gunderson, Tsukayama, Levine, & Beilock, 2016). Park, Gunderson, Tsukayama, Levine, and Beilock (2016) found that first and second grade students who held a growth mindset had higher scores on a standardized math test than those who oriented towards a fixed mindset. Relatedly, in a study with older children that followed four cohorts of students across the challenging transition to junior high school, Blackwell, Trzesniewski, Levine, and Beilock (2007) assessed the mindset of seventh grade students and then monitored their math achievement over the next two years. The researchers found that embracing a growth mindset at the beginning of junior high predicted higher grades in mathematics at the end of the second year of junior high, relative to students holding a fixed mindset.

In addition, there is growing evidence that mindsets play an important role in achievement gaps in math

and science for minorities and women (Aronson, 2007; Dar-Nimrod & Heine, 2006). In two experiments with college females, researchers gave students one of two explanations for gender differences in math before testing them on a challenging math test. One group was told that gender differences are genetically based (fixed mindset manipulation), and the other group was told that differences are based on experience and effort (growth mindset manipulation) (Dar-Nimrod & Heine, 2006). In both experiments, the researchers found that females receiving the fixed mindset manipulation performed significantly worse on the math test than females receiving the growth mindset manipulation. These findings demonstrate that *stereotype threat*—the phenomenon in which concern about conforming to a negative stereotype leads to underperformance for members of that stereotyped group (Steele & Aronson, 1995)—in women’s math performance can be greatly reduced when women orient towards a growth mindset.

Changing mindsets

Given these important links between students’ mindsets and math achievement, the question for parents and educators becomes: how can we direct more students towards a growth mindset? Fortunately, a growing body of research indicates that parents and educators can shape mindsets starting in early childhood, and this, in turn, can have a positive impact on motivation and achievement (Good, Rattan, & Dweck, 2007; Rattan, Good, & Dweck, 2012; Gunderson et al., 2013). More specifically, research has shown that *process praise* (i.e., focus on effort and hard work) leads students to seek new challenges and persist through failure, whereas *person praise* (i.e., focus on intelligence and talent) leads students to avoid challenging tasks, and impairs performance on difficult tasks (Cimpian et al., 2007; Kamins & Dweck, 1999; Mueller & Dweck, 1998). Of note, research with parents and toddlers helps clarify how early mindsets are formed and emphasizes the importance of helping children develop a growth mindset from the youngest ages. In a longitudinal study examining parent-child interactions in a home setting, Gunderson and her colleagues (2013) looked at how mothers praised their toddlers at ages 1 to 3 years old. The researchers followed up with participants

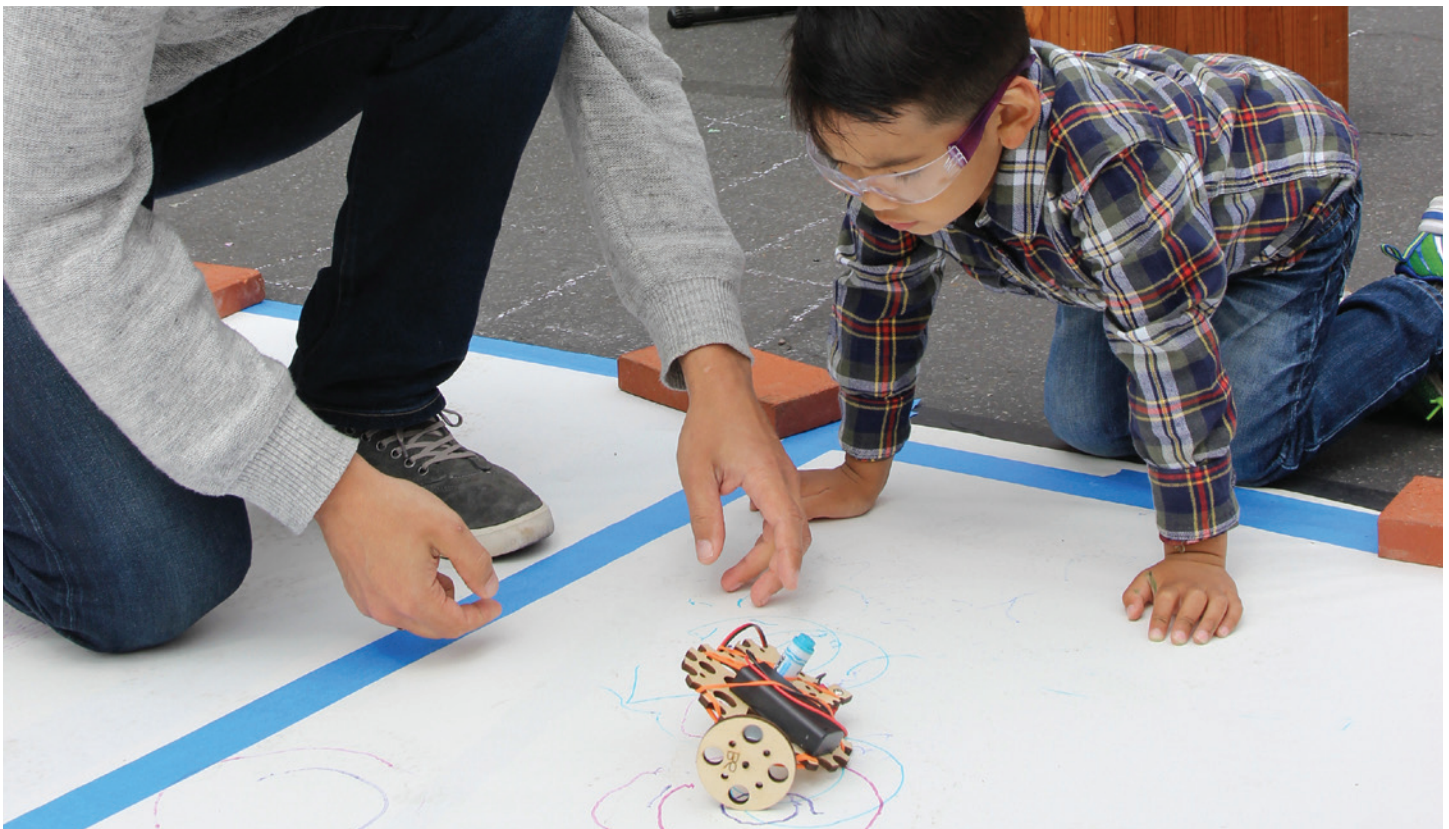


five years later and found that children (now 7 to 8 years old) who heard more process praise from their mothers (e.g., “good job counting”) in the early years preferred challenging tasks, were able to develop strategies when they encountered setbacks, and were more likely to adopt a growth mindset. Notably, parents’ use of person praise (e.g., “you’re good at that”) did not predict children’s later orientation towards a fixed mindset. While this finding goes against research with older students, it is encouraging news for parents and educators who sometimes use sentiments like “you’re so smart” to praise a child.

Relatedly, Good, Rattan, and Dweck (2007) asked adult participants acting as “teachers” to read one of two articles about math intelligence—one explaining that intelligence is fixed and the other that it is malleable—and provide feedback to seventh-graders who received a low grade on a math exam. Teachers who read about a growth mindset were more encouraging and supportive to students (e.g., told students they could improve if they worked hard) and provided more concrete strategies for improving (e.g., changing study strategies or seeking help from a tutor). In contrast, teachers given a fixed mindset article tended to

console students by explaining that not everyone is good at math. Moreover, these teachers gave boys more concrete suggestions for improving than girls. These findings demonstrate how adults’ mindsets can influence how they interact with students, which in turn can impact how students think about their math (or other) abilities. Of note, this growing body of evidence on the powerful role of mindset for STEM learning points to the importance of conveying a growth mindset to children starting in the earliest stages of their development.

A number of training studies provide additional evidence that mindsets are malleable (Blackwell et al., 2007; Good, Aronson, & Inzlicht, 2003; Lin-Siegler, Dweck, & Cohen, 2016). For instance, Blackwell and colleagues (2007) conducted a second study examining the potential impact of a workshop designed to promote a growth mindset. Students in the intervention group were taught that the brain is a “muscle” that develops with “exercise” and grows new connections as we learn. In contrast, students in the control group participated in a similarly structured workshop focused on study skills. As predicted, the math grades of the students who were taught a growth mindset increased



after the intervention, whereas the control group's grades continued to decline.

More recently, Lin-Siegler, Dweck, and Cohen (2016) developed a novel approach for changing the mindsets of ninth and tenth grade students, using a story-based instruction that models how scientists endure failure and struggle to succeed. Students read one of three types of stories about famous scientists such as Albert Einstein and Marie Curie: (1) stories that emphasized the intellectual struggles of the scientist, (2) stories about challenges in the scientist's personal life, or (3) stories that highlighted one of the scientist's great achievements (control condition). Results indicated that—relative to students in the control condition—students who read either of the struggle stories improved their performance in science class after completing the intervention, and that this effect was most pronounced for the lowest performing students.

Strategies for fostering a growth mindset

In a report for the Carnegie Corporation on mindsets in math and science achievement, psychology professor Carol Dweck, the pioneer of mindset research who coined the terms *growth* and *fixed mindset*, described several evidence-based strategies for how educators (and parents) can convey a growth mindset to children (Dweck, 2008). For example, though a prevalent view of intelligence in our society emphasizes inborn talent and giftedness, Dweck posits we can change this view by teaching children about the plasticity of the brain—how the brain changes and becomes stronger the more you exercise it by learning new things. Dweck and her colleagues developed the *Brainology* workshop, an interactive computer-based workshop that teaches students about the physiology of the brain (i.e., how new conceptual and neural connections are formed when we learn something new) and how to approach challenges with a growth mindset. Both small and large scale studies indicate that *Brainology* can change students' mindsets and impact achievement (Chen, 2014; Dweck, 2008). *Brainology* is designed for fifth through ninth grade students, but research tells us that it is important to teach children how their brain works starting much earlier. For example, Marshall



and Comalli (2012) found that while many preschool and early elementary students had limited knowledge of the brain, first-graders who received a series of brief lessons about the role of the brain in a range of sensory activities including seeing, hearing, and feeling improved their knowledge of brain functioning compared to peers who learned about honeybees.

It is also valuable for children to be taught about the struggles and indirect paths to success of prominent scientists and geniuses. When we think about great scholars and artists like Einstein and Jane Goodall, we assume that they were born with exceptional talents. However, conveying to children that it was the individual's passion and dedication that led to their achievement can help shift their perception of the nature of intelligence, and orient them towards a growth mindset (Lin-Siegler et al., 2016). Relatedly, Dweck (2008) emphasizes the importance of communicating the value of challenges, effort, and mistakes to children. Too often in our schools and culture, we value easy success and view this as a sign of true talent. Failures and mistakes are viewed in a negative light instead of as stepping stones to improvement and learning. Questions like "Who had a good struggle? Let's share what we struggled with

today.” and “Who else made a terrific mistake that will help us learn?” can signal to children that adults value challenge, hard work, and learning from mistakes.

Lastly, giving *process praise* or feedback about strategies, effort, and improvement versus *person praise*, which focuses on intelligence or talent, can help shape children’s mindset and influence their motivation. While it may seem counterintuitive, giving process feedback to the most able students is especially important since they are most often praised for their intelligence and effortless achievements. These students may shy away from challenging tasks for fear of failure and exposing weaknesses in their giftedness. In several recent magazine and online articles, Dweck highlights the pitfalls of praising effort, and describes how many educators and parents have misinterpreted her research on praise and mindset (Anderson, 2016; Dweck, 2015). Dweck cautions against offering children “empty praise” for simply trying, which doesn’t convey that learning occurs through hard work and persistence. In a commentary for *Education Week*, Dweck writes:

A growth mindset isn’t just about effort. Perhaps the most common misconception is simply equating the growth mindset with effort. Certainly, effort is key for students’ achievement, but it’s not the only thing. Students need to try new strategies and seek input from others when they’re stuck. They need this repertoire of approaches—not just sheer effort—to learn and improve.

Instead of telling students “You can do anything if you try,” provide feedback that emphasizes the process of learning, such as “Everyone learns in a different way. Let’s try to find the way that works best for you.”

The research discussed in this section clearly demonstrates that children’s achievement and behavior—starting as early as the toddler years—are affected by their beliefs about the nature of intelligence, and their perception of their own strengths and weaknesses. Mindset influences our willingness to try

new endeavors, persist when new skills do not come automatically, and find enjoyment in learning. Young children who struggle to maintain a learning mindset may be more reluctant to take on challenges inherent in learning, and this, in turn may negatively impact their skill development. By communicating that they are capable of accomplishing their goals through hard work, persistence, and seeking help when needed, we can better prepare *all children* to thrive in areas of science, technology, engineering, and mathematics learning.

Practical Tips

- Adopt a “love of mistakes” mentality and see failure as an opportunity for learning. Model your reaction to mistakes for children. When you make a mistake, call it out and celebrate it. Be explicit that you are going to learn from that mistake and make changes moving forward.
- Teach children about the concept of brain plasticity: the brain is a muscle they can shape and grow, and they will improve skills with practice. Teach them to say “I can’t do this yet.”
- Praise children for their process and effort rather than their innate ability and intelligence. Instead of saying, “You are so smart! That test was so easy for you.”, try saying, “I’m so proud of how hard you studied for the math test. You used your fingers and drew pictures to help you understand and solve the problems.”

6

FINDING SIX: Children's abstract thinking potential can be unlocked through both adult support and executive function skill development

Great scientists, inventors, and mathematicians share a common higher order thinking skill: they can reason through ideas and phenomena they cannot directly perceive. Whether it is understanding that germs spread disease, the earth rotates around the sun, living beings evolve to survive, or carbon emissions alter the atmosphere, progress in scientific understanding depends on reasoning through abstract ideas and phenomena.

A critical question for STEM education for young children is the developmental appropriateness of abstraction and conceptualization. For instance, children may understand that a ball rolls downhill and bathwater remains at the bottom of the bath, but can they grapple with the abstract idea of gravity? How do they make sense of information they receive that contradicts what they can see (e.g., the earth is round though it appears flat)? When can children infer that when their mom says her car “died” it is meant as a metaphor, while a plant—which doesn’t appear to move, eat, or breathe—will indeed literally die without water and nutrients? Are children able to meaningfully grasp large quantities—like the difference between 10 cents and 10,000 dollars or the distance to a neighboring park, state, or planet?

Jean Piaget, a pioneer in the study of children and an ardent advocate of education, is most famous for developing a theory that children's cognitive development progresses through distinct stages. Piaget postulated that children in the “preoperational” stage, which begins around age 2 and continues to age 7, were not capable of consistent logic or able to work with complex ideas. Around age 7 children would enter the

“concrete operational stage,” at which point they would demonstrate logic in thinking but would remain unable to reason abstractly. Not until early adolescence could children make sense of abstract ideas and phenomena, he believed.

However, in the last few decades, research has challenged these ideas and demonstrates that children are, in fact, capable of reasoning abstractly, based on information they infer rather than information they directly perceive. Because children have less prior knowledge, as well as less developed skills, they may require more specific support and guidance from adults to reason in a logical and abstract way, but they are in fact capable of doing so. Research indicates that, by having conversations with children that ask them to work with abstract ideas (e.g., “why does the ball move more quickly down the ramp when you increase the angle?”) and introduces them to the words we use for concepts (e.g., *angle, gravity, velocity, prediction*), adults can advance children's capacity for abstract reasoning. Similarly, by helping children pay attention to relevant information (and ignore irrelevant information) through questions and guidance, adults support children to reason through abstract ideas. Finally, research shows that abstract thinking is closely tied to children's developing executive function skills (e.g., higher order thinking skills related to controlling one's thoughts), so strengthening executive function skills through self-direction, play, planning, and games that require inhibition will support children to develop abstract thinking earlier.

Categorization and its relationship to abstract thinking development

A child walking down the street will point to all the different doggies he can find. His father will ask, “What does the doggie say?” and he will delight in yelling “Woof!” whether he sees a Chihuahua or a Great Dane.

These earliest conversations demonstrate our intrinsic interest in forming categories to make sense of the world around us. And of course, such categorization is fundamental to science, engineering, and mathematics, whether determining classes of plants, discovering the relationships between chemical elements, or understanding what prime numbers have in common. Interestingly, research on children’s capacity to categorize also reveals much about their ability to think abstractly. Contrary to Piagetian theory, modern research shows that, at an early age, children demonstrate remarkable flexibility in their categorization and great capacity for inductive reasoning when categorizing. Just as we see with children’s early causal reasoning (see Finding One), young children are capable of far more than is often understood. When experiences and interactions challenge children to think both causally and abstractly, the roots of two of the most important scientific thinking skills—deductive reasoning (i.e., testing theories based on evidence) and inductive reasoning (generating theories based on inference)—are laid.

At times, we use perceptually obvious characteristics shared by two or more items to categorize them as a group. For instance, cars have engines and four wheels, while bikes have no engine and two wheels. Yet perceptions can be deceiving. For instance, while dolphins may look like fish, they are actually mammals because of how their biological systems work. To understand children’s developing abstract reasoning skills, researchers study when young children start looking beyond perceptual features to form categories, and when they are able to use inductive reasoning to transfer their past experience and knowledge to the understanding of new phenomena.

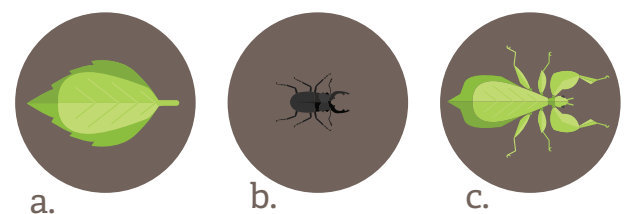
Categorization helps people to think inductively. For example, if a child learns a bird has two wings covered in feathers, categorization allows them to transfer this knowledge to *other* birds, while understanding that perceptually similar objects (e.g., toy planes) are not part of the same group. Remarkably, researchers have demonstrated that babies as young as 9 months old master this sort of abstract reasoning (Mandler & McDonough, 1993).

In a seminal study, Gelman and Markman (1986) showed 4-year-olds sets of pictures that pitted perceptually similar objects with objects that looked different but actually shared category membership. For instance, a child might be shown one picture of a green leaf, another of a black beetle, and a third of an insect camouflaged to look like a green leaf (see Figure 4). When researchers used category labels during the experiment (i.e., (a) “leaf,” (b) “bug,” (c) “bug,”), children were far more likely to group the items based on category membership rather than perceptual cues, putting the two images of insects together, rather than the images that looked like leaves. Similarly, when children learned a new fact about one member of a category (e.g., these bugs live in trees), they tended to generalize that fact to other category members, even if those category members did not look alike.

Figure 4.

Category membership

Four-year-olds understand that when (c) is labeled as a “bug,” it should be categorized and share properties with the “bug” in (b), rather than the “leaf” in (a), despite sharing more perceptual similarities.



Adapted from Gelman (2004)

This study demonstrates the important role of language in supporting young children to work with abstract ideas and to make inferences. With their more limited knowledge, children may be inclined to base reasoning on perception; however, young children use language cues to guide their understanding of abstract ideas and phenomena. This supports Finding Three that STEM learning is inextricably tied to vocabulary development and language exchange. One of the surest ways to support young children to reason abstractly is to talk with them about abstract ideas. After all, without the vocabulary to describe phenomena, children do not have a means of working with abstraction.

The importance of conceptual mathematics in abstract reasoning development

Mathematics—when taught conceptually, rather than as a rote performance of memorization—is a key way to build children’s abstract thinking skills. This translates into reasoning skills beyond the STEM disciplines. In fact, a meta-analysis of results from a number of

longitudinal studies revealed conceptual mathematical understanding to be the strongest predictor of long-term success on school achievement measures. Children who demonstrated strong early math skills were more likely to show long-term proficiency in both mathematics *and* literacy, whereas the same could not be said for early literacy skills (Duncan et al., 2007). So what constitutes conceptual mathematical understanding? Common Core Standards identify *numeracy* (e.g., representing and operating on whole numbers) and *geometry* (e.g., identifying and reasoning about shapes) as two key areas which are foundational to early mathematical understanding. Fortunately for children and their parents, research shows that fun and engaging activities like playing a board game and building with blocks can have a positive impact on young children’s conceptual understanding of numbers and shapes. For example, research indicates that playing linear number-based board games—such as Chutes and Ladders—can target numeracy by improving children’s numerical knowledge and understanding of numerical magnitude (comparing quantities), skills that are often measured by asking children to mark the location of a given number on an empty number line (Siegler & Ramani, 2008; Ramani & Siegler, 2008; Ramani, Siegler, & Hitti, 2012).

Relatedly, research on block building identifies it as an ideal activity for promoting children’s spatial reasoning and knowledge of geometric shapes, especially when children’s block play is guided by an adult (Ferrara, Hirsh-Pasek, Newcombe, Golinkoff, & Lam, 2011; Ramani, Zippert, Schweitzer, & Pan, 2014). Of note, seminal work by Clements and Sarama shows that research-based early childhood mathematics interventions, such as the program *Building Blocks*—a curriculum designed to help children “mathematize” everyday activities like solving puzzles—can have positive and long-lasting effects on early conceptual mathematics skills (2007; 2011). That is, everyday foundational experiences dealing with number, space, geometry, and measurement can provide children



with opportunities to build abstract and conceptual mathematical skills. These experiences are enhanced when adult interaction can help children to gain the vocabulary they need to make sense of abstractions like quantity, relations in space (e.g., words like *over*, *under*, *through*), and relative size. Adult interaction also provides an opportunity to challenge children's incorrect conceptual theories. For instance, while many young children will assume that a taller container holds more water than a shorter, wider container, adults can, through guided play, encourage children to pour from one to the other to see which container actually holds more water.

Abstract reasoning and executive function development

As the previous example (on relative volume of containers) demonstrates, part of what promotes children's abstract reasoning skills is their capacity to revise theories based on new information. Theory revision is a critical, if difficult, skill not just for STEM professionals but for all citizens and should be a primary focus of STEM education for children in later preschool and early elementary school. Otherwise, understandings of how the world works—both in and beyond the STEM disciplines—may be based on misleading perceptions (e.g., that the earth is flat or that, when an object in motion stops moving, it is because the force that was pushing it forward was removed) or on individual beliefs rather than verifiable facts (e.g., that there are significant intrinsic differences between different ethnic groups).

Researchers looking at children between the ages of 5 and 7 have found considerable variation in children's ability to revise previously held, erroneous theories (Zaitchik, Iqbal, & Carey, 2014). These researchers investigated whether children could abstractly reason about life. At what point could children understand, for instance, that a cut Christmas tree, a grandparent who had passed, and the sun are all *not* alive; the first two were previously alive, while the third is inanimate even though it "moves" (a common miscategorization

of living things, not only with preschoolers but also with Alzheimer's patients). Interestingly, Zaitchik, Iqbal, and Carey found that—after controlling for age and verbal IQ scores—children's executive functions (EFs) predicted their understanding of these abstract ideas. EFs are a suite of cognitive skills including working memory, cognitive flexibility, and self-control (For a more complete description, see the Bay Area Discovery Museum's *Reimagining School Readiness*, 2016) (see Figure 5). They theorize that EF capacity enables children to revise previously held theories in a few important ways: EFs allow for the inhibition of old ideas (i.e., the brain may want to revert to a previous explanation but with a more developed EF, the child can suppress the old concept in favor of the new one); EFs include strong working memory, which enables a child to hold all the needed data in her mind simultaneously to grapple with the abstract concept; and EFs provide the cognitive flexibility to switch understandings.

As a result, if we want to support children to develop abstract thinking skills, we need to provide opportunities for them to develop their EF skills. Games and experiences in which children need to inhibit responses (e.g., playing Simon Says, taking turns, delaying gratification) or build on working memory (e.g., playing games that require recall) support the development of EF skills. Additionally children with more opportunity to plan and reflect on their experiences (through free play and opportunities to make choices) develop strong EF skills.



Using analogy to support abstract thinking

One critical way that educators and parents can support young children to grapple with abstract ideas is to provide them with analogies. To teach about brain plasticity as part of developing growth mindset, adults can explain that the parts of our brain are connected like paths in a forest; the more you use one route (by practicing something over and again), the clearer and wider that path becomes. When something is new, it is like walking carefully through a new trail, over roots and occasionally losing one's way. But with time, the work is easier and more automatic. These sorts of analogies help children to make sense of ideas they cannot directly perceive.

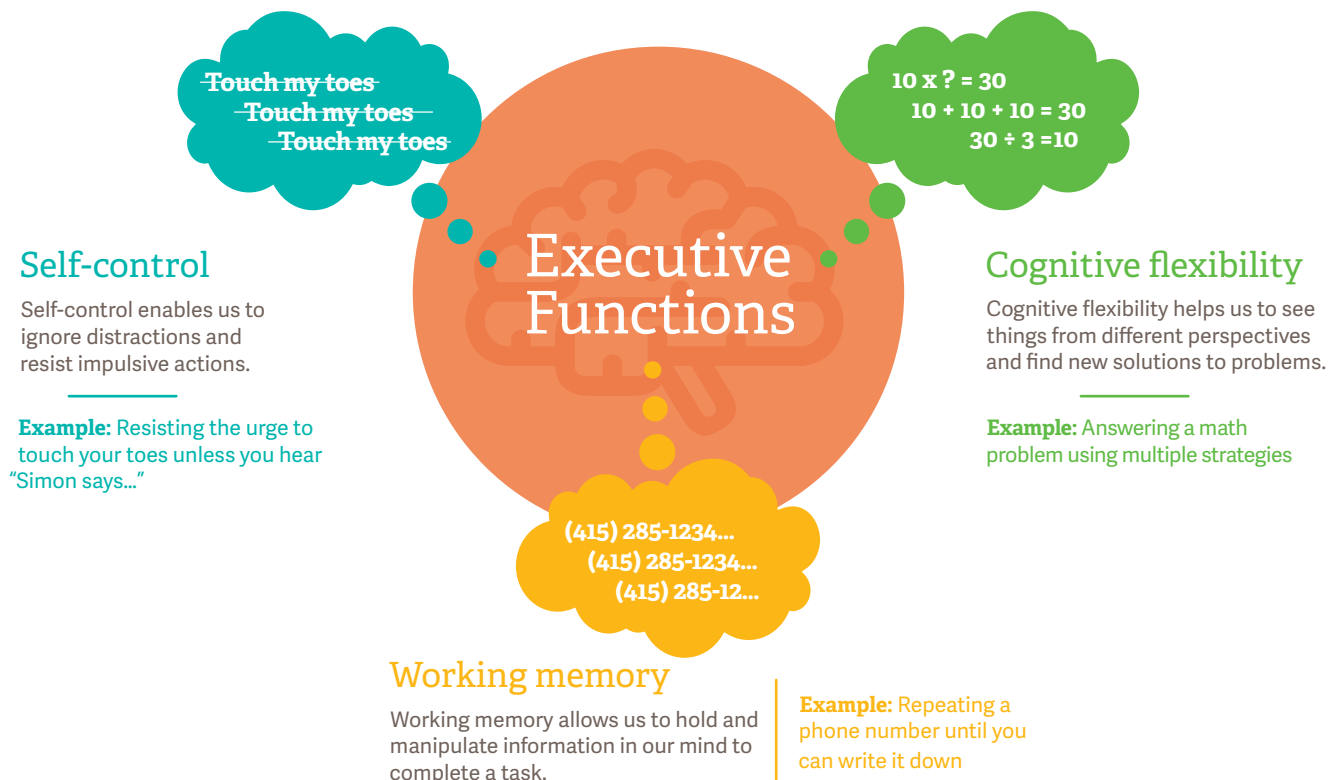
Some research-based tips (adapted from Vendetti, Matlen, Richland, & Bunge, 2015) for using analogies to teach abstract concepts include:

1. Use visuals that show both the new content being learned and the analogy (e.g., showing images of both a solar system and atom to teach about atomic structure) represented side by side.
2. Recognize that children will naturally pay attention to perceptually obvious features (color, orientation, size), and use this bias thoughtfully in visuals. For instance, one might use the same color for the sun in the solar system as the nucleus of the atom to draw attention to the fact that they are analogous.

Figure 5.

Executive functions

Executive functions (EFs) are a set of cognitive skills that serve as the command and control center of our brain. EFs help us to plan, achieve goals, control impulses, and focus attention.



3. Be aware of children's tendency to overgeneralize. If both the sun and the nucleus are colored orange, children might erroneously be led to understand that a nucleus is burning like the sun.

4. Use analogies to highlight both the differences and similarities between ideas, for instance showing three different ways to solve the same math problem.

At the same time, as researchers note (Richland, Morrison, & Holyoak, 2006; Richland & Simms, 2015), there are some important practical limitations of using analogy to support young children to grapple with abstraction. The most significant is that young children are inclined to be distracted by irrelevant information or focus their attention on surface level connections. Educators and parents should probe with questions for understanding and misunderstanding of metaphors used to teach abstract concepts. Also, because children's brains are working hard to process all the information coming in to them, and processing load will inhibit abstract reasoning, adults should make an effort to both simplify their explanations and to start having conceptual conversations with children early. The more frequently children have an opportunity to flex their abstract and analogical reasoning skills and use complex and conceptual vocabulary—as they develop their EF capacity—the less cognitive load it will take for them to process information. While children may seem challenged at first to reason abstractly, only experience and interaction will make this easier for them over time. This is a significant reason why rigorous, cognitively demanding STEM education cannot wait until the end of elementary school.

Practical Tips

- Challenge preschoolers to sort a set of materials in any way they choose as long as they can explain the rules of their sorting. Ask them to try again: how many different ways can they think of to categorize the given materials (e.g., by shape, color, size)? What rules govern their categories?
- Develop children's executive function skills by providing opportunities to make plans, execute them, and reflect on their plans. Record a plan together and refer to it while completing each step. After the plan is finished, ask your child to notice if they accomplished what they set out to do, and where and how they deviated from their plan. Are they satisfied with the final project? What would they change?
- Use analogies and metaphors to explain unfamiliar concepts with ideas that are more familiar. "You know how trains travel around their tracks? Blood flows through the veins in your body in the same kind of way."

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