A MULTIPLE CASE STUDY TO CAPTURE AND SUPPORT THE ENGINEERING DESIGN THINKING OF CHILDREN WITH MILD AUTISM

by

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To my parents, Mariam and Ali, my children, Hana and Hadi, and my partner, Hossein for being my strength in everything I do

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ABSTRACT

Research in pre-college engineering education has been on a sharp rise in the last two decades. However, less research has been conducted to explore and characterize the engineering thinking and engagement of young children, with limited attention to children with special needs. Conversations on broadening participation and diversity in engineering usually center around gender, socio-economic status, race and ethnicity, and to a lesser extent on neurodiversity. Autism is the fastest growing neurodiverse population who have the potential to succeed in engineering. In order to promote the inclusion of children with autism in engineering education, we need to gain a deep understanding of their engineering experiences.

The overarching research question that I intend to answer is *how do children with mild autism engage in engineering design tasks*? Grounding this study in theories of Constructivism and Defectology, I focused on children's engagement in engineering design practices and the ways their parents supported their engagements. To engage children with mild autism in engineering, I have developed an engineering design activity by considering suggestions from these theories and previous literature on elementary-aged children's engagement in engineering design, and by focusing on individuals with mild autism strengths in STEM. This activity provides opportunities for children to interact with their parents while solving engineering design problems. The families are asked to use a construction kit and design their solutions to the problem introduced in the engineering design activity. The engineering design activity consists of a series of five challenges, ranging from well- to ill-structed.

This is an exploratory qualitative case study, using a multiple case approach. These cases include 9-year-old children with autism and their families. Video recordings of the families are the main source of data for this study. Triangulation of data happens through interviewing parents and children, pictures of children's artifacts (i.e. their prototypes), and use of the Empathizing-Systemizing survey to capture background information and autism characteristics. Depending on the data source, I utilized different methods including video analysis, thematic analysis and artifact analysis.

This study expands our understanding of what engineering design can look like when enacted by children with mild autism, particularly as engineering design is considered to be a very iterative process with multiple phases and actions associated with it. The findings of this study show that these children can engage in all engineering design phases in a very iterative process. Similarities and differences between these children's design behaviors and the existing literature were discussed. Additionally, some of the behaviors these children engaged in resemble the practices of experienced designers and engineers. The findings of this study suggest that while children were not socially interacting with their family members when addressing the challenges, their parents played an important role in their design engagement. Parents used different strategies during the activity that supported and facilitated children's engineering design problem-solving. These strategies include soliciting information, providing guidance, assisting both verbally and hands-on, disengagement and being a student of the child.

This study provides aspirations for future research with the aim to promote the inclusion of children with neurodiversity. It calls for conducting similar research in different settings to capture the engineering design engagement of children with mild autism when interacting with teachers, peers, siblings in different environments. Additionally, the findings of this study have implications for educators and curators of engineering learning resources.

1. INTRODUCTION

1.1 Motivation for the Study

As a former certified elementary teacher and a mechanical engineer, I have always been interested in seeing how children learn engineering. I was never surprised that children are able to engage in activities associated with engineering. However, like many others, I used to believe that engineering is only for those we have historically perceived as "skilled, gifted and high ability" — not for others. After learning about how children learn, I came to believe that all children regardless of who they are and how the society have labeled them, have the "ability" to learn and grow in their very own way. Formal and informal educators, however, are required to address children's specific needs, support their strengths and accommodate their challenges.

In my career as an educator in inclusive classrooms, I had the opportunity to work with many children with special needs. Supporting the learning of all children is very important, though requires knowledge and expertise. However, I realized, working with children with Autism Spectrum Disorders (ASD) has been very challenging, as their strengths and challenges are less understood by teachers, parents and their peers. On the other hand, in all the biographies I have read about successful individuals with autism, one factor of success has been "receiving support" by different people in their lives. Thus, aligned with my goal to help all children succeed and grow, I aim to be an advocate for children with autism and find ways for them to be understood and supported in engineering.

1.2 Scope of the Study

This study aims to support the inclusion of neurodiversity in engineering education by promoting **engineering** learning and engagement of **children with mild autism**[1]. I have narrowed down the scope to children with mild autism as they are more likely to attend inclusive classrooms and receive education next to their same-aged peers without autism. According to the Diagnostic and Statistical Manual of Mental Disorders (DSM)-5 (2013), these children need less support than their

[1] Mild autism refers to those who were historically called high functioning autism and those with Asperger's.

other peers on the autism spectrum (Diagnostic and Statistical Manual of Mental Disorders (DSM)-5, 2013) and have higher IQ (i.e. 70 and above) (DSM-IV, 2000). In regard to engineering, I focused on children's experiences during an engineering design task. According to the 2009 report by National Research Council (NRC), engineering design is one of the most important aspects of engineering in K-12 learning settings (NRC, 2009). To be able to support their engineering learning, I looked at ways they engage in engineering design practices to solve engineering design challenges as well as ways their parents support their engineering engagement.

1.2.1 Asset-Based Approach: Rethinking Disability

Aligned with the *Rethinking Disability* framework (Valle & Connor, 2019), I believe that for human learning research, researchers should take asset-based approaches, and focus on individuals' capabilities and strengths while recognizing and accommodating their challenges and weaknesses. When taking an asset-based approach to rethinking disability, Valle and Connor (2019) discourage silence towards and avoiding the subject of disabilities and disorders. In contrast, they encourage raising awareness around disabilities, framing disability as natural human variation and making it a part of everyday life, and not an exception. In light of asset-based approaches, we acknowledge and embrace all differences and focus on strengths. When this awareness is raised and the silence is broken, the education community can engage in improving the inclusion of all in the education system, and collaboratively help with providing appropriate opportunities for all individuals to learn.

Important Note: The use of vocabulary in disability studies is controversial. There is no best way to refer to this population. Different groups with and without disabilities prefer different terminologies, including differently-abled person, person with a disability, person with special needs, disabled person and many others. I believe that every single person is uniquely different, and categories have been created to better make sense of the differences. With this view, I need to acknowledge that the terminologies used in this document do NOT carry the meaning of *less* or *more* and are based on existing literature and what professional communities use to refer to disabilities and specifically autism.

1.3 Neurodiversity, Autism and Engineering

The term neurodiversity refers to a subset of neurological conditions that typically result in an individual being labeled as having disabilities or special needs (Armstrong, 2011). However, the neurodiversity movement calls for seeing the differences of these individuals, identifying their strengths while acknowledging their weaknesses and challenges. These conditions include autism, ADHD, anxiety disorder, dyslexia and many others. Individuals with autism had started this movement requesting society see them differently and not disabled. In 2015, Christensen and his colleagues at the Centers for Disease Control and Prevention (CDC) (Christensen et al., 2016) reported that one in 68 children was on the autism spectrum. However, the 2018 rate according to the Autism and Developmental Disabilities Monitoring Network is one in 59 children is diagnosed with autism (Baio et al., 2018) . Given the increase in the number of children with autism spectrum disorder, this group of learners should have access to preparation to allow them to achieve their full potential in the workforce. This preparation should be directed especially into the fields that they have the potential to be successful, including engineering and many other STEM disciplines (Baron-Cohen, 2009; Wei et al., 2013).

Promoting inclusion of neurodiversity in engineering education has two-folded benefits. Pre-college engineering education benefits neurodiverse individuals. Research has shown that children's interests and perceptions towards their future careers are shaped by the time they reach middle school (Ceci & Williams, 2010). Thus, if effective pre-college engineering education is accessible to neurodiverse children, they are more likely to choose STEM disciplines in higher education and be successful in the workforce (Pilotte & Bairaktarova, 2016). Second, when we have prepared neurodiverse engineers, the engineering community becomes more innovative by incorporating neurodiversity perspectives and benefits from the different ways of thinking and special characteristics that comes with neurodiversity (Gibson et al., 2002). These special characteristics, while vary across neurodiverse conditions, may include being very creative and highly focused on certain tasks. As many standards and accreditation reports such as ABET Accreditation Board for Engineering and Technology (2014) argue that engineering requires many capacities and competencies such as using and navigating technological tools, understanding, framing and viewing problems in a broad sense, generating creative ideas, conducting mathematical modeling and reasoning about physical and virtual quantities. Having an inclusive engineering community that welcomes individuals with different abilities including those with neurodiversity can be an important addition to what engineering needs. Therefore, providing appropriate engineering interventions is very important when exposing children with mild autism.

1.4 Importance of K-12 Engineering Exposure

Having technology and engineering skills and knowledge has become important now more than any time before. Historically, being technology and engineering literate was necessary for some specific vocations. However, we are now witnessing a shift to fluency-based approach to digital literacy (Bilkstein & Krannich, 2013). One main reason is that most of the world we interact with on a daily basis is human-made and heavily based on technology (Miaoulis, 2014). Therefore, children should become engineering and technology literate to perform well in this world. While technological and engineering literacy are related, they are two slightly different literacies. Technological literacy can be defined as the ability to appropriately select and use technology while engineering literacy is the ability to create and improve new and existing technology (Cunningham & Hester, 2007). An effective education should provide opportunities for learners to learn how to interact with this human-made world and to gain engineering and technology competencies. Engineering education can play an important role in helping learners gain these competencies. Over the last two decades, many nations have become aware of the need for engineering and technology skills and knowledge, therefore, K-12 engineering education has gained increasing attention among educators, researchers and stakeholders (Katehi et al., 2009). However, K-12 engineering education has yet to be inclusive enough to accommodate all children with diverse needs (National Academies of Sciences, Engineering, and Medicine, 2020).

1.4.1 Gap in Pre-college Engineering Education: Inclusion of Autism

Children with disabilities, including those with neurodiverse conditions, often underperform in STEM education (AccessSTEM, 2007) and are underrepresented in engineering and other STEM disciplines in higher education and the world of practice (National Science Foundation (NSF), 2017). According to NSF (2017), their underrepresentation can be traced to their participations and achievement in pre-college engineering education related experiences. Israel et al (2013) compiled a list of barriers to children with disabilities' achievement and performance in STEM education that can also be true for engineering in particular. One important barrier Israel and colleagues have mentioned is the use of inappropriate methods for teaching STEM in classrooms. Educators are not always prepared to engage children with special needs in engineering and other STEM activities. They are sometimes unable to recognize their students' needs, and as a result, they cannot address their needs properly (Moon et al., 2012). They are not always aware of strategies and techniques they can use to support and promote their STEM learning, and particularly their engineering learning. As a result, they are unable to develop and implement appropriate STEM instruction. Therefore, children with disabilities are being left out during STEM education experiences and instruction.

While the engineering education community has been calling for the diversification of engineering education practice, less attention has been paid to children with disabilities. For example, one of the main resources for teaching K-12 engineering is the Next Generation Science Standards in which engineering and technology have been embedded into the science standards (NGSS Lead States, 2013). However, the standards are written for typically developing children and the needs of children with disabilities and their special needs have not been considered. Additionally, the recent report by the National Academies Press (2020), *Building Capacity for Teaching Engineering in K-12*, has broadly valued diversity and discussed the underrepresentation of women and ethnic and racial minorities in engineering settings. They discussed the importance of making engineering education more diverse and inclusive; however, no discussion has been made on children with disabilities and/or with neurodiversity.

The same as in practice, pre-college engineering education research has focused limited attention on children with disabilities and special needs. In one review of the literature, Brophy et al., (2008) discussed promising models for teaching engineering to K-12 students. However, among those models, none presented accommodations for children with special needs/disabilities. Similarly, in another recent review of the literature, Hynes and his colleagues evaluated research papers published in peer-reviewed journals since 2000 and the most frequent topics were identified through a word count (Hynes et al., 2017). While "diversity" was one of the most frequent words, words related to disabilities, special needs or neurodiversity were not included.

Previous engineering education researchers have also called for more investigations of autism and engineering (e.g., Pilotte & Bairaktarova, 2016). Engineering activities have been used in autism studies as a medium for improving social interactions in children with autism (e.g. (Albo-Canals et al., 2013; Koenig et al., 2018). These activities included using LEGO bricks, robots, and/or makerspaces. Finally, in a systematic literature review in 2018, my colleagues and I reviewed 42 studies that included STEM interventions for individuals with autism, and the findings showed that no research-based engineering instruction exists for these individuals (Hoda Ehsan et al., 2018). Therefore, promoting engineering learning of children with autism is clearly a gap in pre-college engineering education research and practice that should be addressed.

1.5 Contributions of Engineering Education Research

The gap in the literature that this study aims to address is the engineering learning of children with autism, and how it can be supported. The study aims to address this gap by exploring:

1. the problem-solving approaches children with autism use when engaging in an engineering design activity
2. the parental support and scaffolding they received during this activity

The findings of this study can have potential contributions to both engineering education research and practice. For engineering education research, the findings of this study add to the literature on pre-college engineering design as the findings increase our understanding of how children, particularly those with mild autism, engage in different engineering design practices. Additionally, the findings highlight the importance and impact that parents, as the "more knowledgeable others," play in the engineering learning of children. Finally, this study can serve as a model for other researchers who are interested in increasing understanding of neurodiversity in engineering education. For engineering education practice, this study has implications for formal and informal educators of these children, engineering education curriculum developers, policy makers and other stakeholders who aim to promote the inclusion of neurodiversity and particularly individuals with autism. The findings of this study can help them create and support effective engineering learning opportunities for children with autism.

2. UNDERLYING THEORY AND LITERATURE

The main purpose of this work is to characterize the engineering design practices of children with mild autism. To reach this goal, elucidating the connection between two important aspects of learning is necessary. The two important aspects of learning are *child learning* theory considering autism characteristics and *engineering design*. Hence, this chapter is organized in three main sections. The first section begins by describing my theoretical standpoints which elaborate my philosophy of learning for children, with special attention to engineering learning and children with autism. I begin this chapter by focusing on the theories of learning, because these theories can contribute to the development of children's engineering thinking. Additionally, these underlying theories of learning guide the way I present the engineering design literature.

The second section includes a synthesis of previous literature related to engineering design. The section is organized to discuss *why* engineering design is important for children, *what* engineering design is and *how* engineering design is implemented for children. The aim of this synthesis is to characterize how children engage in engineering design. Finally, by connecting components of these two sections together, I create a conceptual framework that helps frame my study as I investigate ways children with mild autism engage in engineering design. Figure 2.1 provides a map of the main components of the literature review.

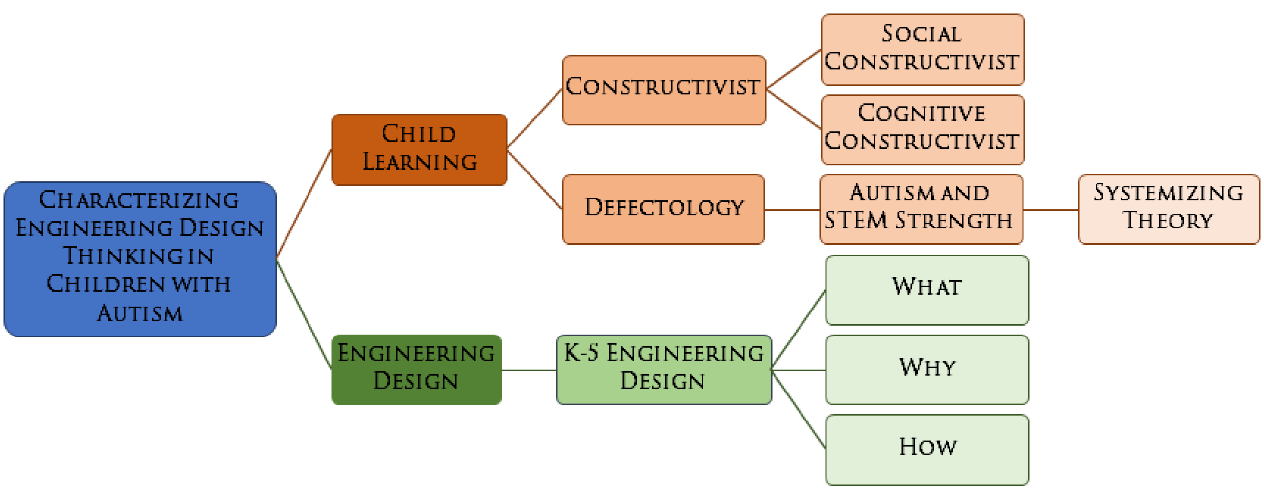

Figure 2.1. Literature Review Map

2.1 Child Learning Theory

In this section I will describe two theories that have shaped this study: Constructivist and Defectology. Both theories are aligned with the neurodiversity movement as they call for taking assets-based approaches when studying neurodiversity. The constructivist theory focuses on how individuals learn and construct knowledge both cognitively and socially. Defectology suggests that individuals' needs should be understood and addressed to elevate the process of knowledge construction.

2.1.1 Constructivist Theory

I start this section by acknowledging that I consider myself a social constructivist. I view learning from this theoretical standpoint and orientation. However, I believe, like many others, social constructivism is aligned with cognitive constructivism (Cobb, 1994). These two theoretical orientations stemmed from the work of different researchers and are fundamentally different. However, their educational implications complement each other in educational settings. In this study, the underlying theoretical standpoint is social constructivism with some considerations of cognitive constructivism. They both come together to form constructivism where learning is "constructed from experience to have a personal meaning for [learners]" (Kalina & Powell, 2009). In this section, I do not aim to compare these two standpoints, but I will discuss what they suggest and how they are relevant to my study.

Cognitive constructivism stems from Jean Piaget's work (1953) where he focuses on a very personal process that individuals construct their own knowledge. He emphasized that individuals construct knowledge and engage in learning at their own pace as they go through the cognitive process of assimilation, accommodation and equilibration. In educational settings, educators should recognize that each individual engages in learning differently and at a different pace. They should provide the appropriate learning opportunities where (1) the instructions are clear for the learners to start the process of constructing knowledge, (2) and time and space are provided for learners to be at their own pace. Educators have to alleviate this learning by understanding where learners have difficulty grasping knowledge.

Social constructivism suggests that learners co-construct knowledge by creating meaning of their social interactions with others and the environment around them, both through construction. The founding father of this theory is Lev Vygotsky (1930s) who believed social interaction is an integral part of learning (e.g. Moll, 1992). Learning does not happen only within an individual and in their mind, neither develops through passive behaviors forced externally (McMahon, 1997). Meaningful learning happens when learners are engaged in social activities (Kim, 2001) as they socially and culturally construct their knowledge (Ernest, 1999). Social constructivist theory defines knowledge as not an abstract construct, but as the information gained from everyday activities and other social interactions. This theory posits that learning is a mental process that develops and functions through the interpretive influence of a sociocultural context (Vygotsky, 1978). In other words, learning arises from the relationship between human thought and the social context.

Another aspect of Vygotsky's theories is the idea of a *zone of proximal development* (ZPD) which distinguishes the learner's actual development from their potential development. Actual performance refers to independent performance and potential development is the performance achieved by assistance. When in this zone, learners can get the most out of a social context. Assistance in a social context comes from a *more knowledgeable other* who can be an adult or a more competent peer or sibling. Assistance enables children to acquire new knowledge and skills that they could not achieve independently. The assistance was later called *scaffolding* by Bruner (1966). When the scaffolding that occurs within a child's ZPD adds up to the child's own independent learning, the child can build on his/her previous knowledge and stretch his/her existing skills and competencies. This assistance can come in different forms, but should be situated culturally and contextually (Kim, 2001).

According to the social constructivist theory, play is an important social context that promotes learning in children. Learning through play supports the development of abstract thought as children independently make meaning of their social interactions and objects that they represent during the play. According to Vygotsky, play positions children in their ZPD, when children interact with more knowledgeable others like their peers or family members. Reciprocity between them cultivates through participation in cooperative play and the sharing of language and actions. Social play increases the cognitive demands on children as they engage in negotiating shared understandings, collaborative planning, solving problems and decision-making in different play cognitive challenges (Mallory & New, 1994; Roskos & Christie, 2001). Through the cognitive challenges presented within social play significant learning occurs in children.

Constructivist, Engineering Education and Special Education.

In various educational settings, approaches and strategies drawn from constructivist theories, both cognitive and social, are widely used (Kalina,& Powell, 2009). For more than three decades, researchers and practitioners in STEM education are discussing the applicability of constructivist approaches in their fields. For example, Cobb (1994) has discussed in depth how constructivist theories are helpful and necessary for math education. Many researchers in the field of science education have highlighted the importance of considering constructivist approaches for science education (e.g. Barak, 2017; Matthews, 2002). Similarly, computer science researchers have been focusing on effectively integrating these approaches in their instruction (e.g. Duit, 2016; Kordaki & Gousiou, 2016). In a comprehensive literature review of pre-college engineering education research, Mendoza Díaz and Cox (2012) stated constructivism was the most common perspective used in the studies they reviewed. Many of these studies used constructivism to shape and conduct their interventions (e.g. Hynes & Dos Santos, 2007).

In 1994, Mallory and New warned that research on learning and teaching of children with disabilities had paid very limited attention to developmental theories and had been more pragmatic than reflective. They stated that researchers were able to improve the lives of these individuals to some degree. They then reported on the growth of sophisticated understandings of constructivist theories to improve childhood education and called for a shift in their conversation towards the necessity of employing constructivist theories for childhood special education research and practice. They advocated for the shift in their conversation using multiple studies that reported on instructional strategies consistent with constructivist theories which were designed for children with disabilities. Later, many researchers developed interventions based on constructivism and conducted studies to investigate the effectiveness of such interventions (e.g. Belland, Glazewski, & Ertmer, 2009; Hanline, 1999; Katz & Girolametto, 2015) and discussed the constructivist perspective for children with disabilities (Bloom et al., 1999; Wolfberg, 2009). Among those, some focused on children with autism (Greenway, 2000; Walker & Berthelsen, 2008; Wolfberg, 2009). For example, Walker and Berthelsen (2008) investigated the nature of play activities and children with autism's engagement in an inclusive setting. They used social constructivist theory as their theoretical background and tied aspects of their research to this theory. Their findings showed that children with autism were able to participate in extensive social and play engagement. Their results also highlighted the need for teachers' support, including scaffolding to increase students' social interactions and play participation. Most of these studies used qualitative approaches and specifically addressed aspects of social constructivist theory in both the activity that was studied and the analysis.

Contributions of Constructivism Theories.

Constructivist theories provide a framework to engage children with autism in engineering activities that lead to cognitive growth in their ability to engage in engineering thinking. Integrating both cognitive and social constructivist theory contributes to our understanding of how children with autism might learn within inclusive groups by acknowledging the role of social activity in learning and the importance of supporting learning through the ZPD. Cognitive constructivist theory helps with framing the context of the study where I focus on children with autism and their engagement in engineering learning as individuals. It highlights the activities that are led by children and gives enough freedom to children to explore and learn on their own pace and desire.

On the other hand, social constructivist theory highlights the socio-cognitive exchanges; the type of support required for cognitive development from humans and the environment around (e.g. activity and setting). The human support should be aligned with the notion of the more knowledgeable others. In K-12 engineering learning settings, human support can come from teachers, facilitators, parents, more competent peers and siblings, who can see the bigger picture of the engineering problems, and guide children to engage in deeper engineering thinking (See section 2.2 for more information on adult support). The supportive environments should be designed with the learning objectives in mind (i.e. demonstrating specific engineering design practices/skills in this study) and considering individuals' special characteristics (autistic characteristics). In the next section, I discuss autism characteristics by taking an asset-based approach through the lens of the theory of defectology.

2.1.2 Theory of Defectology

This study also builds on Vygotsky's theory of defectology in special education (Vygotsky, 1987b). In this theory, Vygotsky suggests taking an asset-based and positive resource-oriented approach to empower any child with special needs. In his view, education should shift from focusing on weaknesses or deviations to giving preference to strengthening children's skills. Selecting tools or pedagogical methods that fully engage children with different abilities is necessary to bring them a feeling of capability and belongingness. In addition, aligned with the social constructivist theory, he emphasizes the role of the more knowledgeable adults who adopt appropriate strategies. More knowledgeable adults' guidance along with the use of tools and pedagogical methods can help the child to internalize and master a skill. Taking an asset-based approach is in line with the neurodiversity movement (Arsmstrong, 2011) as it calls for focusing on capacities and strengths that come with neurodiversity conditions rather than the weaknesses and deficits that historically define them.

To take an asset-based approach for the population targeted in this study (i.e. children on the autism spectrum, 8- to 10-year-olds), understanding their conditions and characteristics is very important. Below, I present a review of the literature on autism and the strengths associated with this condition.

Autism and STEM Strengths.

Autism Spectrum Disorder (ASD) is a neurodevelopmental condition characterized by social and communication challenges and restricted and repetitive interest and behaviors (DSM-5, 2013). Although many researchers have focused on these cognitive challenges, over the last decade, some started the conversation around the developmental and cognitive strengths in ASD (e.g. Baron-Cohen, 2006; Baron-Cohen & Belmonte, 2005; Happé & Frith, 2010). Baron-Cohen and Belmonte (2005) believe that the developmental characteristics that define ASD can lead to cognitive strengths. For example, while paying attention to relevant details may be deemed as deficits in some contexts, such characteristics could be advantageous and necessary, not the only factor though, to achieve excellence in specific areas (Baron-Cohen, 2002; Frith, 1989). Similarly, Happé and Frith (2010) believe an *islet of ability* may exist in children with autism in certain domains. Below, I describe one of the theories that highlight the STEM islet of ability for children with autism. I then discuss the pieces of evidence from the existing literature that supports the theory.

Empathizing-Systemizing Theory.

One theoretical account that supports the existence of *islets of ability* and talent in autism is the Empathizing-Systemizing theory. Over the last two decades, Baron-Cohen and his colleagues contributed to the conversation about systemizing and introduced *Empathizing-Systemizing Theory* (e.g. Baron-Cohen, 2002; 2006; 2009). This theory points out the unique features of ASD which include impaired empathizing and intact or even superior systemizing amongst individuals with ASD (Baron-Cohen, 2002; 2009). Empathizing includes attributes to understand others' emotions and thoughts, predicting their behaviors and appropriately responding to others' mental states (Baron-Cohen, 2002). ASD impairment in empathizing results in difficulties in social development and communication skills.

Systemizing includes attributes that allow predicting and controlling the behavior of a system by underlying rules that govern the system (Baron-Cohen, 2002). Systemizing requires thinking and skills to analyze and/or build any kind of rule-based systems by identifying the input-function-output rules (Baron-Cohen, 2002). Systemizing may result in several ASD characteristics such as narrow interests, paying attention to details, and some abilities such as visual and spatial thinking, system function prediction and identifying the patterns of behaviors observed in a system (Baron-Cohen, 2009). Having intact or superior systemizing abilities enable individuals with ASD to excel in fields that rely heavily on systematic, rule-bound and lawful patterns within procedures, and require attention to for details and variables (Baron-Cohen, 2002).

Science, technology, engineering and math (STEM)-related fields have been identified as examples of fields that require systemizing (Baron-Cohen et al., 2007) for successful performance. People in STEM fields are often involved in analyzing natural, abstract and technical systems, which all require strong systemizing abilities (Baron-Cohen, 2002). As an example, a mechanical engineer may need to construct and assemble a 3D mechanical apparatus from a 2D blueprint that requires systemizing abilities. In addition, scientists and mathematicians score very high on the autism spectrum quotient (Baron-Cohen et al., 2001). Since the quotient measured by this instrument includes elements of systemizing, Baron-Cohen et al (2001) argued that their findings may reflect that math and science fields mostly entail systemizing. Research also shows that both children and adults with ASD score higher than average in the systemizing quotient, a self-report questionnaire measuring interests of understanding different systems (Auyeung et al., 2009; Baron-Cohen et al., 2003).

Evidence of supporting STEM abilities in autism.

Different types of evidence have supported the suggestion, consistent with systemizing theory, that individuals with ASD may have strong STEM abilities. Compiling the pieces of evidence, I have organized them into two categories: (1) anecdotal and self-reports, and (2) empirical results. Below, I discuss each category and highlight the STEM-related strength suggested by each category.

Anecdotal and self-reports.

Anecdotal cases report that individuals with ASD exhibit high STEM skills and strong visuospatial thinking. Anecdotal cases are usually reported by people who have interacted with individuals with ASD. Wing (1976) suggested that individuals with ASD have enhanced visuospatial abilities since anecdotal reports collected in medical clinics showed their high abilities to detect small details in environment changes, restricted interest in reading maps and bus routes. Examples of anecdotal reports include children with ASD discovering very fast methods to solve 3×3×3 Rubik’s Cube problem (Baron-Cohen et al., 2009), and children with ASD being experts at solving jigsaw puzzles (Gillberg & Coleman, 2000; Park, 1982 as cited by McMullen, 2000).

Some people with ASD report having strong spatial and visual abilities. For instance, a math teacher with autism reported on his high visuospatial abilities by bringing an example of his architecture talent he had as a child (McMullen, 2000). Another example is Temple Grandin, a famous scientist with ASD, who has several times described her superior visual thinking which helped her in inventing and designing the squeeze machine which is being used for slaughtering animals (e.g. Grandin, 1995; Grandin & Hale, 2013).

In several documents, individuals with ASD (or people who have interacted with them) narrated stories of their success in STEM fields such as math, computer science, physical and natural sciences and mechanics (Dillon, 1995; González-Garrido et al., 2002; Grandin, 2006; McMullen, 2000; Sullivan, 1992; Thioux et al., 2006; Ward & Alar, 2000). These stories include a math teacher describing his successful math career (McMullen, 2000), a parent writing about his son's savant mental math talents since he was a child (Sullivan, 1992), clinicians reporting on individuals with ASD with brilliant mental calculation (González-Garrido et al., 2002) and computational abilities (Thioux et al., 2006).

Empirical Studies

Many researchers have used different cognitive and educational instruments and interventions that demonstrate STEM-related abilities, strengths and talents in individuals with ASD. In a systematic literature review that my colleague and I conducted, we identified 44 studies that included individuals with autism across all points along the autism spectrum engaging in learning different science, technology and math concepts and content knowledge (Ehsan et al., 2018). Depending on the focus, the studies reported a variety of strengths in STEM skills and knowledge. I share findings of the studies that specifically refer to individuals with autism's STEM learning and engagement as strengths and high abilities.

Reasoning is shown by empirical evidence to be a strong ability in individuals with ASD. Individuals with ASD have shown strengths and superiority in verbal reasoning (Barron-Linnankoski et al., 2015; Reinvall et al., 2013), reasoning about the systems (Baron-Cohen et al., 2003), perceptual reasoning and verbal comprehension skills (Mayes & Calhoun, 2008), fluid reasoning, and the ability to reason and solve novel problems (Hayashi et al., 2008). In addition, children with ASD have shown superiority when reasoning about physical events (Binnie & Williams, 2003). The same study demonstrated that children employ physical causality when reasoning about non-physical events.

Spatial reasoning is often shown to be a very strong ability of individuals with autism. In spatial reasoning tasks, while individuals with autism were slightly better than typically developing children (TD) in the visual mental imagery task, they showed enhanced mental rotation abilities compared to TDs (Soulières et al., 2011). They also showed superior abilities in all visual recognition tasks including tasks using scenes, landmarks and unknown buildings (Blair et al., 2002; Cipolotti et al., 1999). Moreover, comparing to TDs, individuals with ASD exhibited better abilities in the block design task (A. Shah & Frith, 1993; Tymchuk et al., 1977), in tasks involving maps (Caron et al., 2004), and in the embedded figure task when searching for an embedded part in figures (Jolliffe & Baron-Cohen, 1997; Shah & Frith, 1983).

Problem solving skill was reported as another strength of children with ASD. Rutherford and Subiaul (2016) investigated children's (both ASD and TD) explanatory drive when they interacted with humans (social) and when interacted with physical objects (physical). They indicated that children with ASD showed better performance in solving problems in non-social and physical context. In another study, sophisticated analytical strategies, such as decomposition skills, were used by children with autism when solving single-digit addition (Iuculano et al., 2014). Finally, in a recent study my colleague and I conducted, we observed evidence of children engaging in engineering problem-solving practices when building a solution to an engineering design problem (Ehsan & Cardella, 2020).

Computing abilities were observed to be an ability of children with autism. Multiple studies showed that children with autism were able to successfully engage in different coding activities (Knight et al., 2019; J. C. Wright, 2019). These coding activities include web-based, hands-on and hybrid. For example, Wright et al (2019) showed that the middle school students with autism engaged in ozoBlocky, a virtual block-based coding activity, and coded a small robot called Ozobot to perform different actions. In another study, my colleagues and I highlighted elementary-aged children with ASD's computational thinking abilities when coding a child-friendly robot called Cozmo (Ehsan et al, 2020).

STEM content knowledge was also shown to be enhanced or superior in individuals with ASD. Individuals with ASD demonstrated very high performance at physics tests and tests that include engineering problems (Baron-Cohen et al., 2001; Lawson et al., 2004) and showed superiority in phonological learning of science vocabulary (Lucas & Norbury, 2014). Lucas and Norbury (2014) examined science vocabulary enhancing in children with ASD using two phases of learning and testing. In phase learning, children heard the word and seen the corresponding picture at the same time, and then a follow up question was asked about the word. The testing phase included picture naming and picture matching. The results of this intervention indicated that children were superior at learning about the science words they were taught.

In another study, Oswald et al (2016) focused on the characteristics that predict mathematical disability and giftedness of adolescents with ASD. They indicated that only 4% of their participants exhibited giftedness in mathematics. Iuculano et al (2014) characterized and compared the mathematical abilities of children with ASD and their TD peers. They reported higher abilities in numerical operations such as numerical and arithmetic skills in children with ASD.

STEM-based interest is an important indicator of success in STEM (Beier & Rittmayer, 2008) and students who have interest and talent in STEM are more likely to pursue STEM degrees (VanMeter-Adams et al., 2014). Some research suggests that strong interest in STEM topics may lead to proficiency in those topics and individual’s attractions to STEM fields (Wang, 2013). Binnie and Williams (2003) suggest that individuals with ASD manipulate objects in different ways than their TD peers, because they have a profound interest in objects and try to understand how their systems function. Many individuals with ASD are obsessed by a variety of mechanical and electrical objects (Baron-Cohen, 2002) willing to repair home electrical items (Baron-Cohen et al., 2003), and have an obsessional interest to know how those objects work and are superior at it (Baron-Cohen & Wheelwright, 1999). Researchers demonstrated that individuals with ASD have an interest in mathematical patterns (Baron-Cohen et al., 2003), computer tasks and programs, and constructions and building (Guercio, 2009).

Another way to notice that individuals with ASD tend to have high STEM proficiency and interest is to look at the number of individuals with ASD seeking or holding STEM degrees. Wei and colleagues (2013) have noted that individuals with ASD are more likely to be attracted to STEM majors in postsecondary education: 34% of college students with ASD self-reported that they are majoring in STEM (Wei et al., 2013) which is a higher rate than the general population (Chen & Weko, 2009). Another study found evidence that the rate of autism spectrum conditions self-reported by mathematics students was nine times more than that of students in social science, law and medicine fields (Baron-Cohen et al., 2007).

2.1.3 Section Summary

In summary, this section presents the theoretical standpoints that guide this study. I have framed this study using constructivist theories, both cognitive and social. These theories highlight that in order for children to learn, they need to be exposed to a supportive learning environment in which they can construct their own knowledge. Within this supportive learning environment, adults and competent peers facilitate and boost this learning, through developmentally appropriate strategies, and helping children to get to their zone of proximal development. An environment is supportive when it is designed with considerations particularly for individual learners (Mesibov et al., 2005). The theory of defectology highlights that to design these supportive learning environments, we need to take an assets-based approach focusing on individuals' strengths. Conducting a literature review of autism and STEM strengths, I summarized autism capacities that could be considered when designing STEM learning, in particular engineering, environments and interventions.

2.1.4 Changing the Conversation

Typically, the conversation around ASD has focused on deficits and stereotypical inabilities. I recognize autism disorder involves hardship and weaknesses and that underestimating them is not fair to the individuals and probably their caregivers. Knowing about individuals' weaknesses is helpful for designing interventions that target specific weaknesses. However, As Martin Seligman, the former president of American Psychological Association (APA) suggested that we, the community of researchers, have spent too much time and attention on what is wrong with humans and all the negatives, but now we need to shift to the positive side of humanity (Seligman, 2004). Emphasizing the positive and strong dimensions of these individuals is an important way to alleviate the hardship for them (Armstrong, 2011). Identifying the strengths and talents of individuals with autism can help design effective interventions to supporting their growth while building upon strengths and interests. Moreover, if individuals with ASD, especially children, are aware of their strengths and talents which align with their interests, they get to believe in themselves and their capabilities (Benton et al., 2014). Again, focusing on strengths does not mean that weaknesses are ignored or overlooked. It means that interventions should be designed in a way to utilize and boost the capacity of individuals, while also considering and supporting their weaknesses. Hence, changing the conversation around ASD from weaknesses to their strengths is important and necessary.

2.2 Engineering Design Learning of Children

2.2.1 Elementary Engineering Education: Why

Engineering learning is a lifelong process that begins as young children explore the world through tinkering and continues as children become good problem-solvers as they grow up. Children are sometimes called natural engineers (Dorie et al., 2014; Genalo et al., 2000), as they informally and naturally engage in engineering-related activities all the time (Petroski, 2003). They are fascinated with building and taking things apart, and figuring out how things work (Petroski, 2003). They naturally tend to engage in engineering behaviors such as asking questions, explaining cause and effect activities, constructing knowledge, and solving problems (Bairaktarova et al., 2011). However, at the same time, some research has shown a disconnect from these childhood engineering behaviors. Atman and her colleagues (2007) show that as students begin undergraduate engineering studies, they are not exhibiting some of the engineering behaviors noticeable among children, such as problem scoping and rich idea generation (Atman et al., 2007). One possible reason for this disconnect is that children are not encouraged to continue engaging in these behaviors, which highlights the importance of making space to support children in practicing these behaviors.

At the same time, children begin to make preferences about their future careers as they enter middle school as their perceptions and interests have been shaped (Ceci & Williams, 2010). As a result, interest in engineering in adulthood may depend on participation in engineering activities during childhood and knowledge and understanding of engineering from early age. In addition, children’s lack of engineering knowledge and understanding, and their undeveloped engineering skills may result in being less passionate about pursuing engineering degrees and careers, and not seeing themselves as capable of doing engineering. Petroski (2003) suggests that if children's natural engineering activities are described as *engineering*, we can help children make positive associations with engineering and increase interest in pursuing and engaging in such activities in the future. Similarly, Lachapelle and Cunningham (2014) state that elementary grade engineering education plays an important key to opening children's minds to the ubiquity of engineering and to promote attitudes, interest, and habits of mind that help them become agents of change and developers of technology.

Life in the 21st century increasingly depends on engineering and technology. Citizens need to gain an understanding of these fields and be prepared to interact with society. Engineering education can promote advanced skills that help learners to "navigate in the three-dimensional world" (Miaoulis, 2014, p. 27). Engineering education can increase children's (and their adults') technological literacy (Lachapelle & Cunningham, 2007). By providing a meaningful context, engineering can promote children's learning and engagement in science, math and technology, and link that learning to develop problem-solving, communication and collaboration skills (Bagiati & Evangelou, 2016). Additionally, having advanced engineering knowledge and skills results in skills and competencies such as critical thinking and systems thinking (National Academy of Engineering & National Research Council (NAE & NRC), 2002). Those children who have advanced engineering competencies are more likely to become better problem solvers and decisions makers (Morrison, 2006; NRC, 2009; NRC, 2012), and become fulfilled citizens who can function well in the human-made and technology-based world (NRC, 2009; Lachapelle & Cunningham, 2010; Miaoulis, 2014). Thus, providing appropriate engineering experiences is necessary for children to develop engineering skills.

The engineering education community has recognized the lack of and the need for engineering learning experiences for young children (Froyd et al., 2014). Thus, globally we are seeing the shift in development and adaptation of new standards to integrate engineering in elementary grade subjects. In the U.S. this was elevated by the development of the Next Generation Science Standards in which engineering has been added to elementary science standards (NGSS Lead States, 2013). As result, more than anytime before, efforts have been made to promote the inclusion of engineering in to informal and formal learning settings for elementary-aged children. We are witnessing increasing development of engineering-based curricula and programs for use with young children in both school and out-of-school settings. Examples of engineering-based curriculums include, but not limited to, the seminal work of Engineering is Elementary (for in-school), Engineering Adventures (for out-of-school) (Cunningham & Hester, 2007), PictureSTEM (for in-school) (Moore & Tank, 2014), and Novel Engineering (for in-school) (McCormick & Hammer, 2014). Examples of the programs include summer camps such as NSBE-SEEK that was developed to specifically address the underrepresentation of African-Americans students in STEM, LEGO engineering of Tufts' Center for Engineering Educational Outreach (CEEO), University of Colorado Boulder's K-12 Engineering Education Initiatives, and many other summer camps and after school programs. In addition to programs and curriculums, engineering is being included to designed settings like museums and science centers. Many research-based exhibits and facilitated activities have been designed including Computing for the Critters (Purdue INSPIRE Resources, n.d), Tabletop Oztoc (Tissenbaum et al., 2017), Puppy Play Space (Ehsan & Cardella, 2017) and Ingenuity in Action (Wang et al., 2013).

Elementary Engineering Education Research: A Gap.

In the last two decades, many have identified the importance of focusing on pre-college education and have highlighted introducing engineering in the pre-college years (NRC, 2009; National Academies of Sciences, Engineering, & Medicine, 2020). In response to the increasing attention to pre-college engineering education, Froyd et al (2014) stated that many researchers started exploring research questions with the focus on exploring and promoting engineering learning of pre-college students. Consistent with Froyd et al (2014), the two recent comprehensive literature reviews have shown that pre-college engineering education research has been on a sharp rise (Hynes et al., 2017; Mendoza Díaz & Cox, 2012). However, both works showed that research including elementary grades was the focus of a far fewer studies compared to other grades. A review of the literature between 2001-2011 reported that only five studies and four dissertations had a focus of engineering education in elementary grades in the US context (Mendoza Díaz & Cox, 2012). Among 218 peer-reviewed studies that Hynes et al (2017) reviewed, approximately only 30 studies investigated engineering in elementary school ages. Only a few of these studies focused on children or students themselves, and others focused on teacher education. These findings shed light on the gap in K-5 engineering education literature.

Since engineering education research on elementary-aged children is comparatively new, children's engineering abilities are gradually being discovered (Miaoulis, 2014). Numerous calls for introducing engineering to children recognize the problem of defining engineering learning and thinking for early levels. The NAE and NRC report (2009) states that to provide appropriate and high-quality engineering learning experiences, engineering design is the main principle to be considered in the K-12 engineering education (Katehi, et al., 2009). Researchers need to explore what the engagement of engineering design looks like in children, what engineering design behaviors children are capable of engaging in and how these behaviors can be promoted.

2.2.2 Pre-College Engineering Design: What

Engineering consists of domains of knowledge, skills and ways of looking at the world. In the field of engineering, design is a form of an innovative problem-solving process that integrates engineering knowledge, skill and the designer's vision for what can be achieved (Atman et al., 2014). Engineering design process helps learners solve open-ended and ill-defined problems by practicing different skills and multiple forms of higher-order thinking, such as: analytical thinking and critical thinking, understanding of a problem or a system as whole or details, planning and building, and implicit, explicit and procedural knowledge, and iterative thinking (Brophy et al., 2008; Jonassen, 2011; Katehi et al., 2009; Mawson, 2003).

Engineering design is key to effective pre-college engineering education (Brophy et al., 2008; NRC, 2009). Three general principles for K-12 engineering education were identified by the committee who developed the report of *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* (NRC, 2009). In all three principals, engineering design plays an important and crucial role. As the first principle, the committee discusses that K-12 engineering education should emphasize engineering design. In the other two principals, engineering design was discussed as a meaningful context to (1) to incorporate appropriate science, technology and math skills and knowledge in K-12 engineering education, and (2) to develop and promote engineering habits of mind which are the necessary skills for citizens in the 21st century. This report has defined engineering design thinking as the main engineering approach to solve and identify problems, and has associated four attributes with K-12 engineering design. The four attributes include design being (1) a highly iterative process, (2) open to the idea that one problem can have multiple correct answers, (3) a meaningful context to teach and learn science, technology and math skills and concepts, and (4) stimulus to systems thinking, modeling and analysis. These four attributes make engineering design a useful pedagogical approach in K-12 education which was previously suggested and supported by others (e.g. International Technology Education Association, 2000).

As mentioned above, engineering design is integrated into K-12 education as an epistemological and/or pedagogical approach for teaching and learning different skills and knowledge (Purzer & Quintana-Cifuentes, 2019) that provides an appropriate and meaningful context. The Engineering in K-12 Education report (NRC, 2009) makes recommendations for conducting research to determine what works for diverse learners and why. They suggest that before creating engineering curricula (and any learning opportunities) for K-12 aged children, research should explore ways diverse children develop engineering design ideas and practices and determine the conditions necessary to support the development of these skills.

K-5 Engineering Design.

Multiple models for engineering design process have been created and used for K-5 learning resources and curricula (Cunningham & Lachapelle, 2010; Moore & Tank, 2014). Researchers also used different engineering design frameworks in their studies (e.g. Dorie et al., 2014; Hynes et al., 2011; Tank et al., 2018). Previous research has compared and synthesized many K-12 engineering design processes as well as models used for higher education and professional, and made different frameworks and representations (e.g. Crismond & Adams, 2012; Grubbs et al., 2018; Guerra et al., 2012; Moore et al., 2014). While these models capture many similar engineering design practices, they use inconsistent language for design practices and stages. On the other hand, most of the models are prescriptive and offer guidelines on what practices should be taught (i.e., learning goals) and what teaching strategies and pedagogy should be used (Bruner, 1966). However, Dorie et al (2014) provides a descriptive model (i.e. describes design based on empirical studies) which was developed through a synthesis of the empirical and practitioners' models of designers such as Atman et al (2007), and by observing children engaging in engineering design practices.

The descriptive models of engineering design that exist provide an empirical foundation for this exploratory this study. Thus, for this study, I organize the review of engineering design literature using three engineering design phases: (1) Problem Scoping, (2) Solution Development and (3) Optimization (Figure 2.2). These three phases are based on a modified version of Atman et al.'s (2007)'s model. As mentioned before, Atman et al (2007)'s model informed Dorie et al (2014)'s descriptive model of design. The two first phases, Problem Scoping and Solution Development, are very similar to Atman et al.'s (2007) two stages, with an exception that Solution Development in this study may include building a prototype. The last phase, Optimization, focuses on design evaluation and revision activities, similar to Dorie et al (2014). Below, I explain these phases using findings from empirical studies and reviews of literature focused on elementary-aged children, but also including designers and learners of other ages.

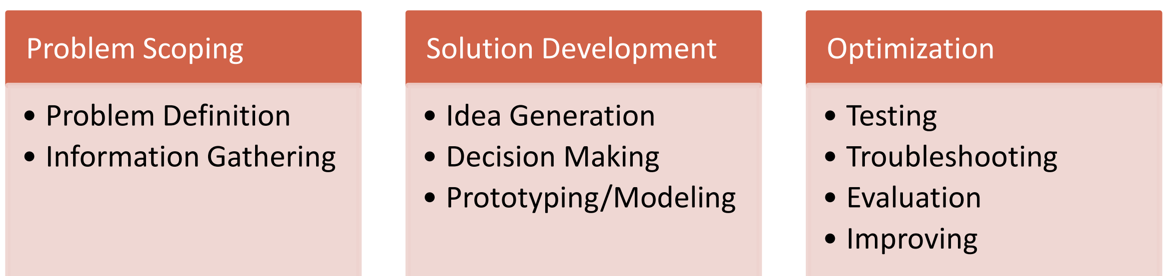

Figure 2.2. Engineering Design Phases

Phase 1: Problem Scoping.

Many design researchers refer to this phase as "Problem Scoping", including Dorie et al (2014) who define this phase as understanding the boundaries of a problem by identifying constraints, identifying and understanding the goal(s), and considering the context . This is an important phase in design as a simple comprehension of the problem is not enough for doing effective design (Crismond & Adams, 2012). This phase may begin by reading and rephrasing the design statement (Dorie et al., 2014; Crismond & Adams, 2012). It also includes identifying (Atman et al. 2007), defining (Atman et al., 2007; Halfin, 1974; Mentzer, 2014), framing (Schön, 1988), decomposing and breaking down the problem into sub-problems (Koehler & Mishra, 2005; Lemons et al., 2010), identifying unstated aspects of the problem and redefining the problem (Hynes et al., 2011; Wilson et al., 2013). Additionally, scoping the problem requires identifying, balancing and prioritizing different aspects of the problem and creating a coherent sense of the problem (Watkins et al., 2014). These aspects of the problems can be identified by focusing on constraints and criteria and/or by gathering information about the problem.

Understanding the problem should involve identifying, reflecting and considering the criteria and constraints (Dorie et al., 2014; Watkins et al., 2014; Atman et al., 2007; Hynes et al., 2011). Criteria include the requirements, standards and characteristics fused too design a successful solution. Constraints are the limitations to be considered when designing such as availability of the materials, cost and time. These criteria and constraints are sometimes given in the problem statement, also called design brief (Crismond & Adams, 2012), and may also be added by children themselves (Dorie et al., 2014). Identifying different criteria and constraints, considering different perspectives influencing the problem, reviewing and elaborating on users' needs, and considering interactions among them and other aspects of the problem leads to framing and defining the problem (Adams & Atman, 2000; Watkins et al., 2014; Welch, 1996).

Understanding the problem should involve inquiry activities to gather information about the space of the problem (Atman et al., 2007; Dorst & Cross, 2001; NGSS Lead State, 2013; Mentzer, 2014). Collecting and processing domain-specific knowledge and information related to the problem is an important aspect of a successful design process (Crismond & Adams, 2012; Atman et al., 2007; Jain & Sobek, 2006). Instead of rushing to solve the problem, designers should engage in gathering information about different components, needs and specifications of the problem (Hynes et al., 2011). To understand the boundaries of the problem, designers should ask questions and make an observation (NGSS Lead States, 2013), explore and experiment with available materials (Bursic & Atman, 1997; Dorie et al., 2014) and material costs (Bursic & Atman, 1997), and learn about different concepts and subjects (Crismond & Adams, 2012). Gathering information can help reframe the problem, help the designer identify criteria and constraints, enrich the representation of the problem in the designers' mind, and uncover the important pieces of the problem (Crismond & Adams, 2012).

K-5 Problem Scoping Research.

Defining and delimiting engineering problems is often called Problem Scoping in research with any age range (e.g. Atman et al., 2007; Dorie et al., 2014; English & King, 2017).Given the importance of Problem Scoping, some studies have focused specifically on elementary-aged children's engagement in this phase (e.g. see below as results are reviewed). However, there is still much that is not yet understood about how children engage in Problem Scoping, and further investigation is needed (stated by Dorie et al., 2014 & English & King, 2017). These studies provided evidence that children are capable of engaging in Problem Scoping. Research has shown that children engage in Problem Scoping by identifying/defining/naming the problem (Kelley et al., 2015; Sung & Kelley, 2017; Watkins et al., 2014), restating and understanding the goals (Dorie et al., 2014; Kim & Roth, 2016), identifying constraints (Dorie et al., 2014; Kelley et al., 2015; Sung & Kelley, 2017) and familiarizing themselves with available materials (Dorie et al., 2014; Kim & Roth, 2016). In their study, Dorie and her colleagues (2014) investigated the design behaviors of 4-11-year old children, evaluated children's conversations and interactions and noticed children's ability to add meaningful context to a problem. Similarly, English and King (2017) observed that 4th-grade children frequently added familiar contexts to their design which helped the children clarify their design and boundaries of the given problem. Watkins et al (2014) and Haluschak et al., (2018) found that elementary-aged children can participate in three meaningful Problem Scoping phases: naming, setting the context and reflecting. Watkins et al (2014) suggested that children can demonstrate greater abilities than "beginning designers" (Crismond & Adams, 2012, p.743). Finally, the findings of a preliminary study related to this project showed that children with mild autism can also engage in Problem Scoping during the open-ended activity, but parental support was also necessary (Ehsan & Cardella, 2020).

Phase 2: Solution Development.

While developing possible solutions has been discussed in NGSS as it is one phase, previous research has associated many practices/actions to this phase. This phase is an open-ended and creative process (NGSS Lead State, 2013) which includes idea generation, idea representation, modeling, reflective decision-making and evaluation (Atman et al., 2007; Crismond & Adams, 2012). A research-based framework for quality in K-12 engineering education created by Moore et al (2014) called this phase Plan and Implement where students develop a plan for designing a solution by brainstorming, and developing and evaluating multiple solutions possibilities. Through all these practices, designers engage in generating alternative solutions to the problem (Atman et al., 2007).

Idea generation is defined by Atman et al (2007) as thinking up potential solutions or parts of the solutions. Dorie et al (2014) associated behaviors such as imagining, brainstorming and planning with idea generation and this way of conceptualizing idea generation was later adapted in multiple studies, including ones conducted by English and King (2017), Svarovsky et al (2018) and Ehsan et al (2020). Similarly, Welch (1996) defined idea generation as discussing an entirely new solution. Designers engage in generating ideas by considering the specifications and information about the problem that they have gathered in the previous phase (Hynes et al., 2011; Mullins et al., 1999; Radcliffe & Lee, 1989). Using divergent thinking and brainstorming (Crismond & Adams, 2012), Crismond and Adams suggest that designers should generate multiple ideas, one idea after another (Crismond, 1997), and then discuss the strategies to carry out these ideas and let the ideas go if recognized impossible or not the best solution (Crismond, 1997). However, research shows that not all the designers list ideas one after another. The co-evolution of problem and solution spaces theory (Dorst and Cross, 2001) suggest that designers would consider one solution, re-explore the problem, reconsider their solution or consider a new solution. A recent empirical study focusing on designers' idea generation observed that designers explored one solution space rather than exploring one idea after another (Shroyer et al. 2018). Collaboration and communication are called an integral aspect of idea generation (English & King, 2017; Hudson et al., 2015). Collaboration and communications can lead to gaining a better understanding of solution processes (English & King, 2017; NGSS lead States, 2013) by explaining brainstormed ideas and justifying and defending why one idea can be the solution.

Modeling/Prototyping includes initial solution development. Literature refers to this design activity as idea representation (Crismond and Adams, 2012), modeling (Atman et al., 2007) and prototyping (Kelley & Littman, 2006; Deininger, Daly, Sienko & Lee, 2017). Halfin (1973) identified modeling as one of the cognitive processes involved in industrial education and defined it as, "The process of producing or reducing an act, or condition to a generalized construct which may be presented graphically in the form of a sketch, diagram, or equation; presented physically in the form of a scale model or prototype, or described in the form of a written generalization (cited by Grubbs et al., 2018, p.908)". Similarly, Crismond and Adams (2012) stated that idea representation can involve detailed drawings and sketching, building a physical prototype, easy-to-assemble structural elements, or computer simulations. Some researchers also talked about using gestures as a way of representing and/or generating ideas (Hegedus & Moreno-Armella, 2009 as cited by English & King, 2017).

According to NGSS, this phase of engineering design is very important as the ability to build and use physical, graphical and mathematical models is an essential part of engineering. Models allow engineers and designers of all ages to visualize aspects of the solution and better understand the elements of the problem, and these representations are also helpful tools for communicating solutions to others. NGSS emphasizes that children in third to fifth grade can create models of their solutions in forms of sketches, drawings and physical models, and can later test and modify them. Modeling can turn an idea into a physical or virtual form; this design action may include creating a three-dimensional (3D) or a two-dimensional (2D) visual models using design software (e.g. Hamon et al., 2014), hand-drawn sketches or building a physical artifact/product (Ullman et al., 1990).

Similarly, prototypes are essential tools for solving a problem and creating a solution as part of a design process (Deininger et al., 2017). As researchers have described engineering design, prototyping is sometimes embedded in modeling (Crismond & Adams, 2012; Hamon et al., 2014; Hynes et al., 2011), but in other cases researchers have considered prototyping as a distinct action in the design process (e.g. Welch, 1996; Carroll, 2014). Through prototyping, designers can uncover unforeseen problems and challenges in their solutions (Brown & Wyatt, 2010), especially when prototyping involves constructing and refining physical and tangible artifacts (Yang, 2005). Therefore, prototyping is a means of communicating aspects of the solution to others (Kolodner & Wills, 1996; NGSS Lead States, 2013).

Designers engage in decision-making in almost all of the design phases (ITEA, 2000; Wendell et al., 2017), and particularly as they are developing their solutions. This activity usually involves weighing options and balancing benefits and trade-offs of solutions and plans (Crismond & Adams, 2012). Decisions may be about choosing an idea as the solution, deciding on the workability of the solution based on selecting the best material, selecting from among manufacturing and building methods, or in critical times choosing among conflicting specifications of the problem and address the priorities (Atman et al., 2007; Crismond & Adams, 2012). These decisions should be made and supported by the evidence and information designers have discovered, collected and processed in the previous phase (Dym et al., 2005) and problem definition criteria (Atman et al., 2007).

The framework for quality K-12 engineering education (Moore et al., 2014) included decision-making as a process in which they evaluate the pros and cons of multiple competing solutions/ideas and judge the importance of different problem specifications. Hynes et al (2011) and Atman et al (2007) have also discussed selecting the best possible solution to the problem (or parts of the problem) as a decision-making process. Hynes et al., (2011) suggest that at the elementary level, this activity is teacher-centered where the best solution is selected by the teacher. Similarly, NGSS included decision-making activity in middle and high school level engineering core ideas leaving it out in elementary levels. While NGSS leave this activity out for elementary engineering education, some research has shown that elementary school children are in fact capable of engaging in decision making independently or by the help of adults (e.g. Wendell et al., 2017; Francis et al., 2017). The phase of design is likely to end with the creation of a prototype, model, or other product (Moore et al., 2014).

K-5 Solution Development Research.

Solution Development is a broad phase in the design process which includes design actions such as generating ideas, modeling and prototyping and decision making. Many studies demonstrated K-5 aged children's engagement in the actions related to Solution Development. Dorie et al (2014) provided evidence of children (age of 4 to 11) engaged in behaviors and actions to develop solutions. They had originally separated out brainstorming, planning and decision-making, and observed evidence of children engaging in them. However, they were not always able to draw clear boundaries between these actions when enacted by the participants. Kelley et al (2015) also observed evidence of 5th-6th grades students engaging in brainstorming and idea formulation. Their findings showed that children tend to emphasize brainstorming with spending over half of their time generating solutions. Similarly, Hill & Anning (2001), Milne (2013) and Ehsan et al (2020) found that elementary-aged children engaged in formulating ideas when solving engineering design problems. These studies also noticed that elementary-aged children were able to participate in planning (Dorie et al., 2014; Milne, 2013). Dorie and colleagues (2014) observed that children as young as preschool-aged engaged in planning, though it was in an undeveloped form compared to older children. In line with them, prior research showed that young children (ages of 5 to 7) tend not to naturally engage in planning when doing design activities (Johnsey, 1995).

Research findings on children's abilities to engage in sketching and modeling during engineering design are not consistent. Some researchers questioned if children should be engaged in sketching and drawing, since findings of some studies (e.g. Welch and Lim, 2000) showed that older students (seventh grade to be exact) spent very little time drawing and they quickly moved to build 3D models. Similarly, MacDonald and Gustafson (2004) suggested that children should not be expected to develop designs until their drawing skills are more developed. On the other hand, Fleer (2000) showed that children were able to create designs using their sketches and drawings. Portsmore et al (2012) argued that sketching is one of the key components of children's design planning. Findings of a recent study (Lottero-Perdue and Tomayko (2019) suggested that while some kindergartners' plans strongly resemble their initial designs, most plans only loosely resemble their designs. English and King (2017) noted that the majority of fourth grade students who participated in their study demonstrated the ability to make their final design using their annotated sketches. They believe initial sketches can help children to generate new ideas, learn and apply STEM understanding to their designs and finally transform their sketches into 3D models.

While decision-making is a core part of an engineering design process (as previously mentioned), Wendell et al. (2015) stated that it has not been necessarily considered as an underlying core intellectual activity of engineering design experiences for children. However, studies have shown that children are capable of engaging in behaviors associated with decision making. Dorie et al (2014) and Francis et al (2017) observed children's engagement in decision-making processes using trial and error when designing a solution. Wendell and colleagues (2017) investigated second and third graders' reflective decision-making during the initial design and redesign phases of an engineering design curriculum. In their study, their findings provided evidence that student teams engaged in different elements of reflective decision-making action. These elements included articulating multiple solutions, evaluating the pros and cons and intentionally selecting solutions. They concluded that elementary students can reflectively make decisions during engineering.

Phase 3: Design Optimization.

While engineering problems can have multiple possible solutions, the goal of engineering is to find the "best" solution. To determine the best answer, engineering designers should engage in "value judgments" (NGSS Lead States, 2013, p.209). While much of the judgment happens before the solution is prototyped, when the prototype is built (or during) value judgment involves fair testing (Crismond & Adams, 2012). Experienced designers conduct testing to generate insights quickly (Norman, 1996), and testing happens often. In Welch's design model (1996) testing is a part of the evaluation and comes with multiple definitions such as testing one element of or an entire prototype while designing and evaluating considering design debrief and criteria. Determining appropriate testing methods may require inquiry (Crismond & Adams, 2012) and reengagement in gathering information (Hynes et al., 2011). During fair testing, designers change one variable at a time from trial to trial, while other variables and parts of the design are kept the same (NGSS Lead States, 2013). Through testing, student designers and engineers come to recognize that the finished prototype is not necessarily the final product (Hynes, et al., 2011).

Testing often refers to the activity of running the experiment, but the process of diagnosing flaws is often not explicitly included in models of the engineering design process. This action is called design-based troubleshooting in Crismond and Adams' matrix (2012) and is described as diagnosing the problematic parts of the design and suggesting a remedy. Halfin's model for the technological problem-solving process has embedded this action in testing, defining it as "the process of determining the workability of a model, components, system, product... to obtain information for clarifying or modifying design specifications (cited by Grubbs et al., 2018, p.909)." In other words, troubleshooting leads to optimizing the solution. Designed-based troubleshooting may happen during conceptual design (when the physical artifact does not exist) where designers run mental simulations of the design works and predict the sources of flaws in the performance (Adams et al., 2003). However, design-based troubleshooting also happens during or after testing, when designers actively look for patterns of behaviors to discover the flaw and the problematic area(s) (Crismond & Adams, 2012). Crismond, (2008) has identified four steps to systematically conduct designed-based troubleshooting including observing, diagnosing, explaining and suggesting a remedy. During observing, designers observe the performance of their design. They then diagnose the problematic area, explain the causes and finally suggest remedy to fix the problematic area.

Once ta problematic area is identified and the appropriate remedy is considered, designers engage in improving the solution. Designers may also engage in improving when theu identify ways an existing solution could be better. Since design is an iterative process (Crismond & Adams, 2012), improving the design may require re-engaging in all aspects of design multiple times (Moore et al., 2014). Experienced designers go back and forth between the problem framing and solution development (Adams et al., 2003) where the understanding of the problem co-evolves as the solution is being developed (Dorst & Cross, 2001). Redesigning the solution may also be required if the solution failed to work or satisfy the design criteria (Braha & Maimon, 1997).

Reflection is often an underlying component of optimizing a solution (Wendell et al., 2017). Reflection-in-Action (Schön, 1988) happens during the process of engineering design and is important for developing a successful Solution Development (Adams & Atman, 2000). Wendell et al (2017) have also noted that reflection is needed in all aspects of design, including evaluation, troubleshooting and redesigning. Engineers and designers engage in reflection and metacognition by standing out of themselves and observing and evaluating their own designs (Crismond & Adams, 2012). During troubleshooting and performance evaluation, engineers engage in diagnostic actions where they revisit their assumptions (Perkins, 1995) when their design fails to perform as expected. Reflective decision-making happens when designers and engineers attempt to improve their prototypes. They purposefully and gradually conduct changes to a solution and simultaneously to their understanding of the problem (Adams et al., 2003) and this requires decision-making about what component needs to be changed and when. When redesigning, designers reflect on the workability of the plan and what they learned from previous design experience (Crismond & Adams, 2012).

K-5 Design Optimization Research.

Optimizing the Solution Development has been discussed as design evaluation in pre-college research (e.g. Dorie et al., 2014, Ehsan et al., 2018). My colleagues and I (Ehsan et al., 2018) examined 7-11-year old girls' troubleshooting abilities as they interacted with an engineering design exhibit in a museum. We observed that the girls engaged in all actions of troubleshooting suggested by Crismond (2008) in a non-linear and iterative order. Similarly, Dorie et al., 2014 observed 4-to-7-year old children evaluating their design and considered revision and Optimization for their design constantly. Francis and his colleagues (2017) observed children engaging in test-assess/evaluate-correct-retest. In another recent paper, my colleagues and Iexamined kindergarten to second grade children's engineering design actions (as well as their computational thinking) as the created a puppy playground (Ehsan, et al., 2020). We observed evidence of children's engagement in testing their playground, while at the same time they demonstrated troubleshooting by identifying and fixing the problematic area. In an iterative, non-linear order, we observed evidence of children's engagement in testing, troubleshooting and improving their design.

Design evaluation has also resulted in re-defining/reformulation of the problem. Children in the Kelley et al (2014) study went back and forth between identifying the problem and analyzing the solution. Similarly, in a study that my colleague and I conducted in an informal setting (Ehsan & Cardella, 2020), in which first grade students engaged in solving an open-ended design problem, we noticed that children's understanding of the problem evolved as their solutions were generated. Similar findings have also been observed amongst experienced engineers where the solution and the problem co-evolves as the design proceeds (Dorst & Cross, 2001).

Engineering design is considered an inherently iterative process (Dorst & Cross, 2001). NGSS also notes that even though these practices are introduced as three phases, the live process of engineering design may not necessarily happen in that order. Children's engagement in these phases may be iterative which children go back and forth between phases until their design is complete. Empirical research also shows that children engage in engineering design in an iterative process. For example, McCormick and Hammer (2016) presented detailed evidence of two fourth grade students who iteratively navigated their design engagement. The researchers noted that children's design engagement included "actions of inferring design criteria and constraints, making informed engaging in assumptions and estimates, co-constructing scaled representations, and defining evaluation criteria served a purpose in helping them achieve this objective (p.52-52)." Another example is the fifth graders who participated in Roth's (1995) study where they iteratively shaped and reformed their goals as they constructed and reconstructed their solutions, and resolved the problems within their solutions.

2.2.3 Elementary Engineering Design: How

Engineering design can be integrated into different activities and a variety of experiences, along the continuum of informal to formal, with and/or without the support of adults. In this section, I first review different types of engineering design experiences. I then present one framework for developing engineering design experiences for children. Finally, I discuss the roles of parents in children's engineering design learning.

Engineering Design Experiences.

In an unpublished systematized literature review of studies focusing on elementary-aged children (2000-2018), the studies provided four types of experiences to engage children in engineering design (Ehsan, 2018). These experiences include engineering and integrated STEM curricula, Robotic programs, open-ended engineering design challenges, and STEAM activities. These experiences happened across formal and informal learning settings. Below I review different research-based engineering design experiences.

Engineering and Integrated STEM Curricula.

As mentioned earlier in this chapter, over the past 20 years, many research-based engineering curricula have been developed. Engineering design is at the heart of most of these curricula which resulted in extensive and important contributions to our understanding of engineering design learning and thinking of young children. Some of these curricula had reached many students across the US and beyond including Engineering is Elementary, Novel Engineering and PictureSTEM. These curricula integrate STEM with literacy and are implemented over the course of multiple days or weeks and have been used in many research studies to examine the engineering learning of children. For example, Tank et al (2018) implemented PictureSTEM which is a 5-day STEM+Literacy integrated curriculum in K-2 classrooms. McCormick and Hammer (2016) implemented Novel Engineering, a multi-day STEM+Literacy curriculum, in a fourth-grade classroom. Novel Engineering is designed to support engineering thinking of children in elementary grades and middle school grades. Finally, Cunningham and Kelly (2017) discussed Engineering is Elementary and how this curriculum can frame engineering practices for children. In numerous studies, children engaged in and learned engineering design through different multi-session STEM curricula and activities in school (e.g. Kelley et al., 2015; Kim & Roth, 2016; Pantoya & Aguirre-Munoz, 2017; Sung & Kelley, 2017; review Hynes et al., 2017 to see more) and out of school (e.g. Magloire & Aly, 2013). Kim and Roth (2016) implemented their STEM integrated curriculum in 4 weeks with second and third grade children. The intervention used by Pantoya and Aguirre-Munoz (2017) was a 5-day intervention beginning with three days of engineering and technology introduction and two days of hands-on and inquiry engineering design. Kelley and Sung (2017) designed two engineering design tasks embedded in math and science that were implemented in six 45-minute sessions. An out-of-school integrated STEM + art curriculum was implemented by Magloire and Aly (2013) to teach electronic concepts to children.

Robotics Programs.

Elementary-aged children can also engage in out-of-school robotics programs to learn engineering (and other subjects). For example, McDonald and Howell, (2012) implemented a six-week robotics project to introduce engineering, literacy and technology to elementary students. In many studies, children engaged in programming and building a robot (e.g. Chang et al., 2017; Chou & Su, 2017; Francis et al., 2017). They learned about different coding software such as Scratch (Chou & Su, 2017) and LEGO Mindstorms EV3 (Francis et al., 2017) to import required actions into their robot they built.

Engineering Design Challenges.

Children can learn about engineering and practice engineering design through activities that do not have a heavy emphasis on science, math and other subjects both in school and out –of school. Children engaged in engineering design as interacted with a pneumatic ball run exhibit in a museum setting (Dorie et al., 2014). Children also designed solutions to engineering tasks using big foam blocks during a pre-school playdate (Cardella et al., 2013; Dorie et al., 2013, 2014) and during a one-session trip to a science center as they designed a puppy playground with their parents (Ehsan & Cardella, 2017). In a study by Tõugu et al (2017), children and their families tried a played-based engineering design activity and solved an engineering design problem by building a model of skyscraper in a museum setting.

STEAM Activities.

Children can engage in engineering while making art (e.g. Bolger et al., 2009; Hill & Anning, 2001a; Milne, 2013; Taylor & Hutton, 2013). Children made engineering pop-up papers (Taylor & Hutton, 2013), masks with paper-mache and an electronic control panel (Hill & Anning, 2001), kinetic toys that include components of push and pull mechanism (Bolger et al., 2009) and photo frames (Milne, 2013). Milne (2013) asked five-year-old children to design a photo frame. Children were asked to draw their design and then create their 3D frame.

Developing Engineering Design Interventions

Among all these studies, the Engineering is Elementary team clearly emphasized to be very inclusive. Moreover, their curricula are age differentiated and are all developed considering aspects of constructivism, the theoretical standpoint framing this study. Therefore, here I review their design trajectory, and present the components they have considered while developing their activities.

Elementary is Engineering, developed by the Museum of Science, Boston, is a seminal curriculum research and development project that aims to foster engineering literacy in all elementary-aged children. As part of their curriculum development, the team considered a set of eight research-based parameters, aligned with social constructivist theory (Lachapelle & Cunningham, 2014) to design inclusive engineering learning opportunities (Cunningham & Lachapelle, 2014). These parameters include situating the problem in a real-world and narrative context, specifying goals, constraints and requirements of the problem, providing opportunities for children to explore and manipulate the materials through concrete activities, applying science and math, providing opportunities for children to collect and analyze data for planning and redesigning, support children's collaboration and development of agency, and finally engaging children in the process of engineering design. They suggest that these parameters look differently for different age groups. In Table 2.1, I have presented the parameters adapted from EiE's Engineering learning trajectories for children ages 7-10 that are applicable to this dissertation study, where the design of the study includes families where children with autism may collaborate with siblings or parents. Please visit the EiE website[2] to see the entire trajectory.

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[2] https://www.eie.org/engineering-elementary/trajectories-preschool%E2%80%93middle-school-engineering-activities-0

Table 2.1 EiE Engineering Learning Trajectory (adopted from the EiE website)

Age Level	Narrative Context	Goals, Constraints, and Requirements	Engineering Design Processes (EDP) and Practices	Application of Science and Mathematics	Analysis of Data for Planning and Redesign	Collaboration
Ages 7-8	• The context can be presented through characters in a longer picture book. The teacher reads aloud and supports comprehension through questioning. The topic is familiar to children indirectly through texts and media. • The teacher reads fiction and non-fiction books, provides video clips and exemplars, and supervises other supplementary experiences to expand children's knowledge base.	• The technology may be new to children. • Children design a technology or model with one or two functions that are readily understood with instruction. • Up to four criteria for success require trade-offs. • Balanced trade-offs ensure that many valid solutions are possible.	• The EDP has 4 or 5 steps. • Children engage in Problem Scoping, brainstorming, drawing up plans, creating and testing prototypes, evaluating to make improvements, and communicating designs. • Teachers model for the class and ask open-ended, generative questions to encourage children to actively engage. • Materials scaffold all processes through simple prompts. • Children communicate ideas, designs, and conclusions with drawings, basic writing, and class discussion.	• The most successful Solution Developments will take scientific considerations into account from age appropriate science content. • Children use standard measures, calculate scores, and collect and record data.	Children test materials and methods of construction for specific qualities. • With teacher support, children construct graphs and charts and discuss and compare results across the class to draw lessons about "fair tests" and planning a Solution Development . • Children judge the success of a Solution Development using a specified testing procedure to make qualitative judgments and quantitative measures. • Children analyze and describe which parts of their technology failed during testing and offer suggestions for modifications they will make in redesign.	Children collaborate in pairs or groups of 3 on a shared Solution Development . • The teacher discusses and models appropriate interactions. • The teacher provides support to consider each other's ideas and negotiate shared solutions.

Table 2.1 continued

Age Level	Narrative Context	Goals, Constraints, and Requirements	Engineering Design Processes (EDP) and Practices	Application of Science and Mathematics	Analysis of Data for Planning and Redesign	Collaboration
Ages 9-10	The context can be presented through illustrated short chapter books. • Children can read independently with significant comprehension support. • The topic can involve personal, social, industrial, or environmental problems. • In addition to supplementary resources and experiences used in earlier grades, children can now read and investigate independently	• The technology may be new to children. • Children design a technology or model that may have multiple functions or be part of a system; functions may require some instruction to understand. • Up to five constraints and requirements may involve calculations and measurement in scoring. • Balanced trade-offs ensure that many valid solutions are possible.	• The EDP has 5 or 6 steps. Children engage in practices from earlier grades with more independence. •Teachers model for the class and ask open-ended, generative questions to encourage children to actively engage, reflect, and draw conclusions. • Materials scaffold all processes through extended prompts and some instruction. • Children communicate ideas, designs, conclusions, and synthesis with drawings, extended writing, class discussion, and brief team presentations.	• A successful Solution Development will take scientific considerations into account from age-appropriate science content. • Children take measurements, calculate variables and scores, collect and record data, and construct charts and tables at an age-appropriate level.	• Children analyze data collected from specified controlled experimentation with materials and methods to inform design planning. • With teacher and written support, children construct graphs and charts and discuss and compare results across the class to draw lessons about reliability, variability, and planning a Solution Development . • Children judge the success of a Solution Development using a specified controlled testing procedure using quantitative measures and qualitative rubrics. • Children analyze data from testing of Solution Development s to understand points of failure and improve upon them in redesign.	• The teacher models for children and prompts them to come up with their own questions and ideas, as well as to make observations and draw their own conclusions. • Children work together to make decisions and plans as a team, and to create, test, and improve their ideas. • Written materials support children to reflect and make connections through open-ended prompts for short answers and basic observations.

Role of Adults in Learning.

Based on underlying theories (i.e. the constructivism and defectology), children's learning can be facilitated by adults' support. Much of the engineering education research focuses on the learning that happens in the context of schools, teachers have been the adults who supported children's engineering learning(Hynes et al., 2017). Since engineering learning also occurs in out-of-school settings, some research has recognized the roles that informal educator, including parents, play in this learning. In this section, I briefly review the role of adults in children's STEM learning.

Engineering Learning and Parental Support.

Parents' involvement in their children's development is very important during their early years as they are the main primary influencer of children's education (Dornbusch et al., 1987; Seyfried & Chung, 2002). As the child gets older, parents continue to impact their children's education, but this is mostly exhibited during out-of-school activities. Consistent with the notion of scaffolding in, parents can help enhance children's STEM learning while they do different activities at home or while visiting designed settings (e.g. museums) or participate in family-based programs (Haden et al., 2014; Pattison et al., 2018). During these activities, parents are children's *thinking guide* (Dorie et al., 2014b) as they play the role of *the more knowledgeable other* (Vygotsky, 1978).

One-on-one parent-child interactions are also a vehicle for improving children's scientific reasoning, logical and computational thinking skills. In a study on parent-child interaction in a museum, Crowley and colleagues (Crowley et al., 2001) found that children who interacted with their parents had more opportunities to build concrete scientific thinking skills than similar peers without parents. Similarly, Palmquist and Crowley (Palmquist & Crowley, 2007), in a study conducted at a natural history museum, demonstrated that parent-child conversations engaged children in complex disciplinary reasoning and problem-solving. In a case study of a homeschooling family, my colleagues and I noticed that the mother played multiple effective roles as she facilitated different computational thinking (CT) activities for her daughter (Ehsan et al., 2019a). Additionally, Ohland and colleagues presented evidence of how parents' involvement helped support children's engagement in computational thinking through a computer-based coding activity in a science center (Ohland et al., 2019). Given the fact that STEM+CT thinking skills overlap with each other, we expect that parents play similar important roles in their children's engineering design thinking.

A wide body of literature has studied the impact of child-parent interactions on STEM learning broadly in out-of-school learning settings. In recent years, special attention has been made to the roles that parents play in children's engineering design engagement. Svarovsky et al (2018) investigated one-on-one conversations that parent-child dyads had during engineering design tasks and emphasized the significant role of parents in their children's engineering thinking engagement and agency. In another study, Benjamin et al., (2010) observed that parents talked about engineering and engineering principles to their children, if they received this information immediately before building, and children considered the information in their design. Moreover, in a different study of the same team, they demonstrated that an increase in parents' STEM talk results in an increase in children's STEM conversation (Haden et al., 2014). In previous work, my colleagues and I found that with the help of parents, children were able to engage in an engineering design task and develop CT (Ehsan et al., 2017). In a different study, Rehmat and colleagues (Rehmat et al., 2020) explored different strategies that parents used during two different engineering design and computing activities and found that questioning, modeling and encouraging were effective strategies to engage children in learning.

Very few studies have investigated the role of parents in STEM learning for children with autism. For example, Wright et al (2011) developed a family-based intervention by considering children with ASD's strong spatial reasoning. It included kid-friendly design software, Google SketchUp, with the aim to develop skills for children's occupations. Parents, grandparents, and siblings were involved in the activity with the child with mild autism. The findings of this study showed that children with autism gained technological skills through this intervention. The findings also suggested that the intervention resulted in negating their weaknesses such as social interactions as they interacted with their family members. Their ability to express themselves also improved through this intervention.

2.3 Study Conceptual Framework for Characterizing Engineering Thinking in Children with Mild Autism

By connecting the concepts and theories from the previous sections together, I have created a conceptual framework that frames my study. The framework is discussed below.

Goal: To explore **the engineering design engagement** of **children** with **mild autism**

Theoretical lens: Constructivism & Defectology

Learning happens when knowledge is co-constructed through social interactions with one another

- Supportive environment including **appropriate activities** and effective peer-interactions and/or interactions with a **more knowledgeable other**

Context: Given the important roles parents play in children's learning in informal learning contexts, this study focuses on parent-child interactions.

Nature of the activity: An engineering design activity was designed considering the EiE trajectory for children's engineering learning, autism STEM-related strengths, and the activities used in similar prior studies. The characteristics of the activity are also consistent with what Cardella (2020) suggested in the proceedings of an early childhood engineering education symposium in an international conference. The characteristics are mentioned below:

- One-session activity similar to what was used in previous research (e.g. Dorie et al., 2014; Ehsan et al., 2020)
- Scenario-based activity with the capacity to engage in STEM+Literacy (Novel engineering and PictureSTEM projects)
- Strength-based by considering STEM-related strengths in autism: strong interest in building and constructing and solving a complex problem

Support: The activity is a family-based activity where adult members of the family and siblings can play the role of more knowledgeable others and can provide necessary scaffolding and motivation for children. One focus of this study is to examine the way family members, especially parents, support children's engagement in engineering design.

3. METHODOLOGY

The goal of this study is to characterize how children on the autism spectrum engage in engineering design tasks so that researchers, educators and parents have a better understanding of how to support their participation in engineering. Constructivist inquiry aims to understand and interpret a phenomenon by making meanings of it. This aim can be obtained through the reconstruction of the meaning of lived experiences. Defectology emphasizes the need to take asset-based approaches to empower learning. Taking an asset-based approach in this study, I aim to understand and interpret the engineering experiences of children with mild autism when they engage in an engineering design activity along with their parents who can serve as the more knowledgeable others. In this engineering activity, the child with autism interacted with his parent and with the activity to make sense of the activity and solve the engineering problem. The overarching question that I intend to answer in this study is: *How do children with mild autism engage in engineering design?* Within the scope of these questions I answered the sub-questions below:

(1) Approaches children take to solve an engineering design problem.

- What engineering design phases (i.e. Problem Scoping, Solution Development and Optimization) do children with mild autism engage in?
- How do they engage in these engineering design phases?

(2) The support and scaffolding that parents provide during these engagements.

- What strategies do parents use to support their children's engineering design engagement?
- How do these strategies help children engage in engineering design phases?

3.1 Nature of the Study: Qualitative and Descriptive

In the past ten years, engineering education researchers have recognized the importance of qualitative research for advancing the field of engineering education (e.g. Case and Light, 2011). Qualitative research tends to produce a deep understanding of a phenomenon by exploring the problem that is little known about them (Creswell, 2013). On the other hand, in a framework developed by Olds et al (2005), engineering education research is categorized into descriptive and experimental. Experimental designs are used in studies with the goal of determining the impact of a specific intervention. However, descriptive designs aim to discover how people's learning and engagement are affected by engineering education (Koro-Ljungberg & Douglas, 2008). Given the research goal and the phenomenon under study, this study is **qualitative** in nature with a **descriptive** design.

3.1.1 Theoretical Perspective

Qualitative research with a descriptive design aligns with the constructivist perspective. As mentioned in Chapter 2, constructivism is the orientation that has applicability in both engineering education and autism research. Thus, this study holds an identity of constructivism and this theoretical perspective has influenced all my decisions for designing this study. The purpose of such a theoretical perspective is to gain an understanding of a phenomenon by making interpretations through a socially made context (Schwandt & Gates, 2017). In this study, the phenomenon is engineering design thinking of children with mild autism during an engineering design activity.

In this theoretical perspective, both the researcher and the research subjects play a major role in constructing knowledge. The construction of knowledge heavily relies on interactions with surroundings and some form of consensual language. The engineering design activity in this study is a social activity and I, the researcher, am making meaning of each child's interactions with the parent(s) and the surrounding environment. Given the theoretical perspective, the research methods and procedures were subject to change and adjustable during the study (Koro-Ljungberg & Douglas, 2008), and may be transferable to other situations.

3.2 Research Design: Case Study

Answering the research questions of this study required exploring an understudied phenomenon of engineering thinking of children with mild autism. Therefore, I selected qualitative case study analysis as my research methodology. Case Study is a form of empirical inquiry that investigates a contemporary phenomenon within its real-life contexts, especially when the boundaries between the phenomenon (i.e. engineering design thinking) and context (i.e. the engineering design activity) are not clear. The qualitative case study aims to "study the experiences of real cases operating in real situations" (Stake, 2006, p.3) which means that by choosing to study a case, the researcher is also studying the situation/context. Both the researcher and the participants have a role in constructing knowledge, and therefore, this methodology is in line with constructivism.

Case study can usually answer *why* and *how* types of questions (Yin, 2018). As previously mentioned, the overarching question of this study is a *how* question with *how* and *what* sub-questions. The phenomenon in this study is the engineering experiences of children with mild autism within the context of engineering activities. Cases (or units of analysis) in a case study should be bounded (Creswell, 2013; Yin, 2018). In this study, each case or the unit of analysis is a child with mild autism, and each case is bounded by space and time, as I studied the children within their families while engaging in an engineering design task in a research lab setting. Since the case is bounded in the child, the focus of the study was what the child did and said, and all his interactions with others and the environment around was important.

The case study approach is systematic and linear, but iterative (Yin, 2018). However, the steps of analysis vary depending on the designation and the type of the case study employed in the study (e.g. Eisenhardt, 1989; Stake, 2013; Yin, 2018). I briefly discuss both the designation and the type of case study I conducted in this study.

3.2.1 Case Study Designs

Case study analysis is not generally confirmatory, but more exploratory (Yin, 2009). However, Schwandt and Gates (2017) recognized four designs for case studies including descriptive, exploratory, explanatory and contributions to normative theory. The "exploratory" design fits this study the most given the study's theoretical perspective, the nature of this study and the ultimate goal. The exploratory case study is also advocated by constructivists (Schwandt & Gates, 2017) and defenders of interpretive and descriptive approaches (Alvesson & Karreman, 2011). The nature of this type of case study is descriptive and specifically focuses on building and developing a theoretical model based on empirical findings (Schwandt & Gates, 2017). The exploratory case study helps with exploring a phenomenon that was never studied before in which a rich description of the phenomenon can lay a foundation for future investigation. The description of emerging themes and their connection to theoretical propositions results in developing theoretical models (Yin, 2018). Since the ultimate goal of this study is to create a preliminary guiding model to capture characteristics of engineering experiences and engagement of my participants (who are on the autism spectrum), this methodology is the best fit.

3.2.2 Type of Case Study

Multiple case study is a type of design for case study in which multiple cases are investigated (Eisenhardt, 1989; Stake, 2006). Multiple case study analysis can help better conceptualize theory and give a broader picture of the phenomenon under study (Stake, 2006). The purposive selection of few instrumental cases in multiple case study analysis can enable greater transferability to a larger collection of cases in the same context. The purpose of the qualitative multiple case study is not to produce a generalizable product, but to provide readers with the opportunity and responsibility to determine transferability to the other context (Lincoln & Guba, 1985). Therefore, in this study, I determined that conducting a multiple case study analysis focused on cases with similar autistic characteristics to be the most effective means for answering my questions and creating a discussion of this topic.

Focusing on multiple cases of children with mild autism allowed me to develop a wider portrayal of my participants' engineering thinking. As Yin (2018) suggests for conducting multiple case study design, the number of cases can be between two to ten. However, decisions regarding the number and selection of the cases should be carefully made based on the purpose of the study. Yin suggests if the study aims for "literal replications" (Yin, 2018, p.55) which predicts similar results, two to three cases should be selected for the study. Thus, I carefully selected three cases for this study (inclusion criteria can be found in the section on data collection), because the research questions were designed to produce literal replication by capturing similar patterns of their engineering experiences; how similar (and different) they engage in engineering design thinking; and how similar (and different) the role of their parents are. Therefore, three cases were included in this study.

3.2.3 Research Procedures

Given the rich but messy nature of data collection in case study methodology, building preliminary theories is possible when researchers iteratively think about the relationship between data points, theoretical constructs and propositions, research questions and cases (Yin, 2018). I aimed to build a preliminary model that characterizes and supports engineering design thinking of children with mild autism. I followed the framework described by Eisenhardt (1989) for building theories or models based on case studies. Several aspects of this framework are pulled out from the literature of case study research. The process described in this framework includes seven highly iterative steps. The process begins by (1) defining the research questions and *a priori* constructs based on existing literature following by (2) selecting cases. Researchers should then (3) construct and plan for multiple data collection methods (4) Collecting and (5) analyzing data come next. Eisenhardt argues that researchers should go back and forth between these two steps to do the possible adjustments. Analyzing data should include analysis of within the cases and across the case (6) Shaping the theory (a preliminary model in this study) is the next step which happens through an iterative tabulation of evidence for each construct. The tabulation of evidence includes finding the relationships between constructs and the reasons behind those relationships. After shaping the theory (a preliminary model in this study), comes next (7) enfolding literature to make comparisons with conflicting and similar literature.

In the sections below, I described steps two to five in detail. Step one was previously discussed along with research questions in the beginning of this chapter. Steps 6 and 7 are discussed in Chapters 4 and 5.

Data Collection.

An important step in the exploratory case study is a purposeful selection of cases to be specifically connected to theoretical constructs (Schwandt & Gates, 2017; Eisenhardt, 1989). To purposefully select the cases, I aimed to collect data from families whose child with autism meet the inclusion criteria below, where the target child:

- is 8- 10 years old (Third through fifth grade).
- is diagnosed with mild autism (high functioning autism). Relying on the family's self-report, the child may meet the criteria below:
  - should meet diagnostic criteria for Autism Spectrum Disorder based on the Diagnostic and Statistical Manual of Mental Disorders-5 (DSM-5, 2013) criteria.
  - is high-functioning (IQ > 70) based on Differential Abilities Scale – II (DAS-II).
- is verbal and have adequate communication skills.
- is able to communicate in English.

Participants. Three families agreed to participate in this study. In each of these families, one parent and a child participated in the activity. The names of the children are all pseudonyms (John, Scott and Tom) chosen by me, and parents are referred to as Mother/Mom or Father/Dad. None of the families provided information about their children's academic success beyond the survey (see Appendix E) as that was optional for them. Table 3.1 shows a demographic summary of the families, but more detail is provided below.

Table 3.1 Participants Information

Case #	**Child's name**	**Gender**	**Age**	**Race/ Ethnicity**	**Participated Adult**
Case #1	John	Male	9	White	Mom
Case #2	Scott	Male	9	White	Dad
Case #3	Tom	Male	9	White	Mom

Scott. Scott is 9 years old and identifies as male. He attends fourth grade in an inclusive classroom in a public school. According to his mother, he has some challenging behaviors. He is White and lives with his married parents with a younger sister in Kindergarten. He came to the lab with his mother. She is White and between 40-44 years old. They engaged in the activity for 58 minutes.

Based on the Autism Spectrum Quotient (Auyeung et al., 2009) that Scott's mother filled out, he has a Systemizing Brain (See the "Data Sources" section for more information). As his mom reports in the survey, he likes to spend a large amount of time lining things up in a particular order. He is interested in different types of vehicles and remembers a large amount of information about a topic that interests him. He would enjoy working on a puzzle but prefers virtual versions. He enjoys events with organized events.

Tom's favorite subjects are science and math. He likes to read and his favorite toy is his Kindle. He would like to be an engineer when he grows up. He likes programming and his favorite game is Minecraft, but his favorite activity is playing with LEGOs. He has lots of LEGOs at home and recently he now works with micro LEGOs. He usually follows the instruction sheets when building things with LEGOs , but he also develops his own solutions. Her mother specified that she does not know how to help her child with his designing, creating or building ideas and skills. However, she strongly believes that learning engineering skills is good for her son and it should start as early as possible. She would want her son to learn about engineering. She provides opportunities for her son to do design, create or build through playing with toys and some projects on a daily basis. They also visit science centers very often.

John. John is a 9-year-old who identifies as male. He is in fourth grade and attends a public school in an inclusive classroom. He has individualized education plans (IEPs) and a special education teacher sees him one hour a week. His favorite subject at school is history. He is White and lives with his married parents and an older sister who is in 8th grade. While his sister came with their mother to the lab, she decided that she did not want to participate. John's mother is White and between 40-44 years old. John and his Mother engaged in the activity for 58 minutes.
Based on the Autism Spectrum Quotient (Auyeung et al., 2009) that John's mother filled out, John has a Systemizing Brain (See the "Data Sources" section for more information). He prefers to have strict rules and enjoys events with organized routines. He is interested in understanding how different machines work. He has the ability to understand the patterns in numbers in math very quickly. His favorite toy is LEGO bricks, and he likes to build a robot out of his LEGOs. According to his mother, John follows the instruction sheet rather than self-guide himself when building models with LEGO. He enjoys working to complete puzzles and he is very good at

making puzzles (500 and up pieces). He also plays and codes with Minecraft and BowMasters. They play family games, especially board games and card games, like Spot It! and Uno. He is very quick at Spot It! which is a matching game.

John's mother believes that she knows how to help her child with his designing and building ideas and skills. On a daily and weekly basis, she provides opportunities for her child to play with toys like LEGO blocks or give him some projects that allow him to use his designing, creating and building skills. They watch TV shows related to engineering topics on a monthly basis. She wants her child to learn engineering skills as she believes that children should learn engineering as early as possible. She believes that "We have all kinds of engineering. Mechanical engineers how thing work, electrical engineers. Inventing things in any specific field and creating things. Engineers even make toys."

Tom. Tom is 9 years old and identifies as male. He attends fourth grade in an inclusive classroom in a public school. He does not have an IEP, but he often has challenging behaviors that impact his participation in class. His favorite subject is drawing and art. He is White and lives with his married parents with two other sisters. One of her sisters is one year older than him and the other is a toddler. He came to the lab with his whole family, but only he and his dad engaged in the activity. His older sister also engaged in the activity for a few minutes, but per Tom's request, she disengaged. His dad is White and between the ages of 30-34. They engaged in the activity for one hour.

Based on the Autism Spectrum Quotient (Auyeung et al., 2009) that Tom's mother filled out, he has a Systemizing Brain (See the "Data Sources" section for more information). He said that he does not have any favorite toy besides video games, but his favorite video games are Scratch Junior, Roblocks and Minecraft. According to him, using Scratch Junior, he usually makes funny stories. His mother also mentioned that he goes to different programming events at a science center and also his father helps him with Scratch. The family plays board games, video games and card games. When he goes to his grandparents' house, he plays different video games by himself. He loves robotics and he plays any games related to robotics, including a coding board game called Code Masters. He is the lead when playing any games. According to his mother, "he is very advanced in those games, so it is very hard to play with him. It's hard to make him enjoy anything else. When he plays games, he likes to be in charge and to make decisions himself."

His mother defined engineering as "Using certain tools to design something. Like creating. Depending on what type of engineering we are talking about." She also shares about engineering as "Engineering is all about everything. Everything needs to be engineered, even ice cream. If something breaks you need to engineer it."

Study Context.

In this study, each family engaged in an engineering design activity called *Design an Amusement Park, Rollercoaster*. Before they attended the session, they received a guide via email in which the activity was described and suggestions about ways to engage in this activity were provided (Appendix A). They were asked to collaboratively think about the problem, solve challenges, and build a rollercoaster. The activity started with a letter from the CEO of a local amusement park, Hannah Noah, stating the problem of "not having a fun and exciting rollercoaster in their park." Hannah invites children to build a rollercoaster model using the available building kit. Then children are given four warm-up challenges to explore the material and get a sense of what the rollercoaster can look like. Finally, they receive a final letter with the given criteria (Ehsan et al., 2019b). The building kit, ThinkFun RollerCoaster Challenge (ThinkFun, n.d.), that was used in this study has been previously evaluated by children without autism during the preparation of the 2017 Purdue INSPIRE Engineering Gift Guide (Purdue INSPIRE Research Institute for Pre-College Engineering, 2017).

***Design an Amusement Park, Rollercoaster*.** As mentioned before the activity included four warm-up challenges and the final master challenge (Letter Two). As mentioned in the Section three of Chapter Two, the activity is designed considering aspects of constructivist and defectology theories, previous literature on engineering design focusing on elementary-aged children and autism STEM-related strengths and instructions. A brief description of the activities is included here, but the entire activity is included in Appendix B. Additionally, the rationale for how the activity was designed was previously published as a Brief paper in the Journal of Connected Science Learning (Ehsan et al., 2019a)[3].

First letter introduces the activity to children. The letter is from Hanna Noah who states the problem.

Warm-Up Challenge Zero is an opportunity for children to look at the material guide and explore the pieces in the construction kit. This challenge asks children to locate different pieces of the given kit. This challenge aims to help children explore the given material.

Warm-Up Challenge One is a well-structured problem that asks children to build an exact rollercoaster in the picture. The goal of this challenge is to help children learn how the main pieces such as the start and end track, black pieces attach to other pieces. The challenge also helps them have a sense of how the rollercoaster works.

Warm-Up Challenge Two builds upon the previous challenge and asks children to build a steeper rollercoaster than the one in the previous challenge. The least to most prompting strategy is included in this challenge and the latter ones. This strategy is commonly used among researchers when implementing science and math instructions for children with autism (Ehsan et al., 2018) which learners gradually receive sequenced prompts, starting with the least intrusive then moving to the next intrusive (Neitzel & Wolery, 2009). In this study, they get three different prompts (least to most) including written hints, suggestions for what slides to use and finally pictures of three different slides.

Warm-Up Challenge Three asks students to build a rollercoaster in which the car turns before it stops. The same as for the previous challenge, it provides three types of prompts (least to most). In this challenge, children get to experience building and testing a rollercoaster and use pieces that they did not use in the previous challenge.

[3] http://csl.nsta.org/2019/05/design-an-amusement-park/

The *Second Letter* is from Hanna Noah who is asking children to build a rollercoaster considering certain criteria and constraints. The problem stated in this letter is very open-ended and ill-structured. The goals of ill-structured problems are not clearly stated and often have multiple sub-problems that may conflict with each other (Jonassen et al., 2006). After reading this letter, children will start building a rollercoaster of their own.

Parent Preparation. A few days before families came to the lab to participate in the study, I sent the parents a parental guide describing for them what the activity is and what they could expect to happen. They were given tips on how to engage in the activity while letting the child lead the activity.

Data Sources.

Exploratory case studies should be conducted in great detail and often rely on the use of several data sources (Feagin et al., 1991) to allow an in-depth exploration of a phenomenon and understanding of its complexities. Therefore, in this study, I have identified multiple sources of data that can help answer my research question. In a review of literature on engineering design education research, Atman and colleagues (2014) listed different sources of data that have been collected in studies related to engineering design engagement and learning including observation, surveys, interviews, design products and sketches. Since in this study I aimed to capture the engineering design experiences of my participants, I decided to collect all of the sources Atman et al (2014) mentioned.

I collected *video- and audio- recordings* of the family members' interactions when engaging in the engineering design task and solving the challenge. While video recording, I also took *fieldnotes*, which became my second source of data, and they especially played a role as a backup source for the video data. In my fieldnotes, I included the date and brief information about the participants. I then described the scene and what has been happening. As I was taking notes, I also reflected on my data collection process and the engineering activity itself. This reflection helped me make the necessary adjustments in the data collection process (Eisenhardt, 1989). These adjustments included the positions of the cameras, where I sat as the facilitator and my involvement and the use of other equipment such as an audio recorder to collect data.

The third source of data was the *design products*. Design products, in this study, are the rollercoasters that children built while solving the challenges using the building kit they were given. I aimed to take pictures of their solutions after each challenge, but I found it distracting to my first participants. Therefore, I decided to capture a screenshot of the video-recordings and use that to take a picture of the final product. In my initial plans, I aimed to collect design sketches that children would create. However, no family created one. Therefore, this data source was eliminated from my list of resources.

At the end of the session, I interviewed both the child with autism and their parents separately asking about their experiences during the activity and their previous experiences with engineering. These *interviews* (see Appendices C & D) were semi-structured and open-ended, and I designed them to help me learn about children’s experiences during this activity from their point of view and their parents’ observation and impressions. The interviews also provided background information about children’s daily lives’ activities, strengths, weaknesses, interests and needs. Finally, parents filled out a *survey* on demographic information, their children's prior engineering experiences, and their child’s *Emphasizing and Systemizing quotient* (EQ-SQ test) (see Appendix E). This test was initially used to describe sex differences and resulted in the identification of five empirically-based brain types (Goldenfeld et al., 2005). These five types included Balanced, Better at Emphasizing, Better at Systemizing, Extreme Emphasizing, Extreme Systemizing. The S-E quotient was later validated to evaluate autism characteristics for adults by Wheelwright et al (2006) and for children by Auyeung et al (2009). The tests showed that individuals with autism have systemizing brain (usually observed in severe autism) or extreme systemizing brain (usually observed in severe autism). The child version of EQ-SQ test is a self-report from families of their children’s abilities, which can present autistic characteristics.

Challenge of Collecting Data from Families with Autism.

Conducting research that involves families with autism is not easy and may require time. In this section, I point out three main challenges, so future researchers can predict and plan accordingly. First, the Institutional Review Board (IRB) process takes a long time, since the board has to ensure that every single step of the process is safe and may not cause any harm to children and their families. In this study, the process of approval took a few months (other studies at the same university are typically reviewed and approved in less than a month). Second, families who have children with special needs are more likely to have a busier and less flexible schedule. They may be busy with different therapies and after-school programs for their children. Thus, research activities may not find a space on their calendar. As a result, recruiting families who have children with autism was not easy for me. Additionally, many children with autism may experience anxiety in new settings and when they are expected to interact with new people. A mother who canceled their session half an hour before their scheduled time, told me that her son was so afraid to see new people and so they had decided not to attend the session. This added another layer of challenge for me to recruit families with children with autism. Finally, working with children with autism can be also challenging if researchers do not have enough experience working with them. Since some children with autism have difficult and challenging behaviors, during frustration and failure they may engage in unpredictable behaviors (like throwing material, yelling at others and/or leaving the room). Therefore, the presence of adults who are familiar with children's behaviors should be available. In one event, the child participating in my study decided that he did not want to participate in the study because he was not capable enough of doing engineering. He ended up leaving the room frustrated. While I respected his decision, his parents insisted that he had to finish the activity. They were able to convince him to come back and help him calm down. After the activity, I described to him that engineering is not all about success, and engineers fail until they succeed. While it did not happen in this study, and like any other research with humans, the data collection could have been paused or stopped if this child decided not to come back to the room. I acknowledge that there may be other challenges that researchers working in this area need to consider before conducting research.

Ethics of Data Collection.

To this study, I have got approval from the Institutional Review Board (IRB). The proposal of this study had undergone full-board review to ensure the ethics of the research. I provided assent and consent forms to children with autism, their siblings and their parents (or legal guardians). All parents received information about the activity and the consent forms before coming to the lab for the study. Upon arrival, the parents were given two different consent forms to sign, one to provide permission for their children and one to indicate consent for their own participation in the study. To recruit participants, I created an advertisement that was distributed at a local science center, parental portal in schools across once county, teachers who previously partnered with INSPIRE and at Purdue's research newsletter. I have also reached out to local autism communities. Participating in the study was defined on the activity ad and in the consent form as being video/audio-recorded while engaging in the engineering design activity and interviews. The children with autism (and their siblings in the two cases) were also read an assent letter in which all the different activities were described, and the children signed the form after they asked all their questions. When siblings without autism decided not to participate in the study, they were not included in the data collection. Finally, to ensure the participants' confidentiality, I secured the data on a password-protected server. Also, all of the children's names in the study are pseudonyms, and parents are referred to as Mom and/or Dad.

Role of Researcher.

I was the main and only researcher involved in the data collection process. Before the activity, I advertised the study widely at different venues (see Ethics of Data Collection section). and recruited participants. I communicated with parents from the first day until after the study and presented information about the study and answered any questions they had. Right before the activity started, I set up the cameras and audio recorder around the room, and I set up all the material for the activity on two big tables. Beginning with each family's arrival to the lab, I played the role of the activity facilitator and the point of contact with the hypothetical client. Children and their families could ask me any question they had about the activity, the material and what the client may need. Occasionally, I was asked to fix and assemble pieces. As the facilitator, I also sometimes encouraged children to test their rollercoasters and cheered with their parents when their rollercoasters worked. However, I tried to limit any interactions with children and families that could provide them with too much information for solving problems, to let the parents and children do the activity themselves.

Data Analysis.

Yin (2018) does not require any particular analytical strategies for conducting case study research. However, as previously mentioned, to create a model by producing literal replication, both analysis within cases and across cases is required. For the within-case analysis, different analysis methods were used depending on the type of data I collected. To conduct across case analysis, I utilized approaches similar to a comparative case study. Each of these phases of analysis is discussed in later sections. However, before describing the phases, I discuss the underlying analysis procedure necessary for both phases.

Analysis Procedure: Engineering Design.

The phenomenon that this study aims to uncover is engineering design thinking of children with autism; this phenomenon was investigated through two main research questions. As mentioned earlier, the first research question focused on ways and approaches children with mild autism engage in engineering design thinking and the second one explores parental supports. For both research questions, having a thorough understanding of engineering design is necessary. Therefore, before I started the analysis, I synthesized literature related to engineering design thinking practiced by designers of a wide range of ages and design experiences (See Chapter 2). Based on descriptive and empirical models of engineering design, I decided to organized engineering design as three phases; Problem Scoping, Solution Development and Optimization. I then summarized the synthesis in forms of engineering design practices and associated actions (see Table 3.2, 3.3 & 3.4). These Tables provide a succinct picture of what engineering design can look like for young designers. These Tables served as a codebook for analyzing all the data sources, but the analysis was not necessarily limited to the design practices and actions included in the table initially. These codebooks directly helped with answering the first sets of questions but were essential for exploring the effective strategies used by parents.

Engineering Design Codebook

Table 3.2 Codebook for Problem Scoping

Understanding the boundaries of the problem	Problem Scoping Actions	Behaviors
	Problem definition (Pd)	1. Reading, rereading, rehashing or reframing understanding of the problem statement and/or the goal 2. Identify and restate limitation of materials, space and resources (constraints) 3. Identify and restate desired features of a solution (criteria) 4. Adding/considering the meaningful context 5. Considering interactions among problem requirements
	Information Gathering (Ig)	1. Exploring material 2. Gathering information/building understanding of how a system/mechanism works and users 3. Gaining/thinking of domain-specific knowledge (e.g. science and math) 4. Learning about the situation by making a connection to the prior experiences and/or other ways 5. Identifying pieces of information in a problem that span across different categories 6. Evaluation of the properties and behaviors of supplied material

Table 3.3 Codebook for Solution Development

Definition: **Finding and creating a solution to the given problem**	**Solution Development Actions**	**Behaviors**
	Idea Generation (Id)	1. Brainstorming and formulating several ideas 2. Stating or building an idea 3. Acknowledgment of having one or more ideas 4. Discussing strategies of how to build the idea (planning) 5. Generating or building characteristics and features of an idea
	Decision-making (Dm)	1. Deciding what material should be used when building the solution 2. Predict possible outcome 3. Evaluating the best possible idea as the solution among several ideas based on the constraints and criteria of the problem 4. Selecting the best idea 5. Describing the reasons of choosing an idea 6. Selecting or specifying a solution component to include or to remove 7. Weighing options and balancing benefits and Trade-offs of solutions and plans
	Modeling/Prototyping (Mp)	1. Sketching design 2. Using gesture to model an idea 3. Physically building the solution using material 4. Using a previous built prototype for a solution of a new problem

Table 3.4 Codebook for Optimization

Definition: Evaluating and improving the solution	Design Optimization Actions	Behaviors
	Testing (Ts)	1. Mental simulation & evaluating the solution without physically testing it 2. Testing pieces 3. Prototype testing by running the car or against criteria
	Troubleshooting (Tb)	Any or a combination of these behaviors with a clear the goal of finding/fixing a problem and/or making a decision of what the problem is; 1. Observe: attempt to find the problem 2. Diagnose: do reasoning about what the problem is 3. Explain: discuss the reasons 4. Remedy: generate alternative solutions or an idea to improve the solution
	Improving (Im)	Any behaviors with the intention of improving the solution [it can be solutions from the previous phases] Make changes to a component of the solution Redesign a component of the solution or the entire solution
	Evaluation (Ev)	1. Reasoning about if the model works 2. Reasoning about if the remedy would work 3. Evaluating the workability of the model

Within Case Analysis.

Video Analysis. To analyze the video recordings of the families while engaging in the activity, I used the video analysis approach suggested by Powell et al., (2003) with adaptations from aspects of the interaction analysis approach (Jordan & Henderson, 1995). Powell and his colleagues suggested an analytical model of seven non-linear phases including (1) viewing attentively the video data, (2) describing the video data, (3) identifying critical events, (4) transcribing, (5) coding, (6) constructing a storyline and (7) composing a narrative. The first three phases helped with acquiring an in-depth knowledge of the content of the video and identifying the sequences of utterances and actions that may have been meaningful regarding the research questions.

During the *second phase,* I constructed a very detailed description of the scene and all the happenings of the video. Adapting from interaction analysis, I focused on "human activities such as talk, nonverbal interaction, and the use of artifacts and technologies (Jordan & Henderson, 1995, p. 39)." Since this description included a detailed transcription of dialogue between the family members, I skipped transcribing in phase 4.

In *phase three,* I used memoing as it was suggested by Yin (2018) as an analytical strategy. Memos are "short phrases, ideas, or key concepts that occur to the reader" (Creswell, 2013,p. 183) and necessary "sense-making tool" (Miles & Huberman, 1994, p. 72). The memos help researchers explore data and capture critical events. I documented my initial thoughts, observations and reflections of what the data was telling. In this phase, I also carefully examined the fieldnotes to ensure the inclusion of any reflections and thoughts I had documented during the observation. Memoing helped me to reflect broadly, create initial and specific ideas and highlight the critical events that were useful for the next steps.

The goal of coding in *phase five* was to search for patterns, insights and/or concepts that were promising (Yin, 2018). For research questions related to children's engagement in engineering design, as I was capturing moments, actions and behaviors that were evidence of the child's engagement in engineering design, I mostly relied on a theoretical proposition (i.e. codebooks) and conducted deductive coding. However, I was also open to capturing the engineering behaviors of children inductively if they were missing in my codebook. For the research questions related to parental strategies, I did not create and use any codebook, and worked with data from the ground up and inductively coded my data (Yin, 2018). Because qualitative coding is a process of reflection (Savage, 2000), this phase was a very iterative process and required moving back and forth between the previous phases.

Finally, *in phases six and seven*, I constructed a meaningful storyline of what I learned by making sense of codes and respective critical moments (Powell et al., 2003). I followed Yin's recommendation (Yin, 2018) of putting information into different arrays, reflecting themes and sub-themes, and creating visuals to make sense of different pieces of finding. I then created a storyline of families' engagement in the activity by including comprehensive evidence and interpretations of children's engagement in engineering design and ways parents supported them. I composed a narrative for each case that fully answered the research questions. According to Yin (2014), presenting the findings in the forms of narratives is important and the most preferred form as it tells a story based on the variables and coded values. I have to note here, that the process of creating the storyline was a very iterative process in which I had to revisit the coding several times to make the most sense out of the data.

Thematic Analysis. To analyze the interviews, I conducted thematic analysis following the suggested approach by Nowell and his colleagues (2017). The aim of analyzing the interviews was to capture anything interesting and meaningful that either parents or children with autism mentioned related to (1) their engagement in the activity and (2) their previous engineering experiences. First, I familiarized myself with data by listening to interviews and transcribing them. Next, I identified interesting aspects in those interviews that could be related to engineering or came out as a pattern. Then, I iteratively looked for themes across all the interesting aspects that I had identified in my data, and reviewed those themes and refined them if needed.

Artifact Analysis. Artifacts include any objects made by a human. Artifacts in this study are the solutions that the families designed and built using the building kits they were given. Qualitative researchers observe artifacts to make special note of aspects of them that can suggest particular meaning to them or their participants (Saldana & Omasta, 2017). In this study, I systematically explored artifacts each family designed in the different challenges to explore their characteristics and quality attributes related to design (Saldana & Omasta, 2017). To conduct this exploration, I captured photos of each artifact that the child with autism referred to as a solution. This could be if the child acknowledges that he is done verbally or if he specifically calls his design as the final/best model he could design. When analyzing the artifacts, I focus on the three characteristics: (1) Function: Does this artifact actually work? (2) Quality: Does this artifact meet the initial and the additional criteria? (3) Complexity: How many pieces do this artifact consist of?

While the analysis of each data source is conducted separately, Yin (2018) emphasizes that the findings of different data sources should feed into each other and contribute to the meaning-making of the phenomenon under study. Therefore, it should be noted that the findings from each data source were very important to answer the research questions. The findings from video-audio analysis and the fieldnotes were the main source of data that construed the long narratives and descriptions. However, the findings of thematic analysis and artifact analysis are embedded into those descriptions and narratives. Table 3.5 shows how different data sources led to answering the research questions.

Across Case Analysis.

Once I analyzed all three cases separately, I explored similarities and differences across cases. Given the aim of this study of producing literal replication and the ways data was collected, I compared findings of all the cases and captured similar patterns of their engineering experiences. Examining the patterns across all the cases, I made meaning and interpretation of the patterns and translated them into a guiding model.

Table 3.5 Data Analysis Summary

Research Question	Source of Data	Method of Analysis	Techniques
1.a	• Video data • Photos of the prototype (solution)	• Video Analysis Artifact Analysis	• Deductive coding: Codebook for engineering design • Inductive coding: codes emerge from interpretations of data
1.b	• Video data • Photos of the prototype (solution) • Interviews	• Video Analysis • Artifact Analysis • Thematic Analysis	• Deductive coding: Codebook for engineering design • Inductive coding: codes emerge from interpretations of data
2.a	• Video data • Interviews • Survey	• Video Analysis • Artifact Analysis • Thematic Analysis	• Inductive coding: codes emerge from interpretations of data
2.b	• Video data • Interviews	• Video Analysis • Artifact Analysis • Thematic Analysis	• Inductive coding: codes emerge from interpretations of data

3.2.4 Quality of Research Design

Like any other research design, the quality of case study research designs should be judged according to certain logical criteria (Yin, 2018). To judge qualitative research, multiple researchers have identified different tests and criteria such as trustworthiness, credibility, sincerity, triangulation and crystallization (Creswell, 2013; Lincoln & Guba, 1986; Merriam, 1995; Tracy, 2010). Engineering education qualitative researchers have identified and used different validity and reliability quality techniques to judge the quality of their work (e.g. Pawley, 2009; Walther et al., 2017). Yin (2018), however, identified four ways to ensure the quality of any case studies including construct validity, internal validity, external validity and reliability. Since this is a qualitative case study, I followed Yin's suggestions and used those that were applicable to this qualitative study, while I also ensured that I addressed the criteria used by other qualitative researchers. Among all four of these quality considerations, internal validity is only recommended for explanatory case studies (Yin, 2018), and therefore, not applicable for this exploratory case study.

Construct Validity

One way to address construct validity is to identify appropriate ways to measure the phenomenon under study (Yin, 2018). Researchers need to collect multiple sources of evidence to allow triangulation of the data (Yin, 2018). Findings should be supported by the convergence of line of inquiry and multiple measures. In this study, I was able to collect and triangulate multiple sources such as audio and video of children's conversations, field notes, and pictures of children's artifacts (their design). A second tactic to establish construct validity is to create a chain of evidence. This chain of evidence must be created through a clear alignment between the case study data sources, the data collection protocol, and the case study questions. I addressed this by clearly describing what and how sources of data were collected, how each source was analyzed and the contributions of each source of data to answer the research questions (See the Research Procedures and Data Analysis sections).

External Validity

External validity deals with the generalizability of the findings beyond the immediate study (Yin, 2018) and how the findings are applicable to other contexts (Merriam, 1995). Yin (2018) suggests using literal replication logic where researchers use the same experimental conditions for each of the cases. In this study, I followed this advice and used the same data sources and data analysis approaches (e.g. the same codebook and coding strategies) for all of the cases. Another strategy for ensuring the external validity is to provide a "thick description" of each case (Merriam, 1995, p. 58). Thick description of findings should provide enough information for the readers to be able to determine the similarities of their own context to that of this study and evaluate the applicability of the findings to their own study. Therefore, the results of the study are presented as multiple cases with a detailed thick description in Chapter 4 and 5.

Reliability

Addressing reliability requires answering this question: If another researcher used the same procedures and redo the study, would they make the same conclusions? (Merriam, 1995; Yin, 2018). I used a peer checking strategy to address reliability by having a two of my committee members check the plausibility of the data, analyses, and results (e.g., Merriam, 1995).

3.2.5 Limitations

Like any other research, this research has several limitations. First of all, the scope of this study is limited by the sample of families who participated in the study. Given the challenges I had with recruiting families, the parents who participated in this study may be more inclined to engage their children in outreach activities, and may be of a similar demographic in terms of socioeconomic status (Farrell & Medvedeva, 2010). Additionally, participants' diversity is a limitation of this study as all children were male and White. Therefore, I acknowledge that the experiences of female and nonbinary children with diverse racial and ethnic background may be completely different. Additionally, all of these children had extensive experiences playing with STEM toys and games, therefore they may have been more prepared to engage in these engineering activities than others who did not have any prior experiences.

An additional limitation is about how well I was able to interpret and make meaning of the children and their parents' interactions and conversations regarding engineering design phases and practices. Two of the children in this study were unwilling to communicate their design decisions aloud, which made the interpretation difficult. However, I tried to overcome this limitation by watching the videos several times, reading the transcriptions and learning from patterns of behaviors observed at different events. I also followed up with interview questions which provided some insights about their design behaviors.

Another limitation of this study is regarding participants' autism diagnosis. In this study, no formal test was implemented to capture autism diagnoses, neither formal documentation was required to be shown at the time of the study. I relied on the parents' self-report on their child's autism diagnoses and their intelligence quotient based on Differential Abilities Scale measures. This decision was made given the limited time I could ask from parents to participant in my study, especially given the amount of compensation I could provide. However, I have used Emphasizing and Systemizing quotient (Auyeung et al., 2009) which evaluated children's autistics characteristics based on the questionnaire that parents fill out. This quotient aligns with the systemizing-empathizing theory that underlies this study and has been widely used in autism studies conducted in Europe (Baron-Cohen, 2009). While the results of this quotient and the parent-self report of diagnoses were sufficient to prove that the children are on the autism spectrum, future research may want to use other measures like Wechsler Intelligence Scale for Children (Wechsler, 1949) and medical diagnoses to conduct studies with individuals on the autism spectrum.

4. FINDINGS: THREE CASES

In this chapter, I describe the findings which respond to the two research foci with their associated research questions:

(1) Approaches children take to solve an engineering design problem.

- What engineering design phases (i.e. Problem Scoping, Solution Development and Optimization) do children with mild autism engage in?
- How do they engage in these engineering design phases?

(2) The support and scaffolding that parents provide during these engagements.

- What strategies do parents use to support their children's engineering design engagement?
- How do these strategies help children engage in each engineering design phase?

Because of the complexity of the findings, I present the findings at two different levels. First, I present a high-level overview of the findings across all the cases. The findings are summarized in four Tables (4.1, 4.2, 4.3 & 4.4). Three of the tables are related to the engineering design phases. The engineering design phases are similar to the ones mentioned in NGSS and are followed by the actions exhibited by the child in each case. The last table is related to the strategies parents used to help their children engage in engineering design practices and the activity itself. Parental strategies are emergent themes that were observed as enacted by parents as they engaged in the activity with their children. The Tables include concrete examples from all cases.

In the second section, I describe all three cases in distinct sub-sections. For each case, I present a summary of the findings related to each case with respect to the engineering design phases. In each sub-section, I provide select examples that illustrate the child's engagement in engineering design as well as the parental facilitation strategies. Within the examples I provide, the engineering design practices (***bold and italic***) and parental strategies (<u>**bold and underlined**</u>) are included in parentheses. To read more about each family, appendices F, H, G include the detailed narrative of what each family did during their engagement in this engineering design activity.

I also provide a description of the scene and what the family says and does regarding addressing the engineering design problem. The design description is created based on the artifact analysis where I examined different versions of children's designs that the child called a solution. The design description is also informed by the interviews with the parents and children. Family conversations that are presented in quotations are the exact transcription with no change in grammar and/or wording. Additionally, the activity with all the challenges and pictures related to those challenges are included in Appendix B. Therefore, I suggest readers review the activity to get a clear understanding of what the materials and challenges look like before reading the narratives. Figure 4.1 is a picture of a rollercoaster designed prior to the study using the same kit.

One final note is that the Tables represent the responses to the *What* research questions. Responses to the *How* research questions are presented in narratives and design descriptions. The discussion of these findings is included in Chapter 5.

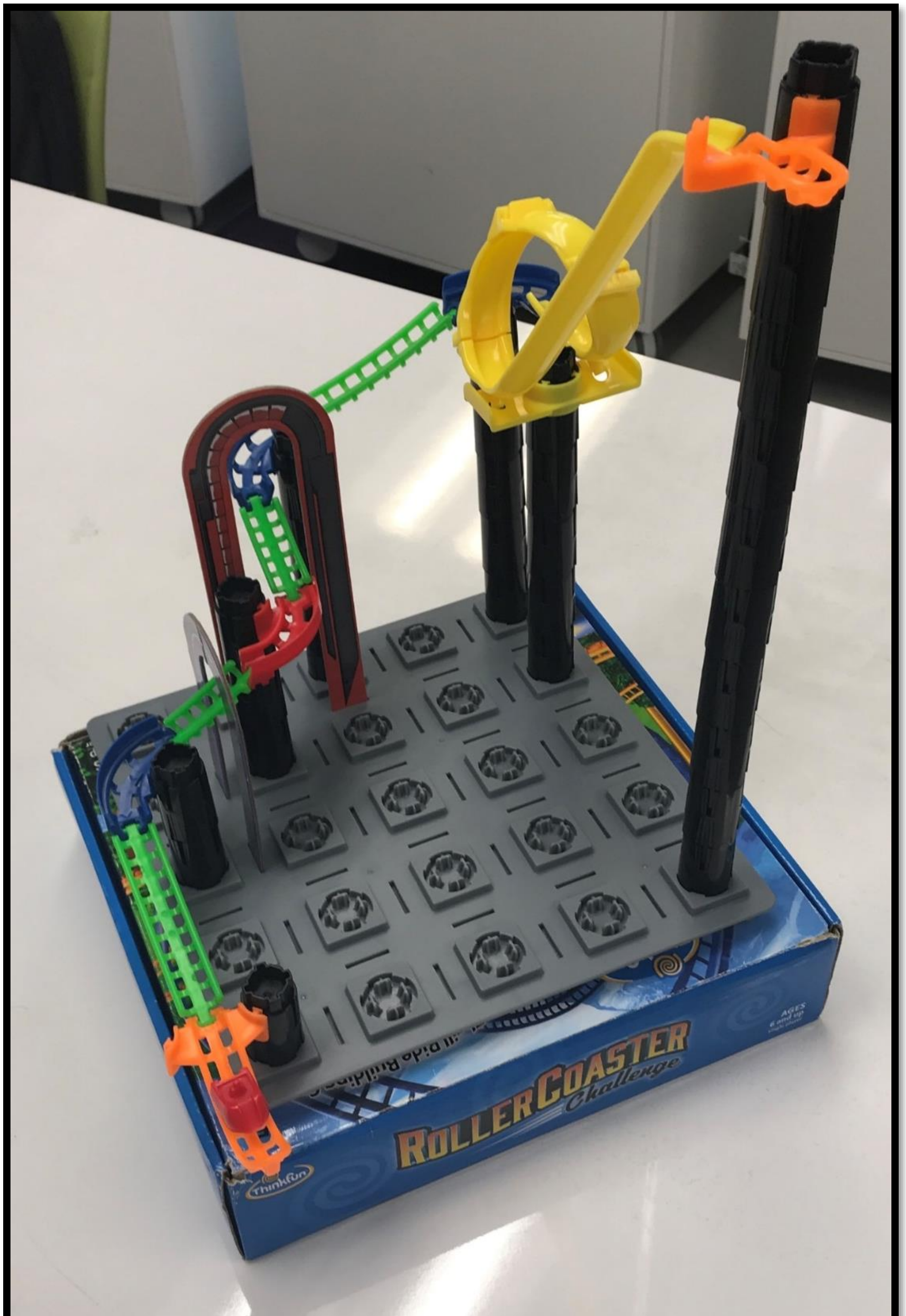

Figure 4.1 Sample of Rollercoaster Designed by ThinkFun

4.1 Overview of Findings: Across Cases

As mentioned earlier, this section presents an overview and summary of findings across all three cases. This overview provides the readers with a summary of what these engineering design engagements look like when enacted by these three children and the facilitation strategies parents used during this activity. The aim of this overview is to make the case narratives and the captured events within the narrative more meaningful for readers. The first three Tables show a summary of what engineering design practices children engaged in when doing the activity. The case numbers are included next to the examples as C1, C2, C3. Some differences can be observed with these Tables in comparison with the engineering design codebook (Tables 3.2 & 3.3, 3.4). These differences are based on the patterns of behaviors observed happening by these three children during the design activity. For example, some of the behaviors that were stated in distinct categories were seen to be very similar, so they were merged to be one category. For example, the first few behaviors associated with idea generation in Table 3.2 happened with a very similar aim. Therefore, they were merged into one category. Some of the behaviors were not observed as behaviors exhibited by these children. Additionally, I observed overlap between some behaviors associated with multiple actions in two phases.

The last Table includes a summary of the parental strategies that facilitated children's engagement in engineering design practices and the activities. The strategies listed in Table 4.4 were observed as enacted by all the parents at different times in different ways. Therefore, the case number is not included.

Table 4.1 Engineering Design: Problem Scoping

Problem Scoping Definition:	Problem Scoping Actions	Behaviors	Examples from the cases
Understanding the boundaries of the problem	Problem definition (Pd)	1. Reading, rereading, rehashing or reframing understanding of the problem statement and/or the goal 2. Identifying and restating limitations of materials, space and resources (constraints) 3. Identifying and restating desired features of a solution (criteria) 4. Adding/considering the meaningful context 5. Considering interactions among different aspects of the problem 6. Considering different perspectives or ways of seeing the problem	1. Child reads the letters or the design challenge and start thinking about new ideas (C1,C2,C3) 2. Child shows understanding of the challenge limitations (C1,C2) “So I only have these many black posts? (C1)” “I cannot go beyond this [gray base]? (C.2)” 3. Child shows understanding of the requirements of the problem (C1, C2, C3) “They say it needs a loop” 4. As Child understands the problem, he adds additional requirements to the problem (C1, C2, C3) “It should also be safe (C2)” 5. Child understand to have a steeper rollercoaster, he needs to build a taller tower. However, this may put the safety at risk, as the car would fall off the rollercoaster (C3) 6. Child’s understanding of the problem is different than the adult’s, and Child discusses why he is right (C1, C3)

Table 4.1 continued

Information Gathering (Ig)	1. Exploring materials 2. Gathering information/building understanding of how a system/mechanism works and users 3. Gaining/thinking of domain-specific knowledge (e.g. science and math) 4. Learning about the situation by making a connection to the prior experiences and/or other ways 5. Identifying pieces of information in a problem that span across different categories 6. Evaluation of the properties and behaviors of supplied material	1. Child explores different pieces given in the construction kit, before and/or during design. This exploration happens by touching & rotating the pieces, reading the guide, trying to attach the pieces to other pieces (C1, C2, C3) 2. Child discusses how rollercoasters (and the physical system) work; what makes a rollercoaster fun and exciting, who rides a rollercoaster and … (C1, C2, C3) (some of the examples have overlaps with 3&4 as children referred to their science knowledge and/or their prior experience of riding a rollercoaster) 3. Mom discusses scientific concepts that make the rollercoaster function (C1, C2) and child engages in the conversation “This needs gravity.” 4. Child talks about different systems he has seen in a rollercoaster to function (C1, C2, C3) “We need to add a break.” 5. No example of this was observed 6. Differentiating between this behavior and decision-making (2) in the Solution Development phase was not possible.

Table 4.2 Engineering Design: Solution Development

Solution Development Definition:	Solution Development Actions	Behaviors	Examples from the cases
Finding and creating a solution to the given problem	Idea Generation (Id)	1. Brainstorming and formulating one idea or several ideas 2. Discussing strategies of how to build the idea (planning) 3. Generating or building characteristics of an idea	1. Child talks about one idea he has as the solution by a. Stating and/or his idea(s) "Here is something I can do…" (C3) b. Acknowledgment of having one or more ideas 2. Child discusses his plans for building the solution (C1, C2, C3) a. at the very beginning ""First I need the…" b. during the design "Right there. And then this would go right here. So that's ... So this would be the end of the tunnel. And then you go down..." 3. As child is building the initial idea, he discusses or builds additional characteristics of his idea (C1, C2, C3) Ex. Child moves a tower and adds a different tower to the current design he had.

Table 4.2 continued

Decision-making (Dm)	1. Deciding what material should be used when building the solution 2. Evaluating and/or selecting the best possible idea as the solution or a component of the solution among several ideas based on the constraints, criteria and other aspects of the problem 3. Weighing options and balancing benefits and trade-offs of solutions and plans	1. Child makes decisions (not always reflective though) of what pieces he has to use in his design based on the features of the pieces or by predicting the outcome, such as slides, turn tracks and/or other pieces (C1, C2, C3) (This may overlap with 2 as the decisions of the adding/removing pieces are often the solution components.) a. Child looks at the given picture and the material on the table, and then decides what pieces were used in the picture so he selects them b. Child puts the slides side by side and next to the two towers, and makes a reflective decision of which one to use. c. Child returns the piece to his mom saying, "This is not going to connect, it's just a slide." 2. Child makes a decision of following his own or the parent's idea since it meets the criteria, constraints and other aspects. The process of decision-making happens by the child himself independently, or by having a conversation with parents (C1, C2, C3)

Table 4.2 continued

a. In response to Mom's suggestion of taking out the loop, child says, "But then I won't get the extra point… Don't touch it mom."
b. When mom suggests building a long tower and make the car turn around this tower, Child agrees by saying, "Yes and that should be fun, right?"
c. Child asks Dad if he has to add two more pieces or three, but Dad doesn't respond. Then, he makes the decision himself, "Okay, I am going to take three."

3. Children articulate their reasoning of why they chose one solution over a second one (C1, C3)

Table 4.2 continued

Modeling/prototyping (Mp)	1. Sketch design 2. Using gestures to model an idea 3. Physically building the solution using material 4. Using a previous built prototype for a solution of a new problem	1. No child made any sketches. 2. Gestures was used as a means to represent ideas (C1, C2, C3) Ex. Child uses his hands to show his rollercoaster will spin around a long tower. 3. Children constantly were building their prototypes, even while engaging in other actions, by adding and removing pieces (C1, C2, C3) 4. Children use the rollercoaster they built in the previous challenge for the next challenge (C1, C2, C3)

Table 4.3 Engineering Design: Design Optimization

Design Optimization Definition:	**Design Optimization Actions**	**Behaviors**	**Examples from the cases**
Evaluating and improving the solution	Testing (Ts)	1. Mental simulation & evaluating the solution without physically testing it 2. Testing pieces 3. Prototype testing by running the car or against criteria	1. Child, without running the prototype, decides if the rollercoaster works or not (C1 , C2, C3) Ex. Child uses his gesture and words to show that the solution would not work, "No I don't think that this works. I need something else." This action sometimes seemed similar to the action of evaluation. 2. Child runs the car on a part of the rollercoaster while incomplete or completely built (C1, C2, C3) 3. Child runs the car on the rollercoaster and tests it against the given criteria or self-specified criteria
	Troubleshooting (Tb)	Any or a combination of these behaviors with a clear goal of finding/fixing a problem or determining what the problem is: 1. Observe: attempt to find the problem 2. Diagnose: reason about what the problem is 3. Explain: discuss the reasons 4. Remedy: generate alternative solutions or an idea to improve the solution	Child attempted to find the problem with the solution, successfully and unsuccessfully, by engaging in a non-linear order and different combinations of these behaviors (C1, C2, C3)

Table 4.3 continued

Improving (Im)	Any behaviors with the intention of improving the solution [it can be a solution from the previous phases] • Make changes to a component of the solution • Redesign a component of the solution or the entire solution	Child realizes that the solution is not working, he attempts to improve their design (C1, C2, C3)
Evaluation (Ev)	1. Reasoning (verbally or non-verbally) about the workability of the solution • Reasoning about if the remedy would work • Giving explanations of why the solution has improved or will work • Providing reasoning based on STEM understanding	1. Child is asked to design a rollercoaster that is steeper than the previous sone. After he builds one, Dad asks him how does he know it's steeper? Well, this is steeper because it's taller.

Table 4.4 Parental Strategies to Facilitate Engineering Design

Facilitation Strategies	Definition/descriptions	Example	Engineering Design Phases
Soliciting Information	Parent asks implicitly or explicitly for child's input with the purpose of • prompting to solve a problem • seeking confirmation/clarification • seeking explanation (e.g. STEM knowledge)	"How are you going to build this?" "And we need to make six, right?" "Why does it go faster?"	Problem Scoping Solution Development Optimization
Providing Guidance	Parent leads the interaction for the purposes of providing information about the design to the child in a form of • Direction • Suggestion • Assessment • Modeling • Explanation	"It says that we need to build a loop, so this is what should be next (Direction)" "I think, we need to have something tall here (Suggestion)" "I don't think that this works (Assessment)" "This is how these connect (Modeling)" "Aren't you learning about gravity at school? (Other comments)"	Problem Scoping Solution Development Optimization
Assisting	Parent offers help to the child or attempts to help • Verbally • through Building	"If you need help, let me know." "I can build this for you."	Solution Development Optimization

Table 4.4 continued

Disengagement	Parent disengages from the activity • Per child’s request • Through self-decision	“Okay. You are on your own now.”	Solution Development Optimization
Affirmation	Providing affirmation through • Encouragement • Confirmation	“Good job, boy” “That’s a good idea.”	Problem Scoping Solution Development Optimization
Acting like Student of the Child	Parent acts like they do not know or know less than children and ask children to teach them	You know more, what do you think?	Did not directly influence any Design Phases; Influenced re-engagement

4.2 Summary Findings: Within Cases

4.2.1 Case 1: Scott and Mom

Case Overview.

Scott, a 9-year-old boy, with mild autism, participated in the study with his Mom. He attends fourth grade in an inclusive classroom in a public school. According to his mother, he has some challenging behaviors. Based on the Autism Spectrum Quotient (Auyeung et al., 2009) that Scott's mother filled out, he has a Systemizing Brain. He enjoys working on puzzles but prefers virtual versions. His favorite subjects are science and math. He likes to read and his favorite toy is his Kindle. He would like to be an engineer when he grows up. He likes programming and his favorite game is Minecraft, but his favorite activity is playing with LEGOs. He has lots of LEGOs at home and recently has started working with micro LEGOs. He usually follows the instruction sheets when building things with LEGO, but he also develops his own solutions. He was independent during this activity, but his mother was very involved too. He solved the first challenge and then decided to build a solution for the last challenge. Overall, he engaged in the activity for 58 minutes and created four rollercoasters.

Case Findings Summery.

While doing the activity, Scott showed evidence of engaging in all of the engineering design phases with and without the help and support of his mother. The summary of the findings below is organized by each engineering design phase. For each phase, I present the synthesis of findings for Scott's engagement in the engineering design phase and the parental facilitation strategies. I also share some examples for each category. Although the findings are organized by phase, the design process was very iterative and not linear, where he would not engage in these phases back and forth and not in a specific order. To read more, Appendix F includes the complete case narrative which includes a detailed narrative of all the scenes and the child-mother's interactions (i.e. what they said and did), and all the codes associated to their interactions.

Problem Scoping.

Child Engagement. I observed evidence of Scott engaging in both actions of problem scoping, problem definition and information gathering. His engagement in problem scoping did not just happen at the beginning. However, his understanding of the boundaries of the problem developed throughout the activity. He showed evidence of problem definition by reading/re-reading the problem statement at the beginning, restating what the problem is asking, identifying the constraints and criteria specified in the problem statement and also considering new ones, adding and considering meaningful context to the problem and finally taking different perspectives into account when scoping the problem. He gathered information about the problem by extensively exploring the pieces individually and how they connected to each other in both of the two challenges he tried. Moreover, his information gathering activities included asking questions about the specifications of the problem, science knowledge, and ways a rollercoaster could work by making connections to his previous experiences.

Parental Facilitation Strategies. Scott's mom facilitated his engagement in problem scoping throughout the activity using several strategies. She provided guidance through different forms of direction, explanation and suggestion. She also solicited information by asking prompting questions and asking for confirmation about different aspects of design. Finally, her affirmation as a form of encouragement motivated Scott to scope the problem.

Examples.

> **Example 1**. Scott began building his rollercoaster, but did not place it on the gray base. Mom indirectly provided step-by-step prompts so he explored other pieces and realized that he needed the gray base. While Scott was building the rollercoaster independently without listening to his mom's comments, Mom's direct prompts helped him explore materials. Below is the conversation that happened between them.
>
> Mom: What does it say first? (**Soliciting Information-Prompting**) [passing the challenge to Scott]
>
> Scott (quickly looks at it): I'm just going to say this that what I'm building works.

Mom: Okay, I know (**Affirmation-Encouragement**). What is the first thing that you're supposed to get? (**Soliciting Information-Prompting**) That one (**Providing Guidance-Direction**) [Mom points to the gray base and gives it to him].

Mom: Okay. What's the second thing? (**Soliciting Information-Prompting**)

Scott: [doesn't pay attention to Mom] Oh, wow, so I connect it (***Problem Scoping-Information Gathering)*** [while connecting the start track to the slide track]... that ... Okay done.

Example 2. Mom and Scott were in the middle of building and fixing the roller coaster at the same time, that Scott got distracted from what they were doing. So Mom provided explanation and prompting questions, and then attempted to act like she knew less than Scott. While the combination of these strategies resulted in Scotts' engagement in all of the engineering design phases, being a **Student of the Child** was a strategy that helped Scott reengage and gather more information about the material (***Problem Scoping***).

Mom: Use the shorter ones [referring to the slide tracks]. You can use a shorter one here (**Providing Guidance-Direction**). Here, let me assist you (**Assisting-Building**). [She helps him to find a small slide track.]

Scott: It needs to be really short (***Solution Development -Decision Making***). [But he distracted by other pieces at the corner of the table.]

Mom: Well, there's a bunch of different lengths here in the green [referring to slides], and there's a few different lengths here in blue (**Providing Guidance-Explanation**), and I don't know what these are, but you probably do (**Soliciting Information-Prompting**) (**Student of the Child**). [Puts all the material closer to the child]

Scott: Slide-tunnels [he points to the tunnel part of the slide.] (***Problem Scoping-Information Gathering***). [and then he explores the rest of materials] (***Problem Scoping-Information Gathering***)

Solution Development.

Child Engagement. I observed evidence of Scott engaging in all three actions of Solution Development: idea generation, decision-making and modeling/prototyping. During both challenges, he engaged in idea generation by generating one idea, but brainstorming several components and features of that idea and sharing strategies to build those features. The behavior of generating sub-ideas was mostly evidenced through Scott’s actions; as he was building and/or by the observable verbal and non-verbal (gesture) cues. While designing and building his solutions, he exhibited different decision-making behaviors. He most often exhibited the decision-making behavior of selecting a piece among different pieces. In many instances, he evaluated his sub-ideas and selected among them. Moreover, occasionally, his evaluation was between his own sub-ideas and his mom’s. Finally, in one instance and with the help of his mom, he engaged in weighing and balancing the trade-offs of two solutions.

It is important to mention that Solution Development was the design phases that took most of Scott’s time as this phase had overlaps with the other two phases. From the very beginning after he read the first letter, he engaged in prototyping and building a rollercoaster while identifying what the problem is asking, what materials he could use. He also was constantly optimizing his solution while prototyping. Thus, drawing a clear boundary between the phases was not always possible.

Parental Facilitation Strategies. Mom’s involvement was very evident during this phase. She supported Scott’s engagement in this phase using several strategies. She provided guidance in a form of direction, explanation and suggestion. She also assisted in building and offered help verbally several times. She solicited information through prompting questions. Finally, she provided affirmation through confirmation and encouragement.

Examples.

Example 1. After a few minutes that Scott worked on his rollercoaster by adding and removing pieces (***Solution Development -Decision-making & Modeling***), Mom attempted to suggest an idea, but turned it to an affirmation, “Up at the top. Umm, I mean that sounds kind of cool” (**Affirmation-Encouragement**). Scott nodded and then talked about his ideas using his words and gestures: “It's going to go all the way ... it's going to go down ... this needs to be the start (pointing to the taller tower with the start track)... and then it's going to go down, down, down, down, down, down, down (***Solution Development -Idea Generation***).” Mom nodded and approved by saying, “okay” (**Affirmation-Confirmation**). Scott continued, “It's going to go really far down (***Solution Development***

-Idea Generation)" The mom looked at Scott, and then said, "It's good" (**<u>Affirmation-Confirmation</u>**). Scott, without paying attention, said, "And that's the start, and then it's going to go whoop, and then it's going to make a sharp turn ... turn ... and then it's going to fall in, and then it's going to go (***Solution Development -Idea Generation***)."

Example 4. During the last challenge, Scott shared his plan with his mom, "go to the loop, and then the end, but there will be a tunnel." **(*Solution Development -Idea Generation*)**. However, Mom disagreed with his plan and directly suggested another plan, "Well, I think you have to start with a loop, sweetie." (**<u>Providing Guidance-Suggestion</u>**) Scott shook his head in disagreement and Mom continued, "Let me see a black piece and see if I can get this in here" (**Assisting-Building**) Scott said, "Just give me a minute" and adds a tunnel to his model (***Solution Development -Idea Generation & Modeling*)**.

Example 2. Scott built a solution that met all the criteria but it did not work properly. Given the similarities Mom saw between Scott's current design and what he first described as a solution, Mom used this opportunity to encourage Scott to build his first idea. While Scott at the beginning disagreed with changing his idea, he engaged in balancing trade-offs and make a decision to build a different idea.

Mom told Scott, "Wow. You know how cool that would've been (Affirmation-Encouragement)? Do you want to start it up there and just go on around the little spin-y thing (Providing Guidance-Suggestion)?" Scott disagreed and said, "Um, No. and that's most of the black pieces. I can't build anything else. And I am not going to get all the points. (Solution Development - Decision Making)" Mom said, "okay. It's his job. He called it done. Are you sure? 100%?" Scott changed his mind and while taking out some of the black pieces from a tower, he said, "That's it. I'm going to start doing." Mom asked for clarification, "that's it, you mean you're done or…" (Soliciting Information-Clarification). Scott shook his head and took out pieces [a non-verbal sign that he is continuing to work on this]. Mom suggested that they take a picture of the version they already have (Affirmation-Encouragement). He got excited and said, "and then I'm going to go back to the

> beginning." Mom responded, "yes, and this way they [pointing to the researcher] will have multiple versions of your work. You're doing great buddy!" (Affirmation-Encouragement). Scott agreed. Later, Scott explained to the researcher that, "I want this one to be sent to them (shows his satisfaction with this design). At least this is gonna work. The old one was crappy" (Solution Development - Decision Making; Optimization-Evaluation).

Optimization.

Child Engagement. I observed evidence that Scott engaged in optimization very often. As mentioned before, Optimization did not happen only at the end of the activity. Scott exhibited behaviors associated with different actions of Optimization throughout the activity, especially when doing the last challenge. He tested his design, not only when the solution was completely built, but also as he was building his solution by testing sub-parts and different components of his solution. He engaged in troubleshooting very often, which resulted in improving his solutions and/or refining his ideas. Finally, in multiple instances, he evaluated his design against different criteria and problem specifications.

Optimization, the same as the Solution Development, did not just happen as an isolated phase. However, most of Scott's engagement in Optimization happened while he was designing his rollercoaster. At times, troubleshooting required making decisions and improving also required generating new ideas and gathering information about the problem. The example I provide below show how these phases were entwined.

Parental Facilitation Strategies. Scott's mom was very involved. She used a combination of strategies to facilitate Scott's engagement in Optimization and design evaluation. She prompted Scott implicitly and explicitly to make him realize ways he was misusing materials. She provided guidance through explanation, suggestion, direction and assessment. She assisted with building and verbally which resulted in Optimization. Finally, her affirmation also effectively helped Scott to troubleshoot and optimize his solutions.

Examples.

Example 1. Scott built his rollercoaster in response to the first challenge. He then tested it (***Optimization-Testing***). He left the coaster car on the first tower. He pushed it slightly, but the car did not roll on the slide by itself. He thought there is something wrong with the car. He grabbed the car, looked at the car trying to figure out how to make it work (***Optimization-Troubleshooting).***

Mom: maybe the bottom [referring to the coaster car to be used upside down] (**<u>Providing Guidance-Suggestion</u>**).

Scott: Oh, Yes (***Problem Scoping-Information Gathering)***.

He left the car upside down on the rollercoaster to see if it ran on the rollercoaster by itself (***Optimization-Testing***), and it did not move by itself either. Finally, he pushed the car himself to roll on the rollercoaster (***Optimization-Testing***). The car stopped in the middle. Mom and Scott started a conversation to find the problem and fix it (***Optimization-Troubleshooting & Improving)***.

Mom: Maybe try turning it the other way to roll better (**<u>Providing Guidance-Suggestion</u>**).

Scott: No, this is the end track (***Optimization-Troubleshooting***).

Mom: Okay. No, no, no, I meant turning the car. Oh, you know what? There's a guy (**<u>Providing Guidance-Direction/Explanation</u>**). Does he have a face? (**<u>Soliciting Information-Prompting</u>**)

Scott: No.

Mom: Okay (**<u>Affirmation-Confirmation</u>**) So you can't tell which way he's facing (**<u>Providing Guidance-Explanation)</u>** [Mom’s troubleshooting with her son.]

Scott: Wait, don't these look like they're uneven? [pointing to the given picture (see Appendix B-Challenge One] Is this? (***Problem Scoping-Problem Definition*** & ***Optimization-Evaluation)***

Mom: You think so? (**<u>Soliciting Information-Prompting</u>**)

Scott: I'm just ... [starts thinking and manipulating with the rollercoaster to find the problem.

After a few minutes, he decided that he did not want to the warm-up challenges and took out the two towers he made.

Example 2. As they were building the rollercoaster, Mom directed the plan. However, after Scott disagreed, she disengaged from the activity by not doing and saying anything, until the child talks to her. She then re-engaged by providing confirmation and continues by encouraging Scott to identify a problem in the design (the location of the tunnel). Mom told him, "Okay, so now we need to build, going around here." (**Providing Guidance-Direction**) Scott disagreed by nodding. Mom responded, "Okay, whatever you want to (**Disengagement**).

Scott worked on his design for a few minutes and then said aloud, "A little bit shorter. Right (***Optimization-Testing & Troubleshooting***) Umm. I have to name it too." Mom showed the excitement and said, "Oh, do we? Okay. Super Crazy?" (**Affirmation-Confirmation**). Scott says, "nope!" Mom changed the conversation and pointed out to a problem, "You know, this thing [tunnel]'s moving here. So maybe we need to take it out." (**Providing Guidance-Direction**). However, they engaged in the conversation below as Scott argued why that is not a problem.

Scott: No! It's the Leaning Tower of Pisa and moves (He made a connection to the real-world experience)

Mom: Yeah, it kind of is (**Affirmation-Confirmation**).

Scott: Wait, no, this is going to be the Leaning Tower of Pisa Future Rollercoaster.

Mom aimed to reengage her son to continue building and to keep him on track. She said, "I was thinking maybe we could just use a longer [Tunnel]. Okay. I think we need a longer." (**Providing Guidance-Suggestion**)

Scott: Pisa Tower?

Mom: Yes. I like the name (**Affirmation-Confirmation**). Going back to this (**Reengaging the child**). I think we need a longer one here (**Providing Guidance-Suggestion**).

Scott: Okay. Let’s try to move the tunnel (***Optimization-Troubleshooting***).

Then he took out the tunnel and moved it to somewhere (***Optimization-Improving***), which the mom verbally disagreed with the placement, but did not provide any additional.

Mom: Nope (Providing Guidance-Direction).

Scott: It won’t go anywhere else

Mom: Okay (Affirmation-Confirmation).

Scott: But something’s really slowing it down [referring to the slide that goes under the tunnel) (*Optimization-Troubleshooting*).

Mom: I think this piece [referring to the slide which goes under the tunnel] needs to be lower because I think it's just too tight here. So get a longer, big piece [Tunnel] (Providing Guidance-Suggestion) (*Optimization-Troubleshooting*).

She grabbed a bigger tunnel to make the changes (<u>**Assisting-Building**</u>). Scott raised his voice and did not let his mom make any changes, and he then provided explanation.

Scott: Oh, no. What are you doing? I think it’ll be fine. It's going to go down really lower. This is going to be low (***Optimization-Evaluation***) [makes changes to his rollercoaster] So now this piece is elevated [the tower before the tunnel] so that it'll go down (***Optimization- Improving & Evaluation***).

Design Description.

In the 58 minutes that Scott and his mother engaged in the activity, he built four different rollercoasters as solutions to two challenges, Warm-up Challenge 1 and Letter 2. I describe the solutions below.

Challenge One. As described before, Warm-up Challenge 1 provided a picture of a model of a rollercoaster and asked children to build the same rollercoaster. The rollercoaster had two towers in which one had five black posts and one had six black posts, one medium green slide track, an end track and a start track. Scott’s first design had two towers both with five black posts. The green slide track was attached to the start and end towers. However, what he was referring to as the end track was the start track. In the original model, both towers are in the same row. However, Scott had placed the towers in two different rows (Rows 2 and 4, see Figure 4.2). While Scott considered this rollercoaster as “the one”, he never tested it and was encouraged by his mother to rebuild/fix the rollercoaster.

Scott’s second solution had two towers with six black posts, the medium green slide and the start and end track (Figure 4.3). He had used the end and start track mistakenly in this solution too. In this solution, he misplaced the towers too. He placed one in row two and the second in row four. He tested his solution and it did not work. After trying a few times to find the problem he gave up and stopped working on this challenge. He then decided to start doing the last challenge (letter two).

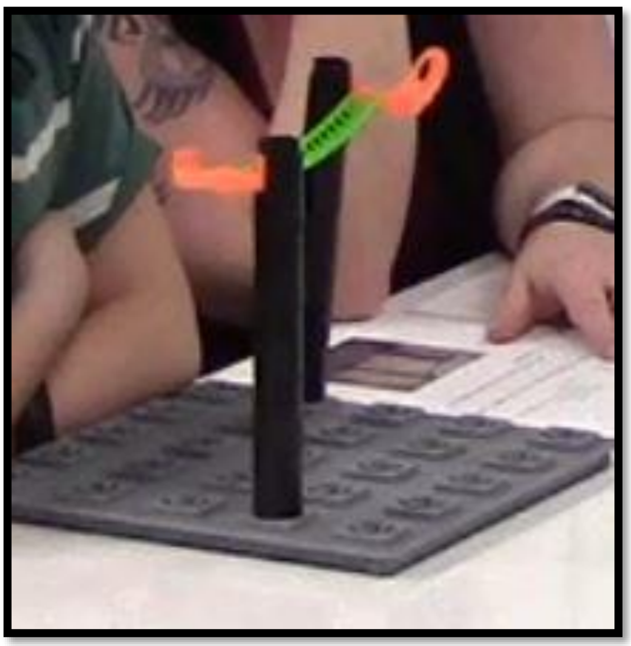

Figure 4.2 *Case 1, Challenge 1, Solution 1*

Figure 4.3 *Case 1, Challenge 1, Solution 2*

Letter Two. As mentioned before, in this letter, children received a letter asking them to design a roller coaster that is very exciting and makes children happy. Three criteria were mentioned including to have the roller coaster start very high and end low, to have a loop and to go under at least one tunnel. They are also asked about other features that make the rollercoaster exciting. The letter also points out the limited space for the rollercoaster which is only the gray base. The rollercoaster could go beyond the base but all the black posts must be built on the gray base. The letter asks children to imagine the fastest, loopiest and steepest rollercoaster and then build it.

Scott’s first solution met all the criteria mentioned in the letter. He used a loop and a tunnel. He started high, with a tower with six black posts and ended low with a tower with one black post that held the end track. The rollercoaster traveled towards four towers; two (two-black posts and one-black post long) were located in between the end and start towers. Aside from the loop, he used two slides, a short one and a long one, and had two turn tracks. He tested this solution and it did not work (Figure 4.4). The first problem the length differences between the two towers were shorter than what the functioning loop needed. Thus, the car would fall out of the rollercoaster. Also, the loop broke in the middle of his engagement and was taped. While the taped part was not actually interfering with how the car traveled through the loop, they both considered the loop as a non-working piece. The second problem was that the last two towers had the same length and the slide inclined upwards. He tested the prototype and realized that it wasn’t working. Because he had already done some troubleshooting and improved his prototype a few times before (see Figure 4.5). for the version of this solution before the final), he decided to stop working on this prototype.

Figure 4.4 Case 1, Letter Two, Solution 1

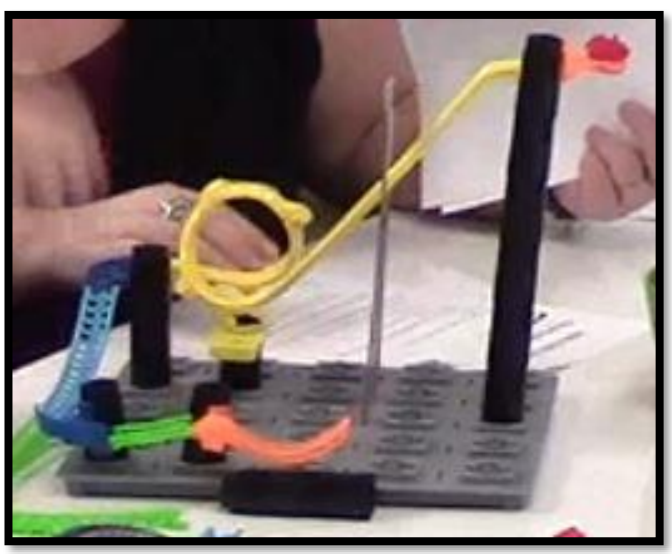

Figure 4.5 Case 1, Letter Two, Solution 2

The second and last solution that Scott designed is shown in Figure 4.6. While designing this solution he decided to not use the loop as he considered it as the problematic area and instead just built what he thought was exciting. He had met all other criteria by adding two tunnels and building a rollercoaster that started high (seven black posts long) and ended low (one black post long). He used all the black posts to meet the criteria. He and his mother interpreted the constraint of "all the black posts should be on the gray base" as they have to use all the black posts. He used a total of seven slides of all provided kind and used six turn tracks. He used the start and turn track correctly. The towers were placed on different rows across the gray base. The use of tunnels was interesting as one leg of both tunnels was off of the gray base. This way he got the most out of the space, but also meet the criteria of using tunnels.

The rollercoaster underwent many troubleshooting actions and revisions. However, the car did not travel smoothly at the end and stopped a few times along the way. Mom and Scott counted it as a success because they both believed that in the real-world, the car would not stop because of the quality of the material they would use.

In his interview, he described his rollercoaster and some additional features that he had in mind for his rollercoaster. According to him, the rollercoaster had an elevator that goes up the long black tower, stays there while there is music band playing (Figure 4.7). And then they come down to the first station where the car would go very fast. He described that he could have included stairs instead of an elevator, "but it would make it very hard for people,… like my mom.. she couldn't make it to up without the elevator [sic]. But anyways, when we can have an elevator that goes very fast, why should one have stairs… all those stairs." He talked about how the rollercoaster was exciting, "It should be fun because it's fast and very wide. So kids can ride all these long slides and three tunnels." His favorite part of his rollercoaster was the slide-tunnel, and his least favorite piece was the loop. Mom believed that he learned how to work with pieces spatially; how to put them together, which one to use comparing the long pieces and smaller ones, and where to place them on the gray base. She also thought that the activity was trickier than what he initially thought it would be.

Figure 4.7 Case 1, Letter Two, Solution 3

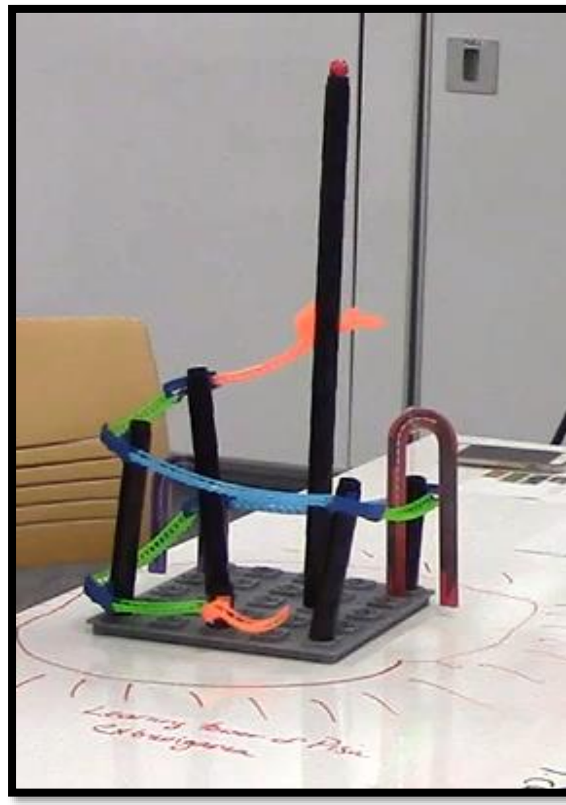

Figure 4.6 Case 1, Letter Two, Solution 3
(a different angle)

4.2.2 Case 2: John and Mom

Case Overview.

John, a 9-year-old boy with mild autism, participated in the study with his Mom. He attends fourth grade in an inclusive classroom in a public school. He has an individualized education plans (IEP) and a special education teacher sees him one hour a week. According to his mother, he has some challenging behaviors. Based on the Autism Spectrum Quotient (Auyeung et al., 2009) that Scott's mother filled out, he has a Systemizing Brain. He loves building things such as robots with LEGOs, and he is very good at making puzzles (500 pieces and up). His mother was confident that she knows how to engage her child in engineering-related activities and mentioned that they do daily and weekly projects that that allow him to use his designing, creating and building skills.

He engaged in the activity for 52 minutes. He was able to complete all the challenges and build a rollercoaster for each of them. His mother played an important role in directing him throughout all the activities and re-engaging him if he became disengaged and/or was frustrated. He engaged in all the engineering design practices.

Case Findings Summary.

While doing the activity, John showed evidence of engaging in all the engineering design phase with and without the help and support of his mother. The summary of the findings below is categorized into engineering design phases. In each category, I present the synthesis of finding for John's engagement in the engineering design phase and the parental facilitation strategies. I also share some examples for each category. Although the findings are organized by phase, the design process was very iterative and not linear, where he would not engage in these phases back and forth and not in any specific order. To read more, Appendix G includes the complete case narrative which includes a detailed narrative of all the scenes and the child-mother's interactions (i.e. what they said and did), and all the codes associated to their interactions.

Problem Scoping.

Child Engagement. I observed evidence of John engaging in both actions of problem scoping, problem definition and information gathering. His engagement in problem scoping mostly happened at the beginning. However, especially as the challenges got more complex, he continued to expand his understanding of the problem throughout the activity. He showed evidence of problem definition by reading/re-reading the problem statement at the beginning, restating what the problem was asking, and identifying the constraints and criteria specified in the problem statement. He also considered some new aspects of the problem by adding and considering meaningful context to the problem and finally taking different perspectives into account when scoping the problem. He gathered information about the problem by extensively exploring the pieces individually and how they connected to each other, especially during the warm-up challenges. Doing the warm-up challenges helped get a good understanding of the problem and the materials he could use. Moreover, his information gathering activities included asking questions about the specification of the problem, gaining science knowledge, and making connections to his previous experiences.

<u>Parental Facilitation Strategies</u>. Scott's mom facilitated his engagement in problem scoping throughout the activity using several strategies. She provided guidance through different forms of direction, explanation and modeling. She also solicited information by asking prompting questions and also confirming. Finally, she provided affirmation in forms of encouragement and confirmation.

Examples.

Example 1. While John was very excited about building a rollercoaster after building the first one, mom helped him gain more understanding of the problem by directing him to first read the challenge, asking prompting questions and providing guidance and confirmation.

Mom gave him the challenge and told him that he has to work on the challenges first (**<u>Providing Guidance-Direction</u>**). John read the challenge (***Problem Scoping-Problem Definition***) and said "Okay". He started building a new solution using the rest of the rollercoaster he built previously. Mom facilitates the activity by initiating the conversation:

Mom: Do you know what you have to do? (**<u>Soliciting Information-Prompting</u>**)

John: Steeper (***Problem Scoping-Problem Definition***)

Mom: Do you know what steeper is? (**<u>Soliciting Information-Prompting</u>**)

John: Yes [He then illustrates what steeper means by putting his hands in an angel and moving from high to low and making the sound of a crashing airplane.] (***Problem Scoping-Problem Definition***).

Mom: [while nodding, bends her arm into an angle (**<u>Providing Guidance-Modeling</u>**)] Yes, (**<u>Affirmation-Confirming</u>**) it needs to have an angle (**<u>Providing Guidance- Explanation</u>**).

Example 2. Mom handed the letter to John and asked him to read it aloud (**<u>Providing Guidance-Direction</u>**). He looks at the letter very briefly and says, "Challenge accepted! I know what to do." (***Problem Scoping-Problem Definition***). Mom then read the letter and shared some main points of the challenge with her son, "Hey, they are asking you to start very high and end low." (**<u>Providing Guidance-Explanation</u>**) John showed his understanding of the criteria, "and a loop and a tunnel." (***Problem Scoping-Problem Definition*****).** John then explored the material and selected the loop and a tunnel, (***Problem Scoping-Information Gathering & Problem Definition*****)** and he said, "I don't think I can do it. Mom can you help me with this, I don't think I can do it." (***Collaboration Requested***) Mom nodded and said, "You can do it and I'll help you buddy." (**<u>Affirmation-Encouragement</u>**). Mom then continued providing guidance by saying, "John, all the posts have to be on this gray thing. But the rollercoaster can be bigger (**<u>Providing Guidance-Explanation</u>**) [modeling it by her hands] (**<u>Providing Guidance-Modeling</u>**)" John responded, "Ha, Okay" (***Problem Scoping-Problem Definition***).

Example 3. Mom and John had many conversations about the specifications of the problem stated in Letter Two. In one instance, after a while of building, adding and removing pieces to the prototype, the loop fell down and broke apart. As mom was assembling the loop, John worried about not meeting criteria of having a loop.

John: Do you have a spare [Loop]? [Asking the researcher]

Mom: Even if they don't, we will make this.

John: No, it says a loop, we need a loop. (***Problem Scoping-Problem Definition***)

After Mom assembled the loop and gave it to John, she asked him to think about his previous experiences with rollercoaster which helped him with scoping the problem.

Mom: Think about all the rollercoasters that we have been on (**Soliciting Information-Prompting**)

John: They always go up and then start very high. And then [go] fast." (***Problem Scoping-Problem Definition & Information Gathering***)

Mom: But if you're starting high up already.

John: But It says you can start very very high (***Problem Scoping-Problem Definition*)**

Mom: It just says, you have to start very high and end very low (**Providing Guidance-Suggestion**).

Solution Development.

Child Engagement. I observed evidence of John engaging in all three actions of Solution Development: idea generation, decision-making and modeling/prototyping. As the challenge got more complex, going from the well-structured (Challenge One) to the ill-structured, their engagement in the engineering design phases got more meaningful and purposeful. Across all the challenges, while designing and building his solutions, he exhibited different idea generation and decision-making behaviors. He engaged in idea generation by generating one idea, but brainstorming several components and features of that idea and sharing strategies to build those features. The behavior of generating sub-ideas was evidenced through John's conversations with his mother as well as his actions, nonverbal cues and gestures, and additional components to the solutions he built. He most often exhibited the decision-making behavior of selecting a piece among different pieces or selecting a combination of pieces for a component/section of his solution.

It is important to mention that Solution Development was the design phases that took most of John's time as this phase had overlaps with the other two phases. His engagement in Solution Development, while helped him physically build a solution, also facilitated his understanding of the problem and the materials to be used in all the challenges. He also constantly was optimizing his solution while prototyping. Thus, drawing a clear boundary between the phases was not always possible.

<u>Parental Facilitation Strategies.</u> Mom's involvement was very evident during this phase. She supported Scott's engagement in this phase using several strategies. She provided guidance in the form of direction, explanation and suggestion. She also assisted in building and offered help verbally several times. She solicited information through prompting questions, and provided affirmation through confirmation and encouragement. Finally, she had many purposeful disengagements that allowed her son to generate ideas about the components of the solution and build them while making a lot of decisions. Overall, John's facilitation would start with providing the least guidance and implicit prompts and when necessary the engagement would shift to a more involved role like supervising, directing and offering assistant in building,

Examples.

Example 1. In challenge three, John was building a rollercoaster that could turn the car before it stopped it. He planned to reuse that rollercoaster, and Mom confirmed his plan but disengaged from the activity; she became hands-off and instead observed (**<u>Disengagement</u>**). He moved both towers across the base and then built the third tower in the middle of them (***Solution Development -Idea Generation & Modeling***). He attached the turn track to the middle tower and to a slide, and then attempted to connect all the other towers to this tower. He tried a few slides, by putting them next to the towers and deciding if they fit or not (***Solution Development -Decision Making***). He then added two black posts to a tower and removed the slide and the turn track, attached a longer slide to the turn track and to the first tower (***Solution Development -Idea Generation, Modeling and Decision Making***). He then asked help from Mom.

John: Can you help me? (***Collaboration***) There you go never mind… No I need, We need something to hold this [pointing to the slide that is attached to the turn track and should be attached to the middle tower] (***Solution Development -Idea Generation***).

Mom: I don't think this works this way, dude [pointing to the turn track that is flipped] (**<u>Providing Guidance-Explanation</u>**)

John: Never mind. This holds it (and leans the turn slides on the tower).

Mom: Turn it around, it is the other way round (**<u>Providing Guidance-Direction</u>**)

Mom handed John a different turn track (**Assisting-Building**). John looked at it, rotated it and replaced it with the other turn track (***Problem Scoping-Information Gathering; Solution Development -Idea Generation and Modeling & Optimization-Troubleshooting***), and moved on to build a different component.

Example 2. While John was working on his prototype, Mom helped him with building when she noticed a flaw in his rollercoaster, but followed up with a suggestion or a prompting question. She took out one of the towers (**Assisting-Building**) and provided suggestions (**Providing Guidance-Suggestion**), "I wonder John, what if we move this to here…" John cut Mom's conversation and said, "No. That looks good there. No, Leave it! (***Solution Development-Decision Making***)" Mom added one piece to the tower and left it where John asked (**Assisting-Building**). Mom asked prompting questions to help John stay engaged in the activity, as he tried different pieces on the prototype (***Solution Development -Idea Generation, Decision-making &*** **Modeling/Prototyping**). He moved all the pieces one row back and then Mom moved a short tower closer (**Assisting-Building**) and asked, "How do you think we can connect these things (**Soliciting Information-Prompting**)?" He looked for a slide that could be connected to the pieces and attached it (***Solution Development -Decision-making & Modeling/Prototyping***). He then looked at the material, grabbed a tunnel and said, "they need a tunnel." and added it to the rollercoaster (***Problem Scoping-Problem Definition & Solution Development-*****Modeling/Prototyping**). John looked at the rollercoaster thinking. Mom pointed to the parts that are not connected, and said, "What pieces do you think can be used here?" John took out the long tower and moved it one square (***Solution Development - Modeling*** & ***Optimization-Improving***) Mom encouraged him, "oh, right." (**Affirmation-Confirmation**), and she took out one black post under the loop and said, "Maybe if we make it shorter here." (**Assisting-Building & Providing Guidance-Suggestion**). John tried to connect them together (***Solution Development - Modeling & Optimization-Troubleshooting***) while Mom thought that the piece would not fit there (**Providing Guidance-Explanation**). He insisted that it would, but moved one more tower to connect them (***Solution Development-Modeling & Optimization-Troubleshooting***). Finally, he asked the researcher for help, "We are very close to be done, but this one piece doesn't connect to the whole things." (***Optimization-***

Troubleshooting). The researcher added a very small slide and connects them together. Mom said, "snap these final pieces together." (**Providing Guidance-Direction**). He did it and he shouted, "Done!"

Optimization.

Child Engagement. I observed evidence that John engaged in all actions of Optimization throughout the challenges. During the warm-up challenges, while he engaged in optimizing the solution as he was building his solutions. He showed evidence of mental simulation to see how the solution works, and at times he identified a problem/flaw within parts of his solution. However, most of John's engagement in Optimization happened as he was evaluating his design towards the end. He also physically tested his design, not only when the solution was completely built, but also as he was building his solution by testing sub-parts and different components of his solution. He engaged in troubleshooting very often, which resulted in improving his solutions and/or refining his ideas. Finally, in multiple instances, he evaluated his design against different criteria and problem specifications.

Parental Facilitation Strategies. John's Mom used a combination of strategies to facilitate John's engagement in Optimization and design evaluation. She made sure to disengage and provide enough space for her son to identify the problems and find a remedy, and improve the prototype on his own. However, at other times, she prompted John implicitly and explicitly to make him realize how he was misusing materials and recognize flaws within his prototypes. She provided guidance through explanation, suggestion, direction and assessment. She assisted both verbally and by building with him which resulted in Optimization. Finally, her affirmation also effectively helped John not get disappointed and discouraged and continue to troubleshoot and optimize his solutions.

Examples.

Example 1. During the first warm-up challenge, John grabbed a green slide track and attached it to the start track (on the first tower) (***Solution Development - Modeling/Prototyping***). He tried to attach it to the end track (on the second tower) but realized that the slide was small to be attached to both towers (***Optimization-***

Troubleshooting). Then, John grabbed another green slide and attached it to the end track and tried to put both slide tracks together (***Solution Development -Idea Generation & Optimization-Improving***). He tried to connect them together, but he could not. Mom offered help without any physical involvement which resulted in the conversation below:

Mom: Let me know if you need any help." (**<u>Assisting-Verbally</u>**)

John: I think that should be orange (referring to the green track on the pictures) (***Optimization-Troubleshooting***).

Mom: Orange? What do you mean? (**<u>Soliciting Information-Prompting</u>**)

John: I think that should be large (***Optimization-Troubleshooting***).

Mom: Ohh. Yes. But we have large, medium and small of the green (**<u>Providing Guidance-Explanation</u>**)

Mom grabbed a larger track and gave it to him (**<u>Assisting-Building</u>**). He tried it but he was not able to attach it either as the track was larger than what it should be (***Solution Development -Modeling/Prototyping***). Then, he looked at his design, rotated it and moved the end tower one square (***Optimization-Troubleshooting & Improving***). He attached the large slide to the start track (***Solution Development -Modeling/Prototyping***). But he could not attach the slide to end tower [Because he rotated the tower while moving it]. He looked at the tower, and whispered, "oh, it was upside down, (***Optimization-Troubleshooting***)" and he fixes it (***Optimization-Improving***). Mom cheered and said, "You got it, good job." (**<u>Affirmation-Encouragement</u>**). Mom suggested him to test the design (**<u>Providing Guidance- Suggestion</u>**). He tested the rollercoaster and it worked (***Optimization-Testing***). Mom cheered for him (**<u>Affirmation-Encouragement</u>**). John turned to the researcher and explained, "I couldn't do it the same as the picture, but I moved the tower to the next spot and worked. I think they used a wrong slide here." (***Optimization-Evaluation***)

Example 2. During the last challenge, while John was completing his design as the solution, Mom said, "I am thinking that we need to make this [tower] higher, then higher and then higher. And…" (**<u>Providing Guidance-Suggestion</u>**). John disagreed, "Almost done. It looks good to me." (***Optimization-Evaluation*)**. Mom said, "Okay, agree! Let's make some final changes only" (**<u>Affirmation-Encouragement</u>**. They both make some minor changes to the rollercoaster (***<u>Solution Development -Modeling/Prototyping</u>***). John said by looking at the researcher, “we’re done, I think. It starts really high, it ends really low, then loop and tunnel.” (***Optimization-Evaluation***). Mom suggested that they test it to see if it works. John tested it (***Optimization-Testing***) and they saw that the car stops in the middle of its way (***Optimization-Troubleshooting***). John looked at his mom and said, “I think I know why.” (***Optimization-Troubleshooting***). He added some black posts around the rollercoaster (***Solution Development -Idea Generation & Modeling***) and explained his new addition.

John: If it falls down this keeps it. It is safe (Problem Scoping- Problem Definition; Solution Development -Idea Generation & Optimization-Evaluation)

Mom: Is this going to solve the problem? (<u>Soliciting Information-Prompting</u>) I think we need to make everything higher (<u>Providing Guidance-Suggestion</u>)

John: Nope. Why?

Mom: Okay coming back to the original problem, I think we need to make this higher, then this higher to make this higher, because we need to use gravity. [referring to the towers one by one] (<u>Providing Guidance-Suggestion & Explanation</u>) (Optimization-Evaluation)

John: No. I think we need to make this higher. [referring to the middle tower]

He took apart the loop and pieces in the middle and added black posts to the middle tower. He then grabbed and looked at the loop, and said, “That’s it.” And then he left all the stuff on the table. Mom, however, built the part with the loop that previously made him frustrated, (<u>**Assisting-Building**</u>) and then she guided John using her gestures, “what do you think would happen if it turns this way and then goes wider? You know what am saying?” (<u>**Providing Guidance-Suggestion & Modeling**</u>). This question reengaged John and he moved some of the pieces following Mom’s suggestion (***Solution Development - Idea Generation &*** **Modeling/Prototyping**).

Design Description.

In the 52 minutes that John and his mother engaged in this activity, he worked on all the given challenges and built four different rollercoasters in total.

Challenge One. In Challenge 2, John was asked to build the same rollercoaster that was given in the challenge. The rollercoaster had two towers with one piece different in height and a medium green slide track was attached to it. Both towers were in the same row.

John first built the two towers, in the same row (Row #3) and with the same height (6 & 5) depicted in the model picture. He used a slide with the same color but longer than he was supposed to use. Using a longer slide was the reason he moved the first tower one square further. Therefore, the distance between the two towers was longer than depicted in the model. He acknowledged that he used a different slide, stating that the picture is wrong that he had to move the tower to build it. He used the same number of pieces shown in the picture. The rollercoaster worked (Figure 4.8).

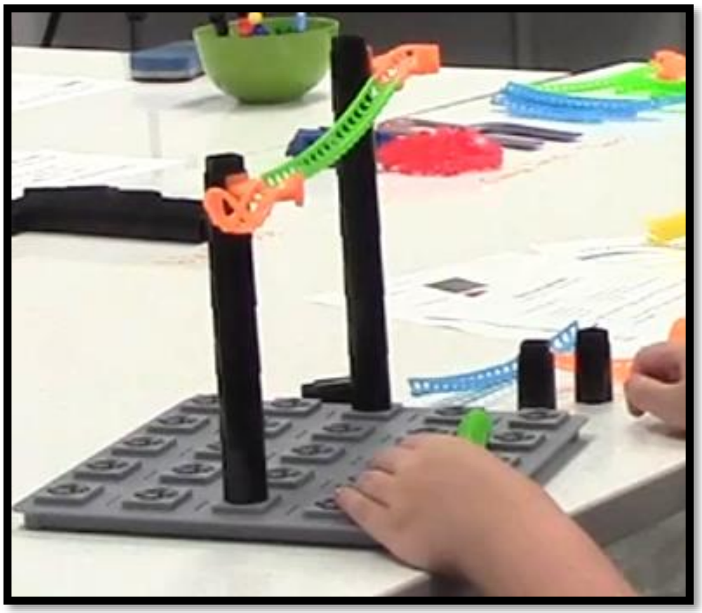

Figure 4.8 Case 2, Challenge 1, Solution *1*

Challenge Two. The second challenge asked John to build a rollercoaster steeper than the first one. The challenge did not have any pictures of a model, but provided two hints: (1) try different slides, (2) try a different number of black posts. Following the second hint, he built the third tower and made the first tower higher. However, he used the same slide as he used in the previous challenge. Therefore, in this challenge, he did not use a variety of pieces, but more pieces.

The rollercoaster was steeper than the first challenge and he emphasized that the rollercoaster is steeper. He tested it and it worked.

Figure 4.9 Case 2, Challenge 2, Solution 1

Challenge Three. In this challenge, John was asked to build a rollercoaster that would make the coaster car complete a turn before it stops. He designed two solutions for this challenge. The first solution (Figure 4.10) had four towers which started from the highest and ended with the lowest. The first tower was eight black posts long, the second was six black posts long and the next two were five black posts long. The towers were located on two different sides of the gray base. He used two slide tracks, a turn track, and the start and end track. In his design, he did not use the expected way of attaching the turn track to a black post of a tower. However, he built two towers in the middle of the start and end tower, and leaned the turn track on one and one of the slides to the other one. This helped the rollercoaster to not break apart (Figure 4.10). This rollercoaster met the criteria mentioned in the challenge. It turned the car before it stopped.

However, it stopped before arriving to the end track. John was satisfied with his design as he acknowledged that “it [the car] turned before it stopped”.

John’s second solution was an improved version of the first solution. The solution was very similar to the first one, with four towers, two slides and a turn track. The only difference was the length of the end tower was shortened by one black post (Figure 4.11). This change made the coaster travel all over from the beginning to the end track.

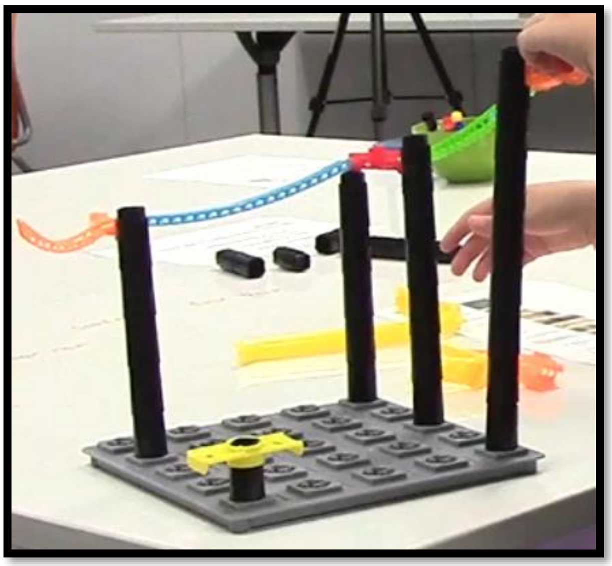

Figure 4.10 Case 2, Challenge 3, Solution 1

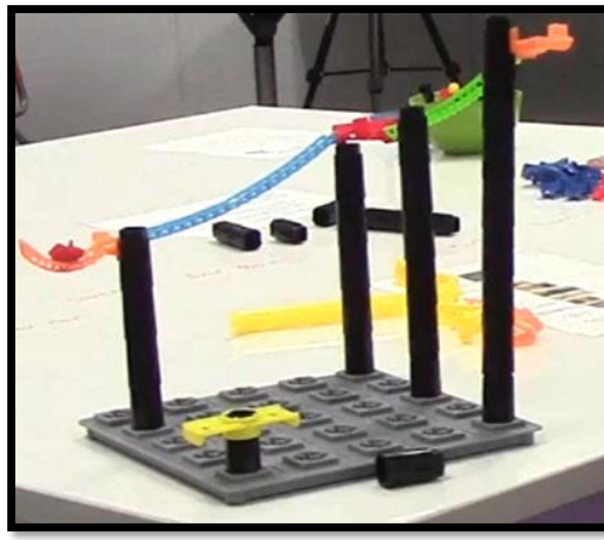

Figure 4.11 Case 2, Challenge 3, Solution 2

Letter Two. In this challenge, John was asked to read the second letter from the CEO of the local amusement park. In that letter, the CEE’s request was mentioned again and the criteria and constraints for building the rollercoaster were stated. The criteria included (1) to start very high and end low, (2) to have a loop, (3) to pass at least one tunnel. The letter also stated that children visited the amusement park had asked for a very exciting and fun rollercoaster.

John used a variety of pieces in his first solution. He used black posts, start and end tracks, loop, two turn tracks, two green slides and a tunnel. His solution also met the mentioned criteria in the letter including a tunnel, a loop and starting high and ending low. The start tower had seven black posts and the end tower had one. He also talked about how his rollercoaster is fun and exciting and also added safety a criterion to his design. He used two black posts next to the green slides and stated that this makes the rollercoaster safe (Figures 4.12 & 4.13). However, the rollercoaster did not work. The car stopped in the middle of its way as the height of the towers holding slides were all the same.

His second solution was the improved version of the first solution (Figures 4.14 & 4.15). After several trial and error, and with the help of his mother and the researcher, he was able to troubleshoot and improve the rollercoaster. In this design, he made the two longer towers by adding one black post to each, so they were longer than the end track. Also, he switched the small green track to a pink track (which is the smallest slide track). This rollercoaster worked.

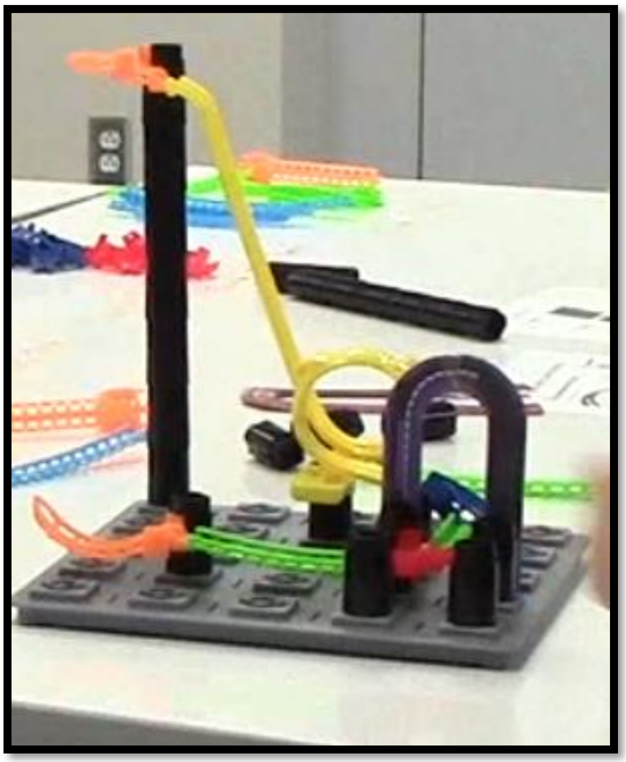

Figure 4.12 Case 2, Letter Two, Solution 1

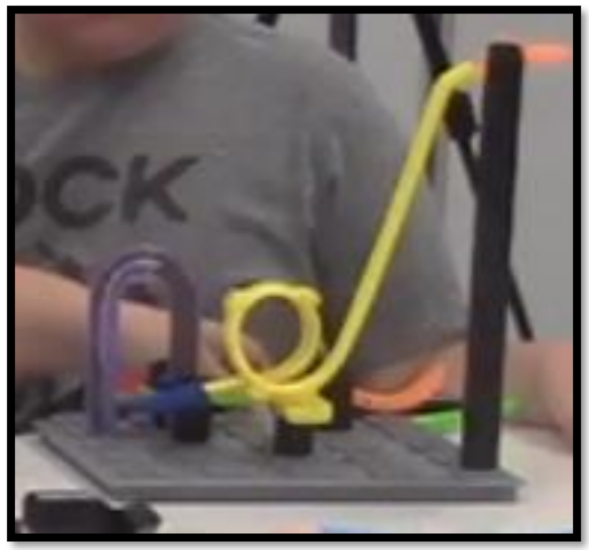

Figure 4.13 Case 2, Letter Two, Solution 1 (a different angle)

During the interview, he shared his experience of making a rollercoaster. His most favorite part was to make the rollercoaster go down fast, and all the slippery stuff. He believed all the pieces were fun, but when they were put together they were even more fun, “like the tunnel and the loop and all the slides, all together, they [are] fun.” He also adds an overall feature, “this should be a themed park. And have lighting. It would be fun.” With his mother, he also talks about that rollercoasters need electricity to be powered. He wondered about if rollercoasters are built by engineers in real life, and he learned that someone, an engineer, is out there who has a job of building rollercoaster. He said “engineering is building stuff and trying to figure out how you make it and make your best”.

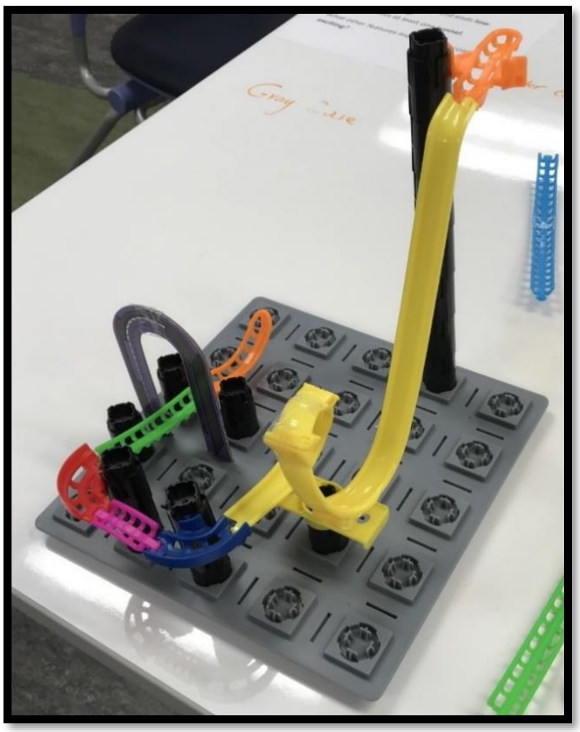

Figure 4.14 Case 2, Letter Two, Solution 2

Figure 4.15 Case 2, Letter Two, Solution 2 (a different angle

4.2.3 Case 3: Tom and Dad

Case Overview.

Tom was a nine-year-old in the 4th grade. He came to the study site with all his family members including his mother, father and two sisters. However, he engaged in the activity with just his father for 59 minutes. At times his older sister (Anne, 10-year-old) also engaged by making comments to her brother. He was very independent and attempted to do self-exploratory work by identifying his own challenge. Throughout the activity, he shared his thoughts naturally through think-aloud. His father played a role in his engagement in engineering design practices, even though Tom was trying to be work independently. He engaged in the first two challenges, skipped the third one and moved to the last one. Before reading letter two, for 30 minutes he built his own rollercoaster (i.e. not in response to any of the challenges). Therefore, he did not get enough time to work on the last challenge.

Case Findings Summary.

Problem Scoping.

Child Engagement. I observed evidence of John engaging in both actions of problem scoping, problem definition and information gathering. His engagement in problem scoping happened throughout the activity. He showed evidence of problem definition by reading/re-reading the problem statement at the beginning, restating what the problem is asking, and identifying the constraints and criteria specified in the problem statement. He also considered some new aspects of the problem by adding and considering meaningful context to the problem and finally taking different perspectives into account when scoping the problem. From the very beginning he asked questions to understand the problem mentioned in the first letter and this continued even during the challenges as he referred back to the letter several times. Thus his engagement in problem scoping prepared him to design a bigger rollercoaster during the self-guided challenge he created. During the self-guided challenge, he continued to refer back to the letter, occasionally. He also gathered information about the materials while building and prototyping by exploring the pieces individually and how they connected to each other. Moreover, his information gathering activities included asking questions about the specification of the problem, gaining science knowledge, and making connections to the real world.

<u>**Parental Facilitation Strategies**</u>. Toms' dad facilitated his engagement in problem scoping throughout the activity using several strategies. He provided guidance through different forms of direction, explanation and modeling. He also solicited information by asking prompting questions

and confirming very often. Finally, he provided affirmation in forms of encouragement and confirmation.

Examples.

Example 1. Dad asked Tom to read the challenge (**<u>Providing Guidance-Direction</u>)** and Tom read half of the letter (***Problem Scoping-Problem Definition*)**. Tom paused and looked at the materials [possibly he is aiming to explore the materials (***Problem Scoping-Information Gathering***)], but Dad encouraged him to read the rest of the letter, "Go on." (**<u>Providing Guidance-Direction</u>).** He continued and read the last part of the letter aloud (***Problem Scoping-Problem Definition***). He then looked at the researcher and said, "Umm. Wait, wait, wait. So, I'm actually building a real rollercoaster? (***Problem Scoping-Problem Definition***). The researcher confirms that he is building the model for a rollercoaster, using this kit. He gets very excited and asks again, "But they are actually going to build it? Oh." (***Problem Scoping-Problem Definition*).**

As Tom got excited about the authenticity of the activity, Dad engaged him in the task, by having a conversation with him.

Dad: What do you think, Tom? (Soliciting Information-Prompting)

Tom: That's cool.

Dad: Yeah? (Affirmation-Confirmation)

Tom: That's something I didn't know (Problem Scoping-Problem Definition)

Dad: Yeah. Let's build this then!

Dad: Okay. So before we jump into the actual challenge, we have some warm-up challenges. It says to get to know the material (Providing Guidance-Explanation) You want to read the first one there, Tom? (Providing Guidance-Direction)

Tom: What? .... I was thinking I could start this at the very top. Start the thing at the very top (Solution Development -Idea Generation) [As he was saying this, he also grabbed a few black pieces and a start track, and attached them together.]

Example 2. As he was building his own rollercoaster during the warm-up challenges, Dad felt the need for him to explore the pieces more. He encouraged him to use other slides. However, with a new slide in mind, Tom decided to make a rollercoaster of his own and not follow the challenges.

Dad: So now you. How would that work? Can you examine this one [showing an orange slide with tunnel], and see how that one works? (**Soliciting Information-Prompting**)

Tom: Huh? It's like a big tunnel. Like they do at the water slides, you know? (***Problem Scoping-Information Gathering***)

Dad: I'm not sure how it works **(Student of the Child**) (Acting like a student of the child to help him figure out the slide works.)

Tom: We could also make this a water slide. Yeah? [looking at his dad and the researcher] (***Problem Scoping-Information Gathering & Solution Development - Idea Generation***)

Researcher: We can tell Hannah, maybe if she's interested in that, that's a good idea. I like it.

Tom: We can make a rollercoaster and a water slide. So, this, the first one I'm going to make is obviously a rollercoaster. And the next one's going to be a water slide (**Providing Guidance-Explanation**)

Researcher: Okay. Yeah. Try it (**Affirmation-Confirmation**) That should be fun (**Affirmation-Encouragement**)

Tom: Yeah, let's do that.

After a while of building the rollercoaster of his own and saying his plans aloud, Dad suggested that he explore more pieces, "okay. See if you can get that piece to fit to it" (**Providing Guidance-Suggestion**). Tom got the orange slide (orange slide with tunnel), He rotated it and tried to attach it to the start track. He then asked for more information about the piece (***Problem Scoping-Information Gathering***).

Tom: Well look, it's a tunnel. But what do these tunnels do? (***Problem Scoping-Information Gathering***)

Dad: What do you think? (**Soliciting Information-Prompting**)

Tom: Oh. Well. Okay. I'll try it.

As Tom got very frustrated, Dad provided another suggestion. He pointed to another tower, "What if you put the curve right here, in this one? (**Providing Guidance-Suggestion**)" But Dad found Tom not looking at him and was still trying to attach the turn track in a wrong way, "Ah, It's not even going in there." He got a turn track from the table and a tower and directly modeled it for him. "Here. Let's put the curve (**Providing Guidance-Modeling**)."

He then gave a tower to Tom, so he could also try it. Tom gets excited. While trying to copy Dad and attach the turn track on the tower, “How did you do that? Uh Like that!” (***Problem Scoping-Information Gathering***), he then looked at the start track and saw the same pattern in the way the turn track and start track could be attached to the towers, “Ah, this is how this connects here?” (***Problem Scoping-Information Gathering***).

Solution Development.

Child Engagement. I observed evidence of Tom engaging in all three actions of Solution Development: idea generation, decision-making and modeling/prototyping. He exhibited idea generation behavior very often throughout the activity and in all the challenges. He would usually either share his ideas (and sub-ideas) and/or his plans to build that idea or just acknowledge that he had an idea and he knew what he wanted to do. Idea generation happened often happened at the same time that Tom was manipulating and exploring the pieces or as he was building a rollercoaster. He also engaged in decision making processes. He exhibited the decision-making behavior of selecting a piece among different pieces, selecting a combination of pieces for a component/section of his solution and deliberately selecting between sub-ideas of the solution. Tom naturally engaged in prototyping and modeling given the type of activity. Through this engineering design action, he also showed evidence of enacting Problem Scoping, Optimization and other actions of Solution Development.

<u>**Parental Facilitation Strategies.**</u> While Dad did not exhibit too much involvement, he used several strategies that helped Tom to do the challenges and engaged in engineering design. He disengaged from the activity to provide space for his child to build his solutions on his own. However, when needed, he would deliberately interact with him and facilitate the activity. He provided guidance in a form of direction, explanation and suggestion. He also assisted in building and offered help verbally several times, especially when Tom was frustrated in the last challenge. He solicited information through prompting questions and seeking explanations and confirmation and provided affirmation through confirmation and encouragement. Finally, he acted like a Student of Child to help him use his knowledge about the pieces and engage in building and prototyping.

Examples.

Example 1. He built a tower with two black posts, attached it to a start track and then added more black posts to that (***Solution Development -Modeling/Prototyping***). Then his sister, Anne, reminded him that he has to do the warm-up challenges, which he ignored. His dad suggested him to do the warm-up challenges. Dad realized that Tom was excited about building a real rollercoaster and the ideas he has. Thus, Dad allowed him to ask questions and express his idea, but then asked him to do the challenge. While Tom is building a rollercoaster, he engaged understanding the problem from other people's perspectives.

Dad: Can you start by going through these steps, Tom? (<u>**Providing Guidance-Suggestions**</u>)

Tom: Hold on just one second. I think I know what I'm going to do with the design (***Problem Scoping-Problem Definition & Solution Development -Idea Generation***) [He attached the long tower that he built to the gray base.]

Dad: You do? (<u>**Soliciting Information-Confirmation**</u>)

Tom: Yeah. I have a fair idea of what it's going to .. (***Problem Scoping-Problem Definition & Solution Development -Idea Generation***)

Dad: What's it going to look like? (<u>**Soliciting Information-Prompting**</u>)

Tom: [Using his gesture and language to describe his idea.] So, this is going to go down here a little bit. There can be loops, I guess (***Solution Development -Idea Generation***) Would people usually like loops? (***Problem Scoping-Information Gathering)*** [As he is exploring the loop by rotating them and checking how it can be attached to the other pieces.] (***Problem Scoping-Information Gathering***)

Anne: Yes. I would.

Dad: Yeah. Most people like loops (<u>**Affirmation-Confirmation)**</u>

Tom: But I'm not even going to ride on this. I'm not going to ride my own rollercoaster, I guess..

Dad: That's fine (<u>**Affirmation-Confirmation**</u>) You can just engineer it (<u>**Affirmation-Encouragement**</u>)

Tom: Yeah. I don't think engineers really ride their own.

Dad: I'm going on that rollercoaster with Anne (<u>**Affirmation-Encouragement**</u>)

Tom then attached the pre-built tower with a few black posts and a start track to the gray base (***Solution Development-Modeling/Prototyping***). He places a loop side by side tower and compares their sizes (***Solution Development-Decision Making***). Then, he takes out two black posts from the tower and pushes the rest on the gray base. He thinks aloud, "Out these two." (***Solution Development-Idea Generation & Modeling/Prototyping***). He then repeats the side-by-side comparison of the loop and the tower, and thinks aloud, "Start with two. Yeah, it's got to be two." (***Solution Development -Idea generation***).

Example 2. After doing Challenge Two, Tom created his own challenge, even with his Dad asking him to continue the warm-up challenges. Tom told his dad to wait until he is done with building his own rollercoaster. Thus, Dad disengaged from the activity and started just observing (<u>**Disengagement**</u>). Tom used the previous prototype he built as the base and expanded that. Tom got up and looked at all the material he had, and grabbed some of the pieces and said, "Here's something I can do now." (***Solution Development-Idea Generation***) and attached it to the orange track (***Solution Development -Modeling/Prototyping***). And he continues, "How do I get these [the orange track and turn track] to stand up, though? (***Solution Development -Decision-Making & Idea Generation***). Do I just let them rest in peace on the thing, or does it ...Do I just let them rest in peace on the thing?" Then his orange slide came off from the start track. He tried to reattach the orange slide to the turn track, but he cannot (***Optimization-Troubleshooting***). He got frustrated and said, "Aah, Dad." Dad offered to help. "Let me see." (<u>**Assisting-Verbally**</u>). But Tom decided not let him help, "No I got it," and he attached some pieces together and then to the start track. He then grabbed the tower he made in the previous challenge, makes it longer and put it on the gray base (***Solution Development -Modeling/Prototyping***).

He is unsure of what he had to do next. He thought aloud about his plans, "So if I just let it ... So I just build something up, and just let it stay like this. [leaves the turn track leaning on the tower] Does that work? Or, is there some sort of trick? You have to connect them to this [the tower]? I don't know, Like this. Do we just let it do that, I guess? I don't know how to fit it on there. (***Solution Development -Decision-Making & Idea Generation***)." Dad provided an explanation, "So, this turns here. And so, do you think we can..." (<u>**Provide Guidance-Explanation**</u>). Tom says, "Oh, okay," and continues his work.

Optimization

Child Engagement. Tom engaged in all actions of Optimization throughout the challenges, as he was building the solution. Before prototypes was completely built, he tested components of his prototypes/solutions without physically running the coaster car on the rollercoaster by mentally running a simulation or manipulating with those components, also by physically running the car on those parts. Moreover, he tested the complete prototype by running the car on parts of the prototype or the entire the prototype. His engagement in troubleshooting was usually announced aloud as he would think aloud about the problems within his solution and ways to fix that problem. He showed evidence of identifying the problem, explaining what the problem was happening as well how to fix it. At times, he showed non-verbal cues using his gestures and facial expressions that provided evidence that he was trying to find the problem and fix it. His troubleshooting usually resulted in fixing and improving his solution, and in evaluating the workability of the prototype and if it met all different criteria and problem specifications.

<u>Parental Facilitation Strategies</u>. Tom's Dad was involved in facilitating the Optimization of the solution. The same as with the previous phases, Tom's Dad did often not get involved and provided space for his son to identify the problems and find a remedy, and improve the prototype on his own. However, he used a combination of strategies to facilitate his engagement in Optimization when needed. He prompted Tom implicitly and explicitly to make him realize ways he was misusing materials and recognize flaws within his prototypes. He provided guidance through explanation, suggestion and direction. When needed, he also assisted both verbally and by building with and for Tom to optimize the solution. Finally, his affirmations and assisting also effectively helped Tom's frustration, and also encouraged him to continue to troubleshoot and optimize his solutions.

Examples.

Example 1. During his self-guided challenge, he built a part of his rollercoaster that has two towers and a turn track attached to two other slides. Then, he aimed to test that part and he grabbed the coaster car. However, he used his hands and checked that part and then ran a mental simulation and without physically testing it he said, "Oh, wait, wait, wait, wait,

wait. Let's see if it stands still. It does stand still. (***Optimization-Testing***)" But he does not seem convinced that it worked right and possibly thought of a problem, and thus, he asked Researcher for more information, "Excuse me, is there something that I need to connect right here?" But before the researcher responded, Dad distracted Tom by suggesting "Maybe if you look at the guide and do the last warm-up challenge you will figure it out," (<u>**Provide Guidance-Suggestion**</u>). Tom responded to his Dad's question and then got back to building his rollercoaster. He explored the problem within his sub-solution by looking at the prototype and examining the pieces (***Optimization-Troubleshooting***). He then engaged in evaluating his design, "Well it did turn. Still has problem (***Optimization-Evaluation***)." Thus, he continued figuring out how to move on with his current design and how to solve the problem of connecting the tower to the turn track, and asks, "I'm just wondering, how do I fit this on here? Ah! (***Optimization-Troubleshooting***)." He took a look at his design and moves that pieces and changes a part (***Optimization-Troubleshooting & Improving***). He then tested the prototype to see if the two pieces worked together which they do (***Optimization-Testing***). Dad cheered and said, "Good job! (<u>**Affirmation-Encouragement**</u>**)**"

Example 2. Towards the end of the session, Tom had already mentioned that he was tired, and he wanted to come back the next day. Thus, he was rushing to build a solution to the last challenge (Letter Two), and was getting frustrated. In one instance, when Tom was not able to attach the loop to the rollercoaster, he got very upset and left the room. Dad decided to fix the rollercoaster and have Tom test it. Dad fixed the rollercoaster by attaching a loop and asked Tom to come in after few minutes (<u>**Assisting-Building**</u>), and they had the conversation below.

Dad: All right. Here, Tom, try it out! (Providing Guidance-Direction)

Tom: Ah, let me see this. Thank you. [He then tested his rollercoaster (Optimization-Testing)]

Tom: It's this. Wait, stop. Wait, wait, wait. We got to fix this, though. [points to the end track and last tower, suggesting that that's the problem (Optimization-Troubleshooting)]

Dad: All right, fix that, and then make a tunnel, too (Providing Guidance-Direction)

Tom: I know what I'm doing [while fixing the rollercoaster] (Optimization-Improving).

He improved the solution by adding a few things (***Optimization-Improving***). He tested the rollercoaster (***Optimization-Testing***). They saw that the rollercoaster did not work. He got upset and said, “This still won't work! Nothing ever will.” He then attempted to change the parts at the beginning. Dad engaged in a conversation to help him find the flaw within the solution which results in troubleshooting.

Dad: No, I wouldn't change anything right there (Providing Guidance-Suggestion) Where's the problem at? (Soliciting Information-Prompting)

Tom: I get this. I mean, I know what I'm doing. Ah! That is why I gave up! How retarded this is. It stops, until it's complete (Optimization-Troubleshooting) Ah! That's always when it stops! Here. (Optimization-Troubleshooting)

Dad: Where? (Soliciting Information-Prompting)

Tom: Right there! I don't get it! (Optimization-Troubleshooting)

Dad: Stops right there? Let me see [Dad tested that part.]

While Dad tried to fix the issue (<u>**Assisting-Building**</u>), but Tom decided to leave the activity at that point.

Design Description.

In the 59 minutes that Tom and his father engaged in this activity, he completed two warm-up challenges by building three different rollercoasters. He also engaged in a self-guided challenge and designed a big rollercoaster. Finally, he engaged in modifying his rollercoaster to fit the last challenge (Letter Two).

Challenge One. In this challenge, Tom was asked to build the same rollercoaster that was given in the challenge. The rollercoaster had two towers; one was shorter than the other one with one post (6 and 5 black-post height). A medium green slide track was attached to them. Both towers were in the same row. Tom first built the two towers at the same size (five black posts), and placed them on different rows and then quickly realizes that they on wrong rows, so he moved them to the rows depicted in the picture (Row # 3), and adds the start and end tracks and then slide.

He tested it and the car did not travel all the way to the end (Figure 4.16). He took out one black post from the end tower which leaves the tower with 4 black posts. The rollercoaster worked, but was shorter than the original model given in the challenge.

Figure 4.16 Case 3, Challenge 1, Solution 1

Challenge Two. Dad asked Tom to build a rollercoaster that is steeper. And he added one black post to the first tower of the previous rollercoaster to make it steeper. The rollercoaster has one tower that six black-post long and the second tower is four black-post long. The slide remains the same. The rollercoaster worked (Figure 4.17). Then, his father asked him to make it even steeper. He also read him the hint that he could use the other slides. He decided to add two more black posts to the tower and keep the rest the same. Since the slide did not get connected so he took one more out. He then had a rollercoaster with two towers of seven black posts and four black posts (Figure 4.18). He decided to make the rollercoaster even steeper. He built a rollercoaster with one long tower (eight black-post long) and a shorter tower (four black-post long) with a longer slide (Figure 4.19).

Figure 4.18 Case 3, Challenge 2, Solution 1

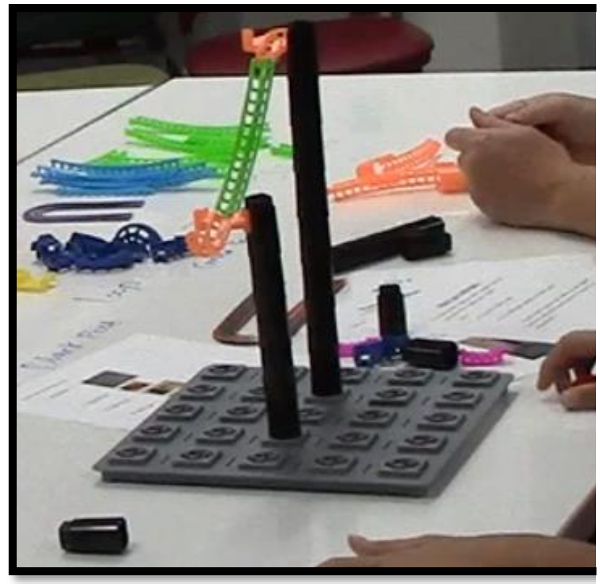

Figure 4.19   Case 3, Challenge 2, Solution 2

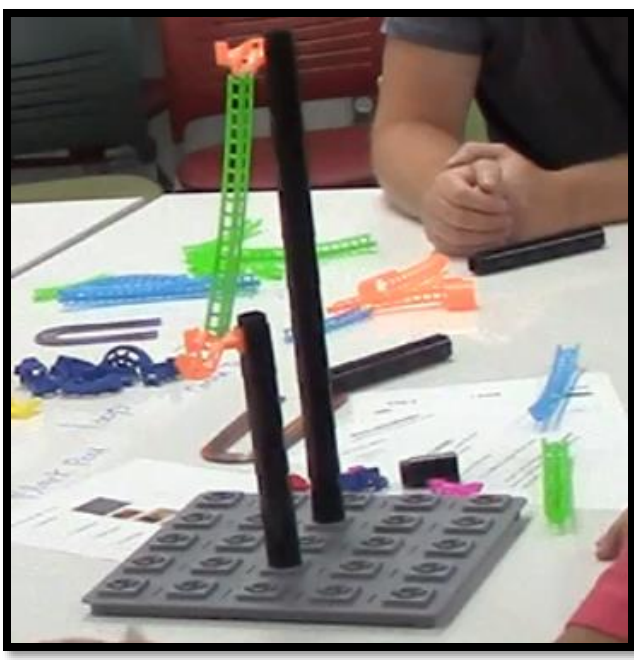

Figure 4.17 Case 3, Challenge 2, Solution 3

Self-Guided Challenge.

Tom engaged in a self-guided challenge to build something exciting. His solution after 30 minutes of work was a more complex rollercoaster with lots of pieces. The rollercoaster included seven towers with different lengths. The longest tower had seven black posts and the shortest had only one black post. He used five turn tracks, with both left and right turn function, the start and end track, and six slides with different lengths. Tom named the rollercoaster "Dragon's Tail." The rollercoaster worked smoothly.

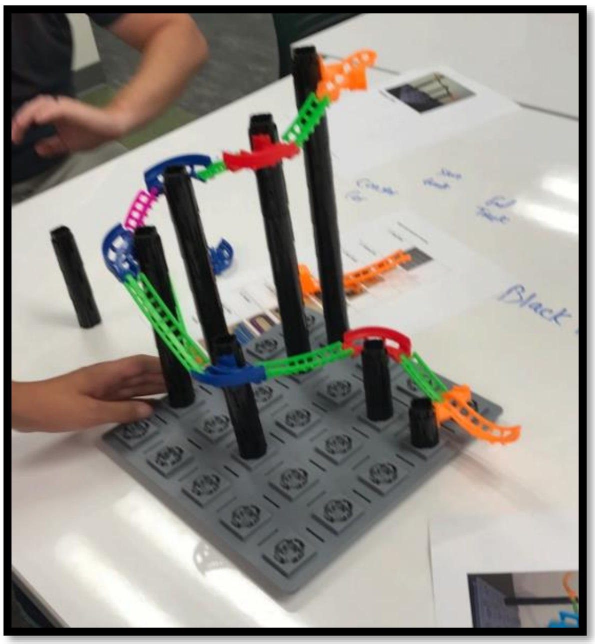

Figure 4.20 Case 3, Self-Guided Challenge, Solution 1

Figure 4.21 Case 3, Self-Guided Challenge, Solution 1 (different angle)

Letter Two. In this challenge, his dad read to him the second letter from the CEO of the local amusement park. In that letter, the CEE's request was mentioned again and the criteria and constraints for building the rollercoaster were stated. The criteria included (1) to start very high and end low, (2) to have a loop, (3) to pass at least one tunnel. The letter states that children had asked for a very exciting and fun rollercoaster.

With his father's conversation, he decided to add the criteria to the previous rollercoaster, Dragon's Tail. He had less than 10 minutes left to design that. While he worked very hard in collaboration with his father, he was not able to build a rollercoaster that actually worked. The first solution that they built included the first three towers and the attached slides of the previous rollercoaster, and a loop and very low end tower. However, the rollercoaster did not work (Figure 4.22).

Tom worked on the challenge for a short time. He modified the rollercoaster slightly by moving some of the pieces. The modified version of the rollercoaster had two tunnels, a loop and started high and ended very low. The rollercoaster could turn twice and had a few slides. However, it did not work (Figure 4.23).

He tried for the last time, making some changes to the structure before the loop. However, since he could not attach the loop, he decided to leave the activity. In Figure 4.24, we can see that had the rollercoaster been built, it could have met all the physical criteria (start high and end low, and having a loop and a tunnel). However, given the time limit and his tiredness, the rollercoaster was never built.

Figure 4.22 Case 3, Letter Two, Solution 1

Figure 4.23 Case 3, Letter Two, Solution 2

Figure 4.24 Case 3, Letter Two, Solution 1

5. DISCUSSING CROSS-CASE FINDINGS

In this chapter, I discuss the findings of the two main research foci and their associated research questions:

(1) Approaches children take to solve an engineering design problem.

- What engineering design phases (i.e. Problem Scoping, Solution Development and Optimization) do children with mild autism engage in?
- How do they engage in these engineering design phases?

(2) The support and scaffolding that parents provide during these engagements.

- What strategies do parents use to support their children's engineering design engagement?
- How do these strategies help children engage in engineering design phases?

I organize this chapter into two main sections: (1) Engineering design challenges, and (2) Engineering design activity as a whole. In each section, I discuss findings across all the cases to address both research foci. The first section is broken down into the challenges, ranging from the well-structured to the ill-structured problems. In each challenge, I have observed evidence of children engaging in all three engineering design phases: Problem Scoping, Solution Development and Optimization. Thus, I further organized each challenge based on these engineering design phases. I first describe how children engaged in these practices, and then share how parental strategies facilitated children's design engagement.

In the second section, I discuss the findings across all of the challenges by viewing the activity as a whole. I have organized this section into two sub-sections. The first sub-section characterizes ways children engaged in engineering design in this activity. I summarize the findings and then present similarities and differences among children's design engagement in this study and ways informed and beginning designers of different ages engage in design practices. In the second sub-section, I discuss the effective strategies parents used to engage children in different engineering design practices.

5.1 Engineering Design Challenges

This section is divided into the five challenges included in this study: Letter One (and Challenge Zero), Challenge One, Challenge Two, Challenge Three, and Challenge Four (called Letter Two). I discuss ways children engage in each challenge as the challenges differ in their structure, ranging from well-structured to ill-structured problems (Jonassen, 2000). Within each challenge, I will discuss ways that the children engaged in engineering design phases of Problem Scoping, Solution Development and Optimization. I will then discuss the strategies that parents used to help their children engage in different phases.

As a reminder, the pseudonyms of children in this study include Scott (Case 1), John (Case 2) and Tom (Case 3).

5.1.1 Letter One & Challenge Zero

The engineering design activity begins by reading the first letter. The letter is from the CEO of an amusement park, Hannah Noah, in which she shares her problem with children. The letter is aimed to provide a context for children and let them know what they are going to do in this activity. During this portion of the activity, children engaged in engineering design thinking by practicing Problem Scoping.

Problem Scoping: Child Engagement.

Reading this letter seemed to be effective in making all three children of this study excited about the activity and building a rollercoaster. However, very limited conversation happened after reading the letter in all cases; as a result, I was not able to capture much evidence of their in-depth Problem Scoping engagement. However, all three children showed some evidence of defining the problem Hannah has posed and also gathering information about the problem, including exploring the available materials. They all read the letter, showed some verbal and/or non-verbal cues of understanding the problem (e.g. nodding) and then started exploring the materials. For example, Scott acknowledged that he knew what he was going to build, which shows his understanding of the problem Hanna is proposing (i.e. building a rollercoaster). Tom, after reading the letter aloud, looked at the researcher and says, “Umm. Wait, wait, wait. So, I'm actually building a real rollercoaster?" which again shows his understanding of the problem. Even in the case of John who did not talk about the letter, his engagement in exploring the given materials can be evidence that he knew he was going to build something. Two of the children, John and Scott, engaged in exploring the materials after reading the letter. They explored the pieces given in the Material Guide, by grabbing each one by one, reading their names, or trying to see how each worked. Tom was so excited about building that he attempted to explore the pieces, but his father stopped him. However, shortly after, he explored the material not as a clear distinct step, but while building a rollercoaster.

Problem Scoping: Parental Strategies.

During this portion of the activity, parents effectively helped children engage in Problem Scoping by providing guidance, using directions and explanations and soliciting information. In all the cases, parents directly guided children to read the letter. John's and Scott's mothers handed the letter to their children and asked them to read it (Providing Guidance-Direction). Tom's father, on the other hand, made sure that Tom read the letter aloud and read it entirely. Tom got excited about exploring the pieces in the middle of the letter, his father reengaged him in exploring the letter with a prompting question such as "what do you think?"(Soliciting Information-Prompting). Tom shared his excitement about the activity by saying that it is so cool to build a rollercoaster, and his father encouraged him to build, "Yeah, Let's build this then!" While his father's follow-up conversation did not result in an in-depth comprehension and definition of the problem, it helped Tom to restate the main idea of the problem, (i.e. building a rollercoaster). Tom's father then restated the letter and explained to him that he had to explore the material first before he could build his rollercoaster. John's and Scott's mothers directly guided their children to explore the materials by pointing to the material guide and individual pieces (Providing Guidance-Direction). Additionally, John's mother asked prompting questions to help him explore how some pieces work (Soliciting Information-Prompting).

5.1.2 Challenge One

Challenge one provides children a model (i.e. picture) of a rollercoaster and asks children to build a rollercoaster the same as the model. The activity is well-structured as the solution is given. The aim of this activity is to get children to explore the materials; what the main pieces are (i.e. gray base, start and end tracks, black posts and the coaster car) and how they connect. Moreover, the challenge provides an opportunity for children to get to build a complete rollercoaster and observe how it works. During this challenge, children engaged in all of the engineering design phases, including Problem Scoping, Solution Development, and Optimization.

Problem Scoping: Child Engagement.

Since the design project statement of "build the rollercoaster you see in the picture" seems to be straightforward, children did not initially engage in any conversation to scope the problem. However, I observed behaviors associated with Problem Scoping enacted by the children. These behaviors appeared differently among the children and included reading the challenge, carefully looking at, analyzing the given picture (as data) and exploring the materials.

All three children defined the problem by reading the challenge statement. The statement conveyed a clear message to the children, and all of the children acknowledged that they knew what they should do, quickly after reading the statement. For example, John said loudly, "I know how to do this." They then looked at the given model. At first, looking at the model helped them understand what they were asked to build and then what pieces they could use. While no criteria were specified, children themselves realized that building "the same" rollercoaster requires paying attention to the variety of the pieces, number of pieces and where they are placed on the gray base. Throughout the activity, all three children clearly engaged in counting the number of pieces they needed and spotting the rows in which the pieces should be placed. For example, Tom counted how many spaces the two towers are apart on the model which helped him place the towers later.

At the same time that children were finding out what pieces they have to use, they were also gathering information about the problem. They engaged in exploring pieces, observing and discovering the differences between some pieces, especially those that looked alike, and how pieces could be connected to each other. For example, both John and Scott were confused about the start track and the end track; they misused them at the beginning and then they realized that they are two different pieces, with different functions. It should be noted that this exploring of material did not happen as a distinct step and for the purpose of gathering information to solve the problem. However, children engaged in this behavior as they were designing the solution. In many instances, exploring the materials did not just serve children’s engagement in Problem Scoping, but also other phases. Therefore, drawing a clear line between this action and other actions was not possible.

Problem Scoping: Parental Strategies.

In this challenge, children’s engagement in Problem Scoping was not facilitated by parents very often. In some instances, parents used strategies that resulted in defining the problem and exploring materials. John’s mother and Tom’s father directed their children to read the challenge (Providing Guidance-Direction). John’s mother did not engage in any conversations and provided space for John to engage in the activity at his own pace. On the other hand, Tom’s father, after asking his son to read the challenged, explained and rephrased the challenge statement for him (Providing Guidance-Explanation) to make sure Tom understood what he had to do and ensure that Tom was going to follow the instructions. Additionally, parents provided directive guidance and prompted their children to select and use the material they needed to design their rollercoasters (Providing Guidance-Direction & Soliciting Information-Prompting). For example, Scott’s mother prompted Scott to use the gray base, and John’s mother directed him to appropriately use the start track.

Solution Development: Child Engagement.

Children’s engagement in this phase of design was mostly evident through modeling and prototyping the design, and making decisions to select materials. Since the solution to the problem was given in this challenge, children did not engage in generating any new ideas and showed limited evidence of having a systematic plan to build the solution. For example, Tom engaged in the think-aloud process which showed his planning to build his rollercoaster using the structure he had previously built, “So let's do this. Then I'll need a higher one. Or I think this was the actual ... Actually, a little, just a little bit lower. This is... Down here. So, two spaces. It's actually this. So then I will continue with it. Now I just need two spaces.” In another example, Scott articulated briefly that he was building the rollercoaster using the picture, which may be a glimpse of evidence that he had made a plan for his design.

Modeling and prototyping happened in the form of building the rollercoaster using the building kit. Children began building the solution right after they read the statement; therefore this design action was observed very frequently and throughout the challenge. At the same time that children were modeling and prototyping, they engaged in making decisions towards what pieces they had to use to build the rollercoaster. They would choose a few pieces by comparing the given physical pieces with those that were used in the model (i.e. given picture). While building the rollercoaster, they kept selecting, adding and removing pieces.

The process of making decisions about what pieces to be used in the design was occasionally the same action as when children were understanding the problem and/or exploring the materials. For example, Scott, after reading the challenge, looked at the given picture and then looked at all the pieces on the table, grabbed a few pieces that seemed to be used in the model. He then compared the pieces closely with the picture and chose ones he needed. In this event, Scott defined the problem, explored the given material and made final decisions towards what pieces had to be used in the solution. Both John and Tom engaged in similar ways. Therefore, in this challenge, children's enactment in Solution Development overlapped with other design phases including Problem Scoping.

Solution Development: Parental Strategies.

In this challenge, parents did not facilitate children's engagement in Solution Development. They were mostly disengaged physically and only observed children when building the rollercoaster using different strategies (Disengagement). This disengagement, in all the cases, seemed to happen by purpose to provide children a space to work independently. In two instances, Scott's and Tom's mothers facilitated their children's engagement in planning and modeling respectively. At the beginning of the challenge, Scott's mother asked a prompting question to help him plan for his design, "how are you building this?" (Soliciting Information-Prompting). John's mother had engaged in assisting her child by giving him the pieces he needed per his request (Assisting-Building).

Optimization: Child Engagement.

Children engaged in this phase of design very often in this challenge. They constantly engaged in testing, troubleshooting, evaluating and improving their solution, in no specific order. The testing happened mostly when children had completed building their design. Children ran the car on the rollercoaster and observed if it worked. In this challenge, through this testing, children were also exploring how the rollercoaster, as a whole system, worked. For example, they all explored if the car should be pushed on the rollercoaster to run or if it should just be placed on the start track. They also explored the materials by testing the rollercoaster. For example, after Scott tested the rollercoaster once, he tested if the car should be used upside down. He also explored if there are any representations of the car driver, so he could know which side to use the car.

Troubleshooting was evidenced as children engaged in an observation process of finding and discovering the problem and suggesting the remedy. During the design, as children were building their rollercoaster, they would notice a problem in their design by observing the differences between their design and the model. The problem could include the wrong number of pieces they used, wrong placement of pieces or misuse of pieces. For example, as John was designing, he noticed that he misused the start track (by confusing it with the end track), he placed the towers on the wrong rows and used a wrong slide in his design.

As children engaged in troubleshooting around the misuse of the pieces, they all also engaged in exploring the materials. Children would learn about the differences between similar pieces in their functionality and/or in physical appearance. For example, John confused an orange slide track with the start track which is also orange. He tried to attach one but he could not. Then he rotated it and looked at the picture carefully and then at the pieces he had in his hand and he realized he chose a wrong piece, by saying "Oh, wait." And then he picked up another one.

In most instances, children acknowledged, either verbally or non-verbally, that some mistakes had happened. However, they often did not explain why the errors occurred. For example, Tom misplaced the towers on the gray base but noticed the problem by pointing to the picture and the row where the towers were are placed, and said with no explanation, "Oh. That one. That one's right there." In another example, when John used a wrong slide, he explained the problem as "I think that should be large [referring to the length of the slide]."

Among all children, only Tom engaged in troubleshooting after testing his solution by observing the solution, finding the problem and suggesting a remedy. The car did not travel to the end track and stopped in the middle of the track. He looked at the rollercoaster, and quickly noticed the problem, "Oh, wait. I'm too tall." He then articulated his plans to fix the problem, while improving the solution, "All right. Like that. Now I just get that out." John's rollercoaster worked after the first round of testing, though he spent a long time building it and engaged in many rounds of troubleshooting and evaluation throughout the design. Scott, on the other hand, after building and testing his rollercoaster, engaged in an in-depth conversation with his mom to evaluate the solution. This conversation made him very frustrated and he decided to stop working on this challenge.

Two of the children engaged in evaluation. Evaluation happened both during the design and after the design, as children provided reasoning to see if the solution had met the design criteria. John engaged in evaluation after he tested his rollercoaster, as he explained to the researcher why he had built his design slightly different than the given picture (i.e. criteria), "I couldn't do it the same as the picture, but I moved the tower to the next spot and worked. I think they used a wrong slide in here." Scott engaged in evaluating his design before and after testing. After he built the rollercoaster, with the help of his mother, he evaluated if he has used the same number of pieces. Afterwards, he tested the rollercoaster which he built with two equal towers of six black posts. The rollercoaster did not work after a round of testing. He evaluated his design by comparing it to the model and noticed that the towers are uneven in the picture, "Wait, don't these look like they're uneven? Is this?"

In this challenge, children improved their solution as they were building it and/or after they tested it. Improving the solution occurred as children engaged in troubleshooting or evaluated their solution. For example, John tried two slide tracks to attach to the towers he had made, none of them worked out. As a result, he identified the problem as the distance between the two towers; he then improved his solution by moving the end tower one square. Similarly, Scott evaluated his solution before testing it and identified a problem in the number of pieces he used when building the tower. Thus, he improved his solution by adding pieces to the tower. Improving the solution also happened after testing. Tom tested his rollercoaster and identified the problem, and accordingly improved the solution by fixing that problem.

Optimization: Parental Strategies.

Parents used different strategies in this challenge to facilitate this phase of design. These strategies included soliciting information by prompting and clarification and providing guidance through suggestions, explanations, and directions. At different events, parents used these strategies as solo or in combination. John's mother provided directions for her son to test his solution (Providing Guidance-Direction). Tom's father used prompting strategies a few times to help his child troubleshoot problems. For example, during design, he realized the towers were misplaced, so he asked Tom a prompting question, "Where's this one located at [pointing to the tower in the picture]?" (Soliciting Information-Prompting). This question helped Tom to identify and fix the problem.

Scott's mother was very involved during this challenge. She used a combination of strategies to facilitate Scott's engagement in design evaluation. She started prompting Scott implicitly to make him realize that he had used the wrong number of black posts in his design (Soliciting Information-Prompting). She then continued guiding Scott by providing explanations on how to count the black posts (which is her own opinion, not necessarily the right way) (Providing Guidance-Explanation). This was followed by prompting and then directly asking him to think about how many black posts he had and he needed, and finally, she confirmed her son's thought process (Soliciting Information-Prompting, Providing Guidance-Direction &Affirmation-Confirmation). Moreover, she guided Scott through suggestions and explanations which helped him troubleshoot problems.

5.1.3 Challenge Two

Challenge two asked children to build a roller coaster that is steeper than the first one. Children were not given an image of the model. The challenge provided three levels of prompts; a written hint, pictures of some pieces that could be used and finally models of a few rollercoasters as appropriate solutions. Only two of the children tried this challenge. I observed different behaviors associated with Problem Scoping, Solution Development and Optimization exhibited by them.

Problem Scoping: Child Engagement.

Both John and Tom briefly engaged in Problem Scoping, through defining the problem and gathering information about it. They both read the design and had a brief conversation on the word "steeper" which was the key to the problem. Tom's understanding of the problem showed up in his early idea generation, as he said, "Oh, Steeper. So should I put this one up on here. Up one more, higher." He referred to the concept of steeper later on as he generated more ideas and engaged in other aspects of design. John, on the other hand, after reading the challenge, confirmed that he understood the problem using the one word, "Okay",, and started building an idea. He then got into a conversation with his mother and showed his understanding of the problem using his gestures to illustrate what "steeper" rollercoaster means. Both Tom and John explored different slides to make a steeper rollercoaster. As Tom got more involved with designing a rollercoaster, he got further with gathering information about the rollercoasters by using and asking about different pieces. He also started thinking about the bigger picture of the problem and broadened the context of rollercoasters by including ways the rollercoaster can be safer for the riders.

Problem Scoping: Parental Strategies.

Parents used different strategies to facilitate children's understanding of the boundaries of the problem. John's mother used prompting to solicit information about the problem (Soliciting Information-Prompting). She asks questions like, "Do you know what you have to do? and Do you know what steeper is?" These questions made John articulate his understanding of the problem. She then confirmed (Affirmation-Confirming) and then restated what he said by modeling and explaining (Providing Guidance- Explanation & Modeling). Tom's father took a similar approach, after hearing Tom's explanation about the problem. He confirmed and restated what he said (Affirmation-Confirming & Providing Guidance- Explanation). He then directed Tom to think more (Providing Guidance-Direction), by simply saying, "Think about it", which made Tom describe his ideas further. After Tom created and tested his first steeper rollercoaster, his father encouraged him to explore other slides by explaining and prompting him. His father referred to the hints given in the problem and had thought that they have to build different rollercoasters using different slides. As a result of this facilitation, Tom talked about the different slides and used some of them.

Solution Development: Child Engagement.

Both children engaged in multiple actions of Solution Development throughout this challenge. Since this challenge was more open-ended than the previous challenges, more evidence of idea generation and decision-making were observed happening by the children. The same as the previous challenges, modeling and prototyping happened throughout the activity.

Children prototyped and built their new ideas not from scratch, but by reusing the rollercoaster they built in the previous challenge. One possible reason is that the challenge stated that they should use a “steeper rollercoaster” than the previous one, so they both tried to make their rollercoaster meet the criteria. Based on the artifact analysis I have done, both John and Tom used more pieces in the rollercoasters they created than the ones they created in the previous challenge. Tom created multiple rollercoasters using a similar structure, but with different numbers of pieces and different types of slides. While John’s idea of his rollercoaster evolved as he built and modeled his new rollercoaster, his rollercoaster ended up having the same structure as the one he built in the previous challenge (and similar to the Tom’s).

They both generated multiple ideas in this challenge. They started generating ideas very quickly after reading the challenge statement. Tom articulated his plan right after he understood the challenge, “So should I put this one up on here? Up one more, higher.” And he then immediately started describing his ideas while modeling it, “Oh, oh. Yeah, yeah. I got this. Man, there's going to be like, there's going to be like. Actually, I don't think we'll ... It probably will only be …umm… one more. Here we go, like this. Dad, this. This is longer.” As he was saying this, he also took out the slide that was attached to the towers and adds a black post to the start tower and put the rest back in place. After testing his first idea, he then generated multiple ideas to make the rollercoaster faster and built some of them. For example, in one moment, he engaged in generating his ideas aloud as he was also modeling, “All right. Now let's make it this way, way higher. Way, way, way, way, way higher. Maybe three or two more [black posts to make the towers longer].”

John started building right after taking out the slide and building a third tower in the middle of the other ones. He kept this idea (i.e. having three towers) until the very end and kept generating characteristics to make this idea work. While John does not talk very often, but during the activity, evidence of idea generation was observed as he was purposefully adding and removing pieces, placing and replacing the pieces on the gray base. For example, he got a slide and held it next to the rollercoaster, and suddenly said, “ha!” and then added it to the end tower. While these behaviors were obvious evidence of generating new characteristics of ideas, they were also evidence of making decisions towards selecting the appropriate pieces and the best placement for them on the gray base.

They both engaged in decision-making while doing other Solution Development actions. As they were building their rollercoasters, they made lots of decisions about what slides to choose by focusing on their length. For example, after John placed the third tower between the two that he already had, he chose a few slides, put them side by side and then held them close to the towers (the first and the middle tower), and finally chose one. Tom engaged in a similar comparison several times with multiple slides as he created towers with different lengths. This form of engagement in decision-making could also be a mental testing process, as children tested parts of the prototype in their mind, and realized that they needed to find another piece.

Tom engaged in making a decision towards selecting between ideas. As Tom and his dad were having a conversation about making the rollercoaster steeper and faster, Tom suggested that they can add one or more black posts to the tower. However, after some moments, Tom mentioned that he could not add more than one because he thought that the slide would not reach both towers. He also modeled what he meant. This modeling and his father’s facilitation later made him choose a longer slide to make a steeper slide. He later acknowledged that this new idea is even steeper and probably better than the previous ones. A similar event happened later when Dad asked Tom to try other slides, and he explained why he could not use any other slides.

Solution Development: Parental Strategies.

Parents used different strategies to facilitate the challenge as their children were designing their solutions. Tom’s father asked him multiple prompting questions (Soliciting Information-Prompting) that facilitated Tom’s idea generation (e.g. how can you make a steeper rollercoaster? Even steeper?) and decision-making (e.g. could we try another [slide], something else?). At times that Tom was distracted, his father re-engaged him by providing guidance through explanations and suggestions (Providing Guidance- Explanation & Suggestion). His father's guidance engaged him in generating and modeling new ideas while making decisions towards selecting pieces. For example, his father explained to him that the challenge had given a hint, and suggested that "do you want to do what they asked?" As a result, Tom generated a new idea, chose a different slide and attempted to model and build his idea. Occasionally, Tom's father also praised his son for his ideas and decisions he made (Affirmation-Encouragement). John's mother, except for once, did not provide any effective guidance or prompting, per her son's request (see next paragraph).

Since children were modeling and prototyping the majority of their time at this challenge, at times parents were either hands-on assisting or not very involved. John's mother helped her son as he was building in multiple events (Assistance-Hands-on). John's mother informed him that she disengaged (Disengagement), but she would be available if he needed any help (Assistance-Offering). And until the end of the activity, she got involved with caution. Her disengagement was mostly a result of John's unwillingness to get help. For example, as John was generating ideas and modeling, his mother provided a suggestion, but he did not react to that suggestion. She then told him, "You do what you want. Don't just listen to me. I am here to help." On the other hand, Tom's father was observant when his son was modeling and building, but was never totally disengaged as he would immediately provide explanation, suggestion or prompt. He would use his attempt to disengage as an affirmation to his child. For example, he once said, "You do what you think you can make (Disengagement). I'm sure you can make it (Affirmation-Encouragement). He had never offered to help or get hands-on and build.

Optimization: Child Engagement.

Children were actively engaged in troubleshooting the flaws they noticed and improving their prototype before or after testing. Children also tested their prototypes (i.e. solutions) when needed. However, they showed limited evidence of evaluation. The process that resulted in improving the solution was embedded into other actions which made drawing the boundary between them difficult.

Troubleshooting that happened after testing was only evidenced once by John. John tested his solution towards the end, which did not work. With the help of his mother, he found the problem and fixed it right away. Tom, however, designed and tested multiple rollercoasters, and they all worked, except for one. Therefore, he did not need to do any troubleshooting. The last solution that he built, the car fell off the track. Instead of troubleshooting that rollercoaster, he decided to do some self-exploratory activities and to build a new rollercoaster.

Troubleshooting, during the design, did not happen as a single action, but as an iterative process in a series of design actions. These actions could include identifying a problem/flaw, finding the cause, suggesting a remedy, evaluating or explaining why the remedy would work, improving the solution, evaluating the improvement, and if needed. finding another problem(s). These actions did not happen necessarily in the order I mentioned above, nor all happened in one event. However, children practiced most of them in one event. Children also identified problems within their design as they were modeling and building their solutions. Bellow, I mention two of these examples; one was demonstrated by Tom and the other by John.

After Tom built his first rollercoaster of this challenge, he stated that he is going to try making a steeper one. He added two black posts to the start tower, and then adds another one, and attaches a slide. However, he realized that he cannot attach the slide to the end tower. He says, “Oh”, which was a sign of identifying a problem. Then, he then said, “Don't worry. I got this. I guess we'd better take one more off. I guess we got to take one more off. Guess.” He then took one black post out of the rollercoaster and fixes it. In this example, Tom was engaged in modeling and prototyping when he noticed a problem. He identified the cause of the problem, suggested a remedy and attempted to improve the rollercoaster following that remedy.

John was trying to attach two slides connected to the start and end towers to the middle tower which they did not reach the tower. He first identified the problem as the distance between the towers, then fixed them by moving the start tower closer. As he observed that trying to attach the slides to the tower was still unsuccessful, he identified the problem as the distance of the end tower and the middle tower, and moved the end tower closer. However, he realized the two slides could not get connected (i.e. he identified the problem). After some examination, he decided that the middle tower was a mistake (cause of the problem), explored options for a remedy and finally removed it. He then built the solution by attaching a slide from the start track to the end track. His series of actions, in silence, showed that he identified problems, one by one, within his design and attempted to fix them.

In some events, Tom also engaged in evaluating the solution which also happened with a series of actions related to troubleshooting and improving. Evaluation happened before and after testing. In one instance, after Tom made his rollercoaster with the aim of making it steeper, by his father's prompting, he evaluated his design aloud, “Yeah. It's one more. It's one more.” In another event, and towards the end, Tom engaged in evaluating his solution which also showed his decision-making process about the material. As he realized that the slide he aimed to use was shorter than the distance between the towers, he dropped it and looks for a longer one. Then he found one, and he says, “Oh yes there is, there is. That's about as high as it'll go. I think. It's about as high as it will go. This will work. I know it.” He also engaged in evaluating after testing his solution, which also showed his STEM understanding. He said, “[it goes faster] Well, because it's steeper, and more like ... More taller. So that one [probably referring to the first design] slows down more. If I were to add more, it'd go down way, way, way faster.”

Both John and Tom engaged in testing their solution by running the car on the rollercoaster. Regardless of the results they get out of testing, they both retested the same rollercoaster multiple times. Since John only built one complete rollercoaster, he tested that rollercoaster and the improved version of it. The first time he tested it, he observed that the car fell off the track. He retested the same rollercoaster several times without making any changes. He also tested the rollercoaster after he improved it. Similarly, Tom also tested and retested his rollercoasters, even if it worked the first time.

Optimization: Parental Strategies.

As mentioned before in the Solution Development phase, John's mother was mostly disengaged and got involved only when needed. During the Optimization phase, she prompted her son to find the cause of the problem (Soliciting Information-Prompting), suggested a remedy (Providing Guidance-Suggestion), and finally praised John for finishing the challenge and building a rollercoaster that worked(Affirmation-Encouragement). On the other hand, throughout the challenge, Tom's father prompted him to engage to in troubleshooting by asking him questions like, “how can we fix it? or “can we find a way?” (Soliciting Information-Prompting). Additionally, Tom’s father solicited information about a scientific fact (i.e. in the same situation, the steeper the rollercoaster is the faster the car travels; the longer height, the steeper) (Soliciting Information-Seeking Explanation), which resulted in Toms’ engagement in evaluation. He also praised him several times when the rollercoaster worked or when he changed the pieces that were not working, using phrases like “Whoa” and “good job” (Affirmation-Encouragement).

5.1.4 Challenge Three

Challenge three was ill-structured with only one specific criterion. Compared to the previous warm-up challenges, it had fewer direct given prompts. The challenge provided an open-ended problem: “Build a rollercoaster that turns the car before it stops.” The same as the previous challenge, it had three levels of hints following the least to most prompt strategy, written which suggests what pieces they can use, a picture of the turn tracks and finally a picture of a model rollercoaster that meets the criteria. Among all three children, only John worked on this challenge. In less than 10 minutes of engagement e, he engaged in all three engineering design phases.

During this challenge, John showed evidence of frustration a couple of times, and his mother was able to help him overcome those frustrations and reengage in the activity. She did that by reminding him of his strong LEGO skills. She also encouraged him several times by saying phrases like ‘You can do it.”. For example, when John said, “oh, no. This is a challenge.” She responded that, “That’s a challenge (Affirmation-Encouragement). Yes, but you can do it (Affirmation-Encouragement),” and reminded him that she believed in him. Like she did in previous challenges, she reassured him that she was there to help if he needed it. She also used several other facilitation strategies to help her child as he designed a solution.

Problem Scoping: Child Engagement.

John engaged in limited behaviors associated with problem definition and information gathering. First, when he first read the challenge, he seemed frustrated, probably because the challenge seemed difficult to him. With the help of his mother, he utilized the first prompt and selected one red and one blue turn tracks and began working on the challenge.

He did not verbally articulate his understanding at the beginning of the challenge. However, throughout the activity, with his selection of pieces and his design, John showed his understanding of the problem. Additionally, at the very end of the challenge, as he was evaluating his challenge, he stated the one specified criterion (i.e. to make a turn). He also engaged in exploring the materials, after receiving the hint. He explored the different turn tracks that he was given by rotating them and putting them side by side. He also explored how they can be attached to other pieces like slides and black posts.

Problem Scoping: Parental Strategies.

John's mother did not facilitate John's enactment in Problem Scoping very often. In only two events, his mom helped in exploring the materials, by providing information (<u>**Providing Guidance-Explanation**</u>) and asking him a prompting question about the pieces (<u>**Soliciting Information-Prompting**</u>). She also provided affirmation to encourage him to do the activity by stating encouraging statements as, "you can do it" and "you can figure out what you want to build." (<u>**Affirmation-Encouragement**</u>).

Solution Development: Child Engagement.

Like other challenges, John was engaged in modeling and prototyping from the very beginning of the challenge. He also showed evidence of generating ideas and making decisions, as he was building and modeling his rollercoaster. Therefore, modeling and prototyping overlapped with other engineering design actions.

From the beginning, he had an idea in mind to build, but he neither articulated the idea nor his plan. However, gradually, as he got more involved with his design, he shared his plans with his mother, "We need something to hold this [pointing to the slide that is attached to the turn track and should be attached to the middle tower]." He also showed evidence of building characteristics of his idea by removing and adding pieces to the same towers that he built at the beginning.

In this challenge, a few instances of decision-making happened as John was deciding what pieces he had available to use. For example, at the beginning, he made a decision of which turn tracks he had to use. Later, as he wanted to select slides to attach the towers together, he used side-side comparison and selection.

Solution Development: Parental Strategies.

While John was modeling and prototyping, his mother provided guidance by explaining how pieces work together (Proving Guidance-Explanation), and directing him through the steps he has to take (Providing Guidance-Direction) and asking prompting questions (Soliciting Information-Prompting). Additionally, per John’s request, she assisted him in building the prototype (Assisting-Building).

Optimization: Child Engagement.

During this challenge, multiple instances of Optimization were observed in John’s process. He troubleshooted some problems and suggested remedies for them, evaluated his solution, tested the solution and also improved the solution. The same as the previous challenges, these actions did not happen in a specific order.

Troubleshooting happened multiple times during the design, as John realized either the selection of pieces was inappropriate or the placement of them. For example, John used a left turn track in his design. As he was going to attach a slide, he realized that he had to use the right turn track. Thus, he replaced them. He also engaged in troubleshooting as he saw a flaw in his design as a whole system, and not individual prices. For example, as he was deigning his solution, he noticed that the prototype was unstable (i.e. problem), and he moved a part of the structure in some ways (trying remedy). He was finally directed by his mother to find an appropriate remedy and improve the solution.

The action of improving happened only in two instances, one before and the other one after testing the solution. The example of before testing was mentioned in the previous paragraph as John stabilized his rollercoaster. The other example of improving happened as a result of a series of actions, testing, troubleshooting, evaluation and improving. In this example, John tested his rollercoaster, but the rollercoaster did not work as the car stopped after it turned but did not get to the end track. He acknowledged that he knew why this happened which showed that he diagnosed a problem and had a remedy in mind. He improved the solution by saying what he thought the improved solution could be that would work, “I think this should hold it.” He then tested it and observed the same problem. He then engaged in evaluating the solution and showed his satisfaction as the design met the given criterion, “articulated that the well, it turned before it stopped, and it’s so close to the end, so this counts [as the solution].” However, even though he was satisfied with his design, he found the problem and improved the solution in silence. He finally tested his improved solution and cheered as it worked.

Optimization: Parental Strategies.

In the Optimization phase, John’s mother used similar strategies to the previous phase, but she was less involved. She directed her son to test his rollercoaster and also directly told him what the problem was and how to fix it (Providing Guidance-Direction). She disengaged from the activity when John faced the problem in his design and provided space for him to fix it (Disengaged), but she provided affirmation when he fixed the problem (Affirmation-Encouragement).

5.1.5 Letter Two

Letter two is the last challenge where children receive the second letter from the director of the amusement park. The challenge is ill-structured and open-ended, and children are asked to design and built the fastest, loopiest and steepest roller coaster to be exciting. Children have to consider three other specified criteria (i.e. starting high, having a loop and at least one tunnel) and a constraint (i.e. limited space).

All three children were very excited about this challenge to build an actual model for Hanna. Scott spent most of his time on this challenge and built two rollercoasters. John spent the least amount of time among all three children on this challenge, because he followed all the challenges. He was able to build a working rollercoaster that met all of the criteria and considered the constraint. Tom spent less than 15 minutes on this challenge, since he had spent a long time designing his own rollercoasters on self-guided challenges. Given the limited time he had, he was not able to build a working rollercoaster.

Parental involvement was greater than in previous challenges. However, not all strategies were helpful and effective for engaging children in design. Children also requested help directly from the parents and at moments, they welcomed unasked assistance from parents. Parental involvement seemed necessary for helping children deal with frustration.

Problem Scoping: Child Engagement.

All three children engaged in scoping the problem. They all showed evidence of understanding the problem and exploring how some of the pieces worked. In the beginning, they all had some conversations with their parents about specifications of the problem and functions of the pieces. Throughout the activity, they also showed evidence of Problem Scoping. In this challenge, Problem Scoping that happened at the beginning was slightly longer than Problem Scoping in other challenges with the in-depth conversation happening between children and parents. In this challenge, children delayed modeling and prototyping until after the Problem Scoping related conversation.

They all talked about the criteria or constraints of the problem, after learning about the content of the letter. Scott briefly asked for clarification on the constraint, “Am I going to have to use all of the black posts?”, and then he started generating ideas and building a new rollercoaster. Later on, he mentioned that he had to use the loop, “the curve thing, the loop.” John acknowledged that he knows what he has to do. When his mother was rephrasing and summarizing the letter, he mentioned some of the criteria, “and a loop and a tunnel.” He also confirmed that he understood some other pieces of information from the letter when his mother explained them to him. Tom was the only child who took notes, not readable though, but he said the criteria aloud, “To have a loop, and to pass at least one tunnel. So, it needs a tunnel.” Throughout the challenge, a pattern of emphasizing the problem criteria was seen among all of them. During their design, they all considered the self-specified criteria of the problem like, being fun, and the given criteria of starting high and having a loop and a tunnel, and the constraint of space. For example, even when the loop was not working properly for Scott, he still insisted that he was not going to take it out because “I won’t get the extra point.” Similar decisions were seen happening by Tom and John too.

Additionally, throughout the challenge, children showed evidence of understanding the broader context of the problem. John considered "safety" an aspect of his design. He also referred to his previous experiences of riding a rollercoaster and talks about rollercoaster speed and height. Scott discussed additional characteristics that a rollercoaster should have, "So in theory, it also would have... if that was going the opposite way, it would also have the metal thing that makes it drag all the way up?..... like those pulleys and gears." Although Tom, during the self-guided challenge had talked about aspects of his design to make a rollercoaster fun, scary, exciting and safe, in this challenge he did not bring up any additional criteria for the rollercoaster context in his conversations.

In this challenge, less evidence of exploring materials was observed than the previous challenges. One purpose of the warm-up challenges was to get familiar with the pieces in the construction kit, so children would spend less time exploring the material in the later challenge. This seemed to be observed amongst all the children in this challenge. They all engaged in exploring some of the pieces, especially ones they did not use before, including the tunnel and the loop. For example, Tom explored how the tunnel worked. He examined it by rotating it, tried it several times with different pieces and on different points of the gray base. He finally figured out how the tunnel could be connected and used. For Scott, because he did not try the other challenges, he explored some of the slides and the turn tracks. Assembling and using the loop was also difficult to figure out for all of them, and required assistance from adults.

Problem Scoping: Parental Strategies.

All parents helped their children define the problem. They started by reading the letter to their children. Tom's father and Scott's mother started by reading the letter aloud, but they decided to summarize and rephrase the content for their children (Providing Guidance-Explanation). Scott's mother realized that her son was not listening, but was building a rollercoaster of his own. Therefore, she changed her strategy in the middle of reading the letter, and just summarized the main points of the letter. John's mother asked her son to read the letter, but she then summarized the main points to make sure her son understood what he needed to do (Providing Guidance-Explanation).

All parents also helped their children to learn about pieces using prompting and explanation. Tom's father used a combination of prompting strategies and confirmation to help him learn how to use the tunnel in his design (Soliciting Information-Prompting & Affirmation-Confirmation). Scott's mother provided explanation of the materials he needed, including the loop, (Providing Guidance-Explanation) at the beginning of the challenge. Throughout the challenge, she also used explanations and prompting to facilitate material exploration. In one instance, as Scott's mother was prompting her child to learn about some pieces, she also pretended that she knew less than her son (Student of the Child). This strategy seemed to be very effective as Scott started explaining the differences between the pieces to his mother.

John's mother also helped him to gather information about the rollercoaster by reflecting on his prior experience, "Think about all the rollercoasters that we have been on (Soliciting Information-Prompting)." This helped him consider the additional context of the problem which later helped him with generating ideas. Tom's father also used the same strategy which resulted in a similar conversation before this challenge as Tom was trying his self-guided challenge.

Solution Development: Child Engagement.

Children spent most of their time designing solutions during this challenge. As children were modeling and prototyping, they enacted other aspects of Solution Development like idea generation and decision making. Idea generation happened frequently and making a decision was also needed more often in this challenge. All in all, Scott generated one idea and then switched to his second idea in the middle of the challenge. John, the same as he did during the previous challenges, stuck to one idea, added characteristics to that and finally improved it. Tom had built a working rollercoaster before this challenge. He attempted to modify that rollercoaster in response to this letter.

Idea generation happened in forms of brainstorming and generating one broad idea, generating characteristics of that idea and planning and sharing ways to create an idea. In some instances, idea generation happened while or right after scoping the problem. As children understood aspects of the problem, they would articulate an idea or some of its characteristics, and strategies to carry out the plan for creating it. For example, as soon as Scott listened to the first part of the letter, that he has to build a very exciting rollercoaster, he generated an idea and shared it aloud, "It's going to go all the way ... it's going to go down ... this needs to be the start (pointing to the taller tower with the start track)... and then it's going to go down, down, down, down, down, down, down…It's going to go really far down. And that's the start, and then it's going to go whoop, and then it's going to make a sharp turn ... turn ... and then it's going to fall in, and then it's going to go. It'll be exciting." He continued adding characteristics of the idea after learning that one criterion was to use all of the black posts. Accordingly, he shared his plan to meet the criterion, "To reach the limits, so it's going to have to go all the way up [showing a few black posts to be used on top of one tower]. Then yes. I need all of them [blocks]."

John, on the other hand, did not share his plans verbally but started modeling his idea after reading the letter. At times, he also added characteristics to his solution by removing and replacing pieces and asking questions. After he had some conversations about the problem with his mother, he knocked down what he had built in the previous challenge and started building his idea. Most of his idea generation happened at the same time as modeling and building in silence. However, at times he also articulated his ideas and plans while having a conversation with his mother. As he was building his idea, he asked questions that showed parts of his idea, such as, "can it be this short?" or "oh yeah, that's a good idea. Can you give me a black post?"

Tom did not engage in brainstorming ideas, as he planned to slightly modify the rollercoaster he already had built to meet the criteria. Thus, he was mainly engaged in generating additional features of the existing solution. He showed evidence of idea generation verbally while building. For example, he aimed to add the tunnel to his rollercoaster. After moving the tunnel several times, he placed the tunnel on top a part of his rollercoaster and confirmed the place and shared why this was a good addition to his solution, "Right there. And then this would go right here. So that's ... So this would be the end of the tunnel. And then you go down...".

Tom and Scott continued to share their plans and several characteristics of their ideas throughout the activity and even towards the end as they were also modeling and prototyping. Tom shared the additional characteristics of his idea and plans for making them by thinking aloud. For example, he was trying to find a way to place the loop into his rollercoaster, he needed to make the beginning tower bigger. While he was not happy about it, he shared his plan, “I already ruined my design. But I will not give up… And a few more of these.” And he collected black posts and put them on top of each other. In one instance, Scott identified a problem in his design, and after he suggested a remedy for it, he continued by sharing how he planned to build his idea, “and then go to the loop, and then the end, but there will be a tunnel.”

All children engaged in many incidents where they needed to make decisions while modeling and prototyping. These decisions were made when choosing materials to use in their design and evaluating components of their solution and making a decision for modifying accordingly. For example, when Scott’s mother gave him the tunnel-slide piece to attach to his rollercoaster, he examined it and then he said, “This is not going to connect. It’s just a slide.” Or in another instance, he describes his reasons for not selecting a piece in his solution, “I don't know. I just need it to something here [inaudible], but it doesn't. The pink ones do. I do not think that they belong to this. Nope.” John made decisions about components of his solution, with the help of his mother. As an example, he decided that his tower should be smaller after having a conversation with his mother. Similarly, Tom decided that the length of his tower was enough for the purpose of his design.
In this challenge, in the opposite of the other challenges, solution trade-offs were considered. Scott and Tom engaged in weighing the solutions and considering the trade-offs of the benefits of the different solutions to select one a couple of times. After seeing that the loop was not working, Scott and his mother had a conversation which resulted in knocking down the rollercoaster they built and designing a new solution. Scott came to this conclusion after weighing between building a rollercoaster that works and the car travels from the beginning to the end or a rollercoaster that meets all the criteria but does not work properly which he described it, “the old one was crappy.”. In their initial solution, the loop was not working and therefore, the car was not able to pass the loop and would fall off the track. Similarly, while Tom was resistant to make a change in his rollercoaster to one that met the criteria, “ I can’t ruin my rollercoaster just for this!”, he finally decided to modify the solution to meet the criteria so it’s what “they asked”. He made this decision after the researcher promised that his prior rollercoaster would count as a solution. He made this decision since the loop was not working properly. In the end, Scott concluded that he had to build a new solution

The same as in other challenges, modeling happened very frequently in the form of building prototypes and final solutions. Although children were reminded that they were given markers the same color as the pieces and the table is a whiteboard, none of the kids engaged in sketching their solutions even though in this challenge. Probably this was due to the nature of the activity. As mentioned above, other actions of the Solution Development phase happened while children were modeling. Modeling helped them to generate ideas and even make decisions regarding the solution. Additionally, modeling was also helpful for optimizing the solution. The only design phase that did not happen during the modeling very often was Problem Scoping. In this challenge, as mentioned before, children delayed modeling until they scoped the problem.

Solution Development: Parental Strategies.

During this challenge, children seemed to be more independent and willing to work independently. Therefore, parental involvement was not always welcomed by the children. However, parents managed to use effective strategies to help children engage in design. Additionally, during the Solution Development phase, parents were effective in managing their children's frustration. Parents also used strategies that appeared to be ineffective given the context. Since learning from the ineffective parental strategies can also help us as educators and researchers understand how to support children with autism, I also share them at the end of this section.

Parents used prompting to help their children engage in idea generation and planning (Soliciting Information-Prompting). John's and Scott's mothers used explicit prompting to encourage them to generate ideas and plan. John's mother asked him a prompting question, such as "do you have a picture in your head on how you want to build it?" or "What should we do next kiddo?" Similarly, Scott's mother used prompting, "Let's think together. What's our plan again?" However, Tom's father used implicit promoting which was still effective for his child to engage in idea generation. His father shows him the gray base and says, "Yeah. That's the base, right? So where do you think that would fit? Where do you think that would fit, inside there?" Tom in response says, "Right there. And then this would go right here. So that's ... So this would be the end of the tunnel. And then you go down...".

Parents' guidance and suggestions facilitated children's engagement in evaluating ideas and making decisions towards their design (Providing Guidance-Suggestion). In different events, they suggested children make changes to the ideas they were modeling and building. While in most of the instances, children disagreed with their suggestions, they considered those suggestions to evaluate their ideas and brought reasoning of why they disagreed. For example, Scott's mother suggested that, "or another option is just to get rid of the loop altogether.", but he disagreed referring her to the criteria. John's mother modeled what she was suggesting and described it by saying, "I wonder John, what if we move this to here…". John then responded that he thought what he had built looked good and he was not going to change it. Similarly, Tom's father suggested some changes to the beginning parts of the rollercoaster, which Tom disagreed bringing reasons which showed his satisfaction of the current design, "I can't ruin my rollercoaster just for this!". However, his father followed up with another suggestion, explaining what he meant, and clarifying what he would change, "What if we started it up at the very top [pointing to the start track]? Then we fit the loop at the beginning here and then we change the height of the tower only." Tom accepted his suggestion, possibly because the idea was now clearer to him.

Parents purposefully disengaged from the activity very often both voluntarily or per their child's request or desire. John's mother had practiced effective, temporary, disengagement since the first challenge usually per John's request or voluntarily when felt needed. In this challenge, for example, she would disengage from the activity by sitting in the back and hands off the table, to let her son work by himself, especially when John announced that he had an idea that he wanted to build. She re-engaged if John asked a question or if he needed help, either if he requested or not. Similarly, Tom's father was cognizant of when to disengage from the activity and when to re-engage to provide guidance or assistance. He allowed Tom to model and build his ideas without saying or doing anything. However, if Tom paused or showed frustration, he would assist by handing him an appropriate piece, giving suggestions and prompting him verbally so he could build his idea. This disengagement, however, mostly happened before Tom asked if they could come back a different day to complete the task. His father became very involved to help his son build the rollercoaster and complete the task. Scott's mother was very involved in this challenge, but also disengaged several times. For example, in a few instances, when her son announced an idea, she disengaged by saying, “you are in charge” or “do what you want to do”. In some events, Scott asked his mother to let him do the task by himself, thus she had to disengage.

In two instances, parents assessed and evaluated their children’s design. One of them was effective, and the second seemed to be ineffective. Both of these assessments happened as children were modeling and building their solutions. As John was building the start tower, his mother evaluated the design and said, “This is too high (Provide Guidance- Assessment)” and John looked at it and agreed and applied the change. The other instance is discussed below in the paragraph on not effective strategies.

Parents became more hands-on in this challenge. They assisted their children by building their solutions with them and/or finding them pieces that they needed (Assisting-Building). This assistance was sometimes per the child’s request. For example, all three children asked their parents to fix or assemble the loop for them or help attach it to the rollercoaster. John was very explicit about asking for help from his mother, “can you help me?”, and she helped accordingly. Parents sometimes verbally offered to assist (Assisting-Verbally). This offer was always helpful, as children could ignore or respond, but they were aware of parental support. Very often, John’s mom reminded him that she was available if he needed any help. Scott’s mother and Tom’s father also verbally offered to help add or remove a piece or even build a part by saying phrases such as, “I can replace it.”, “Let me see.” Or “Can I suggest something?” This verbal offering resulted in helping children in modeling and building. For example, As Scott was looking to find some pieces for his design, his mother offered to help, “Here [pointing to some pieces], let me assist you.” Scott then described what he needed, “it needs to be really short.” After realizing that Tom was tired and willing to not continue the activity the same day, Tom’s father offered that he could help him quickly wrap the activity. His assistance was effective, as he would not build everything himself, but he would provide suggestions and guidance first, and if needed he got very hands-on and helped Tom find and attach pieces.

Providing affirmation in forms of encouragement and confirmation helped children continue generating ideas, making decisions about what the solution could be and building their solutions. Confirmation mostly happened to confirm the pieces children used are appropriate or the new additional component of the idea would work (Affirmation-Confirmation). These confirmation phrases were as simple as saying a word “okay”, “good” , “right” and sentences like, “this is gonna work.”. The encouragement phrases were usually a complete sentence capitalizing and focusing on children’s strengths (Affirmation-Encouragement). For example, when John looked confused and frustrated, his mother reassured him of his abilities, saying, “No worries. You can do it. I know you can.” Similarly, Scott’s mother reminded him of his previous frustration and success, “Well, you found LEGOs really frustrating before you knew how to use them, too.” When Scott’s first solution did not work, his mother encouraged him to start redesigning a new solution, “They will love both of them [both solutions].” Her encouragement helped him decide between the solutions and continue generating ideas for the selected solution. Also, reminding children that they are doing engineering was very encouraging for them to continue modeling and prototyping. At the very beginning, when Tom learned that he had to use the loop in his design, he evaluated this option and explained that this couldn’t be included in his solution. However, his father encouraged him by referring to him as an engineer, and he was convinced to think about ways to include the loop in his design. Tom’s father continued to encourage him by reminding him that he is an engineer when he was disappointed with aspects of building his rollercoaster.

In this challenge, more than other challenges, parents were flexible in terms of the strategies they used to facilitate the activity and children’s design engagement. In many instances, this flexibility resulted in a sudden change of strategy. For example, John’s mother was very flexible to disengage from the activity if John requested. In an event, while John was prototyping his solution, his mother suggested that he use some pieces in his design saying, “this green one maybe?” or “This [piece]?”, (Providing Guidance-Suggestion/Direction). However, John did not show any willingness to take those suggestions. Therefore, she disengaged from the activity temporarily to provide a space for John to work independently (Disengagement). In another example, Scott’s mother suddenly changed her strategies by suggesting a design change to providing an affirmation. She said, “Up at the top [pointing to a tower] Umm, I mean that sounds kind of cool.” (Affirmation-Encouragement). The phrase “up at the top” was a follow up to a suggestion she made prior to saying this. This affirmation resulted in Scott sharing his design idea. Tom’s father also several times changed his strategies from providing guidance to disengagement. However, one effective strategy he used was when he decided to help his son in modeling the rollercoaster (Assisting-

Building), so he could re-engage in design without getting frustrated. This action helped Tom refocus on designing his solution. Parents' flexibility, as well as their affirmation strategies, helped children overcome their frustration.

In this challenge, in times when Scott's mother exhibited too much involvement, it did not seem to be effective. As Scott was modeling and prototyping, Scott's mother provided lots of directions. Scott followed some of these directions. However, he either ignored most of them or got frustrated by her involvement. Many times he even asked his mother to let him work by himself. Her direct assessment of Scott's design was not helpful either. For example, after seeing that his rollercoaster was starting low and was going higher, Scott's mother told him, "I don't think that works with gravity (Providing Guidance-Assessment)." After Scott ignored this feedback, she continued providing a suggestion followed by an explanation, which was ignored too with Scott saying, "It will work."

Optimization: Child Engagement.

All three children engaged in testing their solutions, troubleshooting the problems, evaluation and improving their solutions. Similar to the other challenges, improving the solution was a result of one or a combination of other actions. The improved solution was not always the "best solution," as children did not engage in effective troubleshooting, and children needed to go through rounds of improvement to get to their final solution.

Like other challenges, troubleshooting happened during Solution Development and after the solution was tested and was usually followed by improving (and attempting to improve) the solution. To troubleshoot, children mostly engaged in a combination of the actions associated with troubleshooting: observation, name, explain and remedy. During Solution Development, children would face problems within their design before running the car on the rollercoaster. These problems included not being able to connect a part of their rollercoaster to the second part, using the wrong number of pieces in a solution component or using the wrong piece. In one instance, Tom was not able to connect a loop to his existing solution. He identified and acknowledged the problem that the loop did not fit. Influenced by parental scaffolding, he finally acknowledged that he knows how to fix it, "I got this, I got the idea. See, look, check this out, Dad. Now it can totally fit.” And he then attempted to fix and improve the problem. In another example, as Scott was building his rollercoaster, he identified a problem within his design that parts of his rollercoaster could not be attached. He named the problem aloud, “but that will not be it” and he took an action to fix the problem, without mentioning what his remedy was.

Towards the end of the activity, all of the children engaged in troubleshooting after the solution was tested. For all of the children, their first solution needed improvement. Thus, they had to engage in identifying the problem to fix it. Children did not always identify the problem correctly. For example, John identified the problem of his rollercoaster, not within the design but the car itself, and he tried to fix the car. After several rounds of testing, examining the rollercoaster by rotating it, and identifying the problem within some parts and pieces, and improving by moving pieces, he was finally able to identify the problem and fix it. One reason for not finding the flaw in the solution (i.e. the prototype) was that he did not engage in unconfounded and fair testing (Crismond & Adams, 2012), but instead he would change many variables in his design before retesting .

Testing happened during Solution Development or after the solution was designed. All of children engaged in testing during design by running the car on parts of their solution. For example, as Scott was working on his roller-coaster, he tested a part of his design to see if the tunnel was at the right place. Tom and John both tested the loop as they attached it to their design by running the car. Additionally, sometimes testing happened hypothetically without running the car, which overlapped with making decisions about the solution or a component of the solution. Children also tested their rollercoaster after it was complete. The pattern of testing the rollercoaster several times before attempting to find the problem was observed in this challenge in the processes of both John and Scott. Tom engaged in testing two times. The first time, he identified the problem and attempted to improve it, and then the second time, after seeing that the rollercoaster did not work, he left the activity.

John and Scott engaged in evaluating their design both after and before physical testing. Evaluation happened as children provided reasoning for the workability of their solutions (or parts of the solution). After Scott tested part of his solution, he evaluated his design and showed his satisfaction by saying, “Yes, yes, yes! It goes through the tunnel! Yay. It goes through the tunnel.” In another instance, he evaluated his design before testing it, “Yay, this might actually work. Might be able to. They are just going to hit the top of the tunnel. Where did that little car go?” And he then sought confirmation by testing. John engaged in evaluation after observing that his solution did not work. He evaluated the appropriateness of his remedy by explaining that the new design is safe. Towards the end, he also engaged in a conversation with his mother, expressing his satisfaction while pointing out to the problem, “You know what. I think it is working. It’s just the car that is not working sometimes. I’m done.” He also provided reasoning to the researcher when announcing his final solution, “It has all the things you asked and the car sometimes works. It looks good. It’s good. Done.”

Optimization: Parental Strategies.

Parents engaged in different parental strategies to help their children optimize their solutions. Parents encouraged children to test and improve their final solution by directly asking them (Providing Guidance-Direction). They encouraged testing by telling their children phrases like, “Okay, now try it”, and sometimes they passed the car to them to encourage them to test. When children identified problems, parents sometimes directed them to improve. For example, Tom’s father said, “All right, fix that, and then make a tunnel, too.”

Right after Scott evaluated his solution and expressed his design satisfaction, his mother provided her assessment of the design, “Okay, this tunnel can’t... This can’t.” (Providing Guidance-Assessment) which led Scott to emphasize his reasoning again, “It’ll be fun when hitting the top. Trust me, [It] works. That’s the idea.” However, he ignored his mother’s assessment and did not test his rollercoaster. He did not touch the tunnel section until towards the end which worked after testing it.

Parents provided guidance and asked their prompting questions to facilitate troubleshooting, improving and evaluation. For example, when John’s design did not work the second time, his mother asked him an explicit prompting question to encourage him to troubleshoot the problem, “We need to know… Why do you think it worked the first time?” (Soliciting Information-Prompting) and she continued by directing him to first name the flaw and identify the cause, (Providing Guidance-Direction), "We need to find out why it's not working now." This resulted in John retesting the rollercoaster and observing it carefully a few times. At times, John's mother also provided explanations about possible problems such as, "You know, I think it's how the car rolls." Or "I think there is something wrong with this." These explanations helped John to focus on identifying the problems and made design decisions accordingly. In another example, Tom's father provided a suggestion (Providing Guidance-Suggestion) and followed by prompting (Soliciting Information-Prompting), "No, I wouldn't change anything right there. Where's the problem at?" This prompting encouraged Tom to explain the problem and the cause before changing an unproblematic area something from the rollercoaster that would potentially cause more frustration. In Scott's case, his mother's explanation resulted in design evaluation, "It would be going fast enough that it would just shoot him down there." (Providing Guidance-Explanation). This explanation helped Scott to feel satisfied with his design.

Parents also assisted children by getting hands-on themselves, troubleshooting and improving the design (Assisting-Building). Assisting happened by parents pointing to a problem, giving the children the pieces that they needed to fix the problem or even fixing the problem themselves. Assisting sometimes was followed by providing suggestions (Providing Guidance-Suggestion). For example, John's mother removed a piece from the rollercoaster and then suggested that, "maybe this is not plugged in correctly." Later John's mother provided guidance by modeling how to find the problem (Providing Guidance-Modeling). When both John and his mother were trying to identify the problem, she rotated the design so he could observe the other view of the solution, and explained to him that "this way we may find the problem, if we look at it from this side." In another example, Scott's mother handed him a small slide track and said, "Maybe this would work. You may even need to move this over and that there." They collaboratively continued troubleshooting, testing and improving. Mother assisted Scott finding the problem by finding him the pieces, replacing them and directing Scott to do some actions (Providing Guidance-Direction).

Affirmation also helped children during Optimization. Saying encouraging phrases helped children to continue to be engaged and suggest remedies and fix the problem. For example, Scott's mother encouraged him after hearing her son's idea by saying, "Okay, Uh, somebody's got an idea"

(Affirmation-Encouragement). John's mother also encouraged him by saying, "You did really good boy (Affirmation-Encouragement)."

5.2 Engineering Design Activity as a Whole

In this section, I characterize ways children engaged in engineering design during the Design a Rollercoaster Activity. I present and discuss findings of cross-case and cross-challenge analysis when looking at the activity a whole.

5.2.1 Children's Engineering Design Engagement

Design is an iterative, exploratory and sometimes a chaotic process (Braha & Reich, 2003). I have observed that these children also engaged in engineering design in an iterative, non-linear and non-cyclic process. This process consisted of all of the design phases that emerged from my synthesis of the literature, including Problem Scoping, Solution Development and Optimization. In each of the cases in this study, for almost every challenge, this chaotic process of design began with the child understanding the boundaries of the problem and ended by evaluating those boundaries in their solution. Within and across the challenges, children engaged in "meaningful learning, where improved solutions grew out of the evolving understanding of the problem" (Crismond & Adams, 2012, p.770). At the same time that children defined the problem and gathered information, they designed their solutions. As they designed and tested their solutions, their understanding of the problem evolved. This is a pattern of behaviors similar to adult designers, where the formulation of the problem and ideas for their solutions co-evolve together throughout an iterative design process (Dorst and Cross, 2001). Below is an excerpt from case three (i.e. Tom) that can illustrate what this iterative process looks like when enacted by children along with the parental involvement.

> Tom looks at Challenge Two and reads it and while pointing to the start tower, and says "Oh Steeper (***Problem Scoping-Problem Definition***) So should I put this one up on here. Up one more, higher (***Solution Development -Idea Generation***)" Dad responds, "Yeah, it says a steeper rollercoaster (<u>**Affirmation-Confirming & Providing Guidance-Explanation**</u>) Think about it (<u>**Providing Guidance-Direction**</u>)" Tom then immediately starts describing his ideas and prototyping. The conversation below happens between Dad and Tom.

> Tom [as he is prototyping]: Oh, oh. Yeah, yeah. I got this. Man, there's going to be like, there's going to be like. Actually, I don't think we'll ... It probably will only be …umm… one more. Here we go, like this. Dad, this. This is now longer. [While the slide is attached to both start and end track, he breaks the start tower. He adds a black post to the tower and puts the rest back in place. The start tower is now longer.] (***Solution Development -Idea Generation & Prototyping***)
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> Dad: Is that steeper? (Providing Guidance-Assessment)
>
> Tom: Yeah. It's one more. It's one more (*Optimization-Evaluation*)
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> Tom tests his rollercoaster (*Optimization-Testing*). It works. He retests it and says, “Oh, look at this. Look how fast this one goes. It’s exciting” (*Optimization-Evaluation*) Dad uses this moment as a learning opportunity for his son, and asks, “Goes faster, why does it go faster?” (Soliciting Information-Seeking Explanation) Tom responds immediately, “Well, because it's steeper, and more like ... More taller (*Problem Scoping-Information Gathering*) So that one [probably referring to the first design] slows down more. If I were to add more, it'd go down way, way, way faster.” (*Solution Development -Idea Generation*)
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> Dad encourages Tom to try building a faster rollercoaster by asking, “You going to try that [the idea his just articulated]?” While Tom looks at his rollercoaster and points out to the height of the first tower, he says, “I don't think it will let me do another one.” (*Solution Development -Decision Making*) He then models what he means by breaking the start tower and pointing to the part where he could possibly add a piece (*Solution Development -Decision-making & Idea Generation*) Dad asks another question, "Can we figure out a way?" (Soliciting Information-Prompting) While Tom is listening to Dad, he adds a black post to the start tower and is able to attach the slide to the end tower (*Solution Development - Idea Generation & Prototyping*) He then acknowledges that he is going to do what Dad wanted, “Oh, I get it. This.” He then decides to add another black post to the start tower to make a steeper rollercoaster, “Trying that. That makes it even more steeper, it's like ..” (*Solution Development - Idea Generation*) At the same time Dad asks "How can we do it even steeper?"(Soliciting Information-Prompting) Before Tom answered Dad’s question, they notice that the slide cannot reach the end tower any more as the start tower has gotten longer. Tom, says, "Oh." (*Optimization-Troubleshooting*) Dad follows up and asks, "how can we fix that?" (Soliciting Information-Prompting) Tom reassures his dad that he knows how to fix it, "Don't worry. I got this. I guess we'd better take one more off. I guess we got to take one more off. Guess. " and he takes off one and fixes the rollercoaster (*Optimization-Troubleshooting & Improving*)

As seen in the example, the child practiced engineering design phases very iteratively and in a non-linear process. By looking at chapter four and all three cases, I can find many examples where children engaged in design iteratively. Design actions associated with each phase were embedded and had overlap with each other. I also see the important role that the parent played in engaging his/her child in design.

Below, I discuss children's engagement in engineering design phases during this activity. The same as the previous section, to better characterize the design phases I discuss these phases and their actions separately. However, I acknowledge that drawing a boundary between them was not always possible.

Looking at the activity as a whole, I see how children gradually understood the boundaries of the problem. The main problem was introduced in the first letter. They were explicitly told that the warm-up challenges are to help them get familiar with the construction kit, and then the second letter would provide more information about the problem. Therefore, all three children treated the first letter as the main problem and sought to construct knowledge about the problem and its specifications throughout the challenges. This was evidenced by talking about their willingness to build the "master rollercoaster" (said John) or sharing ideas of what they want to include in the "actual model" (said Tom).

In this activity, children delayed building and designing their main solution (i.e. rollercoaster) given the nature of the activity, with having the warm-up challenges in between. After reading the first letter, children showed their desire to dive into the activity and start building a solution to Hanna's first letter. They started exploring and grabbing material that they could possibly use in their rollercoaster, or they announced that they have an idea and they know what they want to build. This is a behavior that is usually observed in beginning designers, especially children (Christiaans & Dorst, 1992; Crismond & Adams, 2012). However, parents' direct instructions guided them to explore the warm-up challenges first. Aligned with the aim of the challenges, exploring the warm-up challenges helped children learn about the material and think thoroughly about the problem. Throughout the challenges, they discovered other features and aspects of the problem that were not written in the letter, like safety, and considered them in their solutions.

As these children engaged in Problem Scoping throughout the activity, they showed behaviors that can be associated with behaviors of more experienced engineering designers. In contrast to the beginning designers described by Crismond and Adams (2012), none of them tended to oversimplify the problem or observe the problem as straightforward with only one single right answer (Crismond & Adams, 2012). They engaged in identifying different aspects of the problems and gaining pieces of information related to the problem that could impact designing the solution. Especially, after the second letter, they focused on the given criteria, they named them and explored materials needed to include those in their solution. Additionally, the same as experienced designers, they invented and identified requirements for the solutions that were not explicitly mentioned as important aspects of the problem (Liu, 1996). These requirements were invented and identified during all of the challenges, even with the well-structured ones. For example, at the least, children recognized that the solution's requirements in the first challenge was to select the same pieces shown in the picture, the same number and to be designed on the same rows of the gray base. The same as experienced designers, after reading the second letter, children delayed building their solutions instead of designing immediately (Elio & Scharf, 1990). They engaged in conversations or think-aloud processes to understand what Hannah was asking them to build.

Throughout the activities, they gathered information about the problem and attended to expanding the problem space. They explored specifications of the problem; what they needed to include in their rollercoasters and what materials they needed for building their solutions. Exploring these specifications later helped them with building their solution, and this is similar to what Watkins et al. (2014) observed when their fourth graders engaged in Problem Scoping. At times, parents helped them explore these specifications by suggesting that they think about their previous experiences with rollercoasters and providing further explanations about rollercoasters. With or without the help of adults, they all considered defining what "fun and exciting" and "safe" rollercoasters look like. They added additional context to the problem, such as talking about having fun in a water slide (said Tom) and being safe needing some additional design components (said all). The addition to the context is aligned to what previous researchers observed in elementary-aged children when doing design (e.g. Dorie et al., 2017; English & King, 2017).

Considering the problem from the perspective of multiple players in the problem was reported as a behavior of expert designers (Cross, 2007). During this activity, children were supposed to design for their client, Hannah. As mentioned before, all three of the children considered Hannah's perspective through naming different criteria mentioned in the letters. However, examining children's dialogues showed evidence of children trying to see the problem from other's perspectives. John and Scott saw themselves as the users (who would ride the rollercoaster). For both John and Scott, this behavior of perspective taking was a result of their parents' facilitation. They referred to their previous experiences of riding or seeing rollercoasters and talked about what they, as users, would like to see in their design. On the other hand, it was interesting to see that Tom considered users' perspectives in his design. He asked about who was going to ride this rollercoaster and what riders would like. After sharing some of his ideas for the solution, he specifically asked his older sibling and his father if they would ride this rollercoaster, while acknowledging that he, himself, would not ride this "scary" rollercoaster. These examples of children's shift in perspective taking is an important evidence of their abilities to unpack the problem and develop a better sense of the problem than just simply reading the design statement. Considering both clients and users' perspective in design was similar to what Cross and Cross, (1998) observed in the design process taken by an experienced designer. These behaviors were also observed amongst children of the same age in Watkins et al.'s study (2014). One important note to consider is that the children in Watkins et al.'s study were typically-developing, while children in my study were on the autism spectrum with their unique characteristics. They are known for having challenges and difficulties in empathizing abilities which results in not being able to consider other's perspective. However, the children in this study took others' perspective into consideration during their design.

Across all of the challenges, children engaged in exploring materials very often while modeling and prototyping their solution. In many instances, the initial process of exploring and selecting the materials was similar to the information gathering process that beginning designers often engage in as "found-object designing" (Crismond & Adams, 2012). In this process, the first objects would act as a source of inspiration for Solution Development. For example, children tried using the first few slide pieces or the first turn tracks in their solutions. While this "found-object designing" process helped them gather information about the materials' physical specifications (Bursic & Atman, 1997), at times it resulted in not selecting the right piece which created frustration for children. However, gradually, as they advanced within and across the challenges, they fully explored function-behavior-structure (Gero & Kannengiesser, 2004) of the pieces and material. Exploring the function (i.e. what the piece is for), the behavior (i.e. what the piece does) and structure (i.e. what it is and its relationship with other pieces is) of each piece happened naturally while modeling and prototyping, and children did not take a systematic approach to do so. However, in many instances, parents systematically facilitated their exploration, by purposefully guiding them to use a piece or asking them prompting questions about what pieces they have to use. When they all got to the last challenge, they had already explored almost all of the pieces and knew how to use them along with other pieces.

Overall, the information children gathered throughout the activity helped children frame and reframe the problem, enrich their representation of the problem in their mind (i.e. what the rollercoaster would look like) and uncover the some underlying principals and clues (e.g. the use of gravity and what pieces to be used). However, children did not exhibit behaviors of experienced designers to do much of their research during very early stages. Neither did they exhibit the behavior of student engineers of gathering too much information but not being able to utilize the information in their design (Bursic & Atman, 1997). They felt the need to gather information at different points during their design (Crismond & Adams, 2012), and not particularly at the beginning. As a result, children collected information and gained knowledge gradually. They processed the pieces of information as they collected them and utilized them in their design decision making. This data collection strategy seemed to be very helpful for these particular children, especially given their possible difficulties in executive functioning (Ozonoff et al., 1991). Executive functioning refers to individuals' ability to process information, by planning, organizing, and sequencing pieces of information. Some individuals with autism are not able to hold a piece of information in mind while processing others and putting all of the information in a sequence of actions. Thus, it is possible that the gradual data collection strategy is helpful for children with mild autism to apply in their design.

As children were designing their solutions, they paid a lot of attention to the problem specifications and requirements. These specifications include design criteria that were explicitly mentioned in the design statements or the criteria that were identified later by the children. However, among all these specifications, meeting the given criteria had a greater value for the solution than other criteria identified throughout the activity. Children's main goal for design was to consider and meet all the design criteria and this was obvious in their dialogues and actions during Solution Development and Optimization. During Solution Development, this goal was obvious especially when making decisions to select pieces and building components of their solutions. At times when children struggled in designing their solution, their priority for building a rollercoaster was to include the criteria that were explicitly mentioned in the statement. For example, in the last challenge, when Tom struggled to continue building, given his tiredness, he made sure to include the loop and the tunnel in his design.

Children's satisfaction with their design seemed to also be dependent on meeting all of the design criteria, even though they articulated a list of features when designing their solutions. During the third challenge, John expressed his satisfaction with his design because it met the criteria, even though the car did not initially travel from the beginning to the end. The same behaviors were seen amongst expert engineers. For example, Cross and Cross's (1998) findings showed that the expert engineer in their study considered some criteria in his design but selected the essential criterion and prioritized it as the point of success. Similarly, Watkins et al., (2014) reported on multiple examples of the fourth-grade students prioritizing the problem specifications and criteria at different circumstances.

Children generated ideas to solve the problems of the challenges. However, they did not exhibit idea fluency which refers to divergent thinking and working with an abundance of ideas (Crismond & Adams, 2012). They showed evidence of idea scarcity where they were reluctant to spend the time (and probably the mental effort) to come up with multiple rich ideas that they could choose from (Adams, 1986). They would get excited about one single idea and become fixated on that idea and its functionality (Gero, 2011) until they got stuck in their design (Sachs, 1999 cited by Crismond and Adams, 2012). Tom's engagement in the last challenge was a clear example of not being willing to think about and work with an abundance of ideas as he was fixated on his idea and solution from his previous attempt. He finally got stuck, and given his level of energy and patience, he decided to leave the activity. Similar patterns of idea scarcity were observed in the activities of the two other children. Scott insisted on building his idea and attempted to ignore his mother's ideas and suggestions at the beginning of Challenge Four (second letter). He designed his idea and finally got stuck, and then made an informed decision (Crismond & Adams, 2012) to build his mother's suggestion.

During Solution Development phase, the children constantly engaged in generating features of their ideas. Although the bigger picture of the single idea for the solution remained the same for the most part, their ideation towards the features seemed to be very deep. As they identified a new sub-problem, they sought to add new features to solve that sub-problem. Generating characteristics of ideas was observable as children “shared back” (Shroyer et al., 2018) those characteristics verbally or through non-verbal cues as they were modeling their prototypes. They engaged in brainstorming multiple features for a specific part of their rollercoaster, while making decisions to figure out what pieces and how many of them would help build a better characteristic for their design. Several times and in all of the challenges, I observed that they added or removed pieces to build a different component that seemed to be a better fit for their rollercoaster. They had to also make decisions towards where to place the new components of their rollercoaster on the gray base when building their solution.

This behavior of identifying the sub-solutions (of the single idea) and generating characteristics of them seems to be similar to the depth-first approach described by Cross, (2000), which is usually associated with beginning designers. Using this approach seems concerning to researchers as it may result in spending too much time developing a single idea (Crismond & Adams, 2012), getting trapped by characteristics of these ideas (Daly et al., 2012), focusing on the surface level of the problem (Ho, 2001) and not having enough time for implementing more profound plans. However, in the context of this study, this approach seemed to be working well for them and helped them in multiple ways. Focusing on sub-solutions helped to systematically gather information about the material and identify the ones they needed, while having progress on their modeling and prototyping. This information gathering saved their time and helped them generate deeper idea characteristics as they knew what pieces would do what. Using this approach, they were able to make narrow plans at the detail level which helped them not get distracted by considering other aspects of their solution. Therefore, they could focus on one component of the solution at a time, generate ideas and build a solution for that component, without wanting to work on other parts of their solution at the same time. While Cross, (2004) stated that novices who use the depth-first approach rather than the breadth-first approach may not possess the abilities to decompose the problem, these children were able to decompose the problem and solution accordingly. This fact

that these children benefitted from the depth-first approach may be because they utilized their strengths of being able to narrow down and focus on details (DSM-5, 2013) of the problem.
Children’s idea generation did not always follow a formal structure. Formal idea generation is when designers explicitly acknowledge that they are setting time aside to generate ideas (Shroyer et al., 2018) and deliberately use specific techniques and systematic methods (Geschka et al., 1976) such as brainstorming, brainwriting and also sketching (Purcell & Gero, 1998) and affinity diagraming (Mizuno, 1988). While children in this study were given color markers and whiteboards, and were told they can use them to “draw your ideas” or “take notes”, they did not. Arguably, some formality in these children’s idea generation could be observed when parents got involved and directly or through suggestions guided them to brainstorm and come up with ideas. However, most of the instances of idea generation, both at the big picture level or the detail and characteristics level, seemed to happen naturally as part of building and modeling, where perhaps they did not have any intention or were not aware that they were coming up with these ideas. Sometimes, after the child thought aloud or made a change in his rollercoaster, he would make a comment indicating that he considered that as an idea and details on how this idea could go further. The natural idea generation process was also observed in a recent study capturing idea generation of a team of designers (Shroyer et al., 2018).

While children did not generate multiple ideas (i.e. quantity), their ideas were deep with a lot of characteristics and had novelty and quality (Shah et al., 2003). While the challenges were similar in all the cases, all three children designed solutions that were totally different from one another. The attributes of the solutions varied in each case. These attributes included the type and number of pieces that they used, the expected function for each rollercoaster, the hypothetical components that could be included and finally the story behind the solution. Tom and Scott told stories about their designs and even named them. John also briefly talked about how he would imagine people riding his rollercoaster. Additionally, the solutions were all different than the ones that appeared as prompts in the activity which were built by two adults with engineering backgrounds prior to the study. The solutions also had quality in terms of performance and meeting the criteria and constraints stated in the Solution Development and other problem specifications. Even with the last challenge, that children were stuck in their first solutions, except for Tom who left the activity. The other two designed a solution that worked and addressed all the specifications. Thus, the

quality and novelty of the children's ideas was evidence of their effective engagement in idea generation and accordingly Solution Development (Shah et al., 2003).
Paying too much attention to the specified criteria was a pattern of design behavior observed among all the children. While having the design criteria was helpful for considering the necessary components of their design (as mentioned before), at times, it caused challenges for them. For example, as they were stuck with the design criteria, they would design unworkable elements in their rollercoaster. For example, Scott insisted on using the loop at the beginning of his design, to cross that criterion off his list. Scott's mother reminded him of gravity. Because he was very certain of needing to add the loop, he did not listen to his mother and insisted that the loop should be included as the first component. Additionally, I observed that in many of the challenges, after the design criteria were included in the rollercoaster, children started taking a higher level view of the problem space and stepped outside the existing criteria and engaged in considering the broader context and additional features that they could include in their design (Dorie et al., 2014). Children held to these additional features and considered them in the development of their next solution either when improving their solutions or creating new solutions in next challenges.

Throughout the design process, children faced several decision points that required making many choices. The choices were made mostly over deciding which idea characteristics carry the value they were looking for and/or which pieces could be used to help them build that characteristic. They used trial-and-error techniques (Razzouk & Shute, 2012) to make decisions which could be observed through children's actions. One of the early examples was when John took out a slide and placed a longer one to see if it would work as a steeper rollercoaster. They also engaged in articulating their reasoning when making decisions. For instance, when Tom was building a steeper rollercoaster than the first one, he added black posts to the first tower, and explained that the taller tower makes a steeper rollercoaster.

Children's reasoning behind many of their decision points was not always clear. For the most part, children did not naturally communicate their thinking process. With the exception of Tom, who showed a habit of thinking aloud, often parents had to initiate conversations to elicit the reasoning behind children's design actions. Therefore, in many instances, I was not able to infer if their decision-making action of selecting a piece or building a component was based on any systematic and informed reasoning, or was a result of a random trial-and-error technique. In those instances that children provided verbal or non-verbal cues, it was evident that meeting the criteria and considering the constraints were the underlying factor for making any design decisions. At times, they clearly articulated that they were considering the criteria while making the choices. Other times, their decision-making process could be understood through their actions. For example, John chose one slide, among others, that could be attached to the loop that was placed at the beginning of his rollercoaster. Scott and Tom made decisions about the size of the towers they used to be able to fit the tunnel and the loop respectively. These findings are similar to the patterns of reflective decision-making behaviors Wendell et al (2017) observed when fourth and fifth grade students engaged in planning and designing solution.

Tom and Scott clearly considered the trade-offs between two ideas for their final solution. They both partially articulated some of their reasoning about the benefits of selecting their final solution. Tom focused on the positive aspects of his initial solution, but finally decided to build a new solution to address design criteria. Scott, on the other hand, decided to shift to build the second idea because he thought the workability of a rollercoaster is more important than meeting the criteria (i.e. having a loop and a tunnel), saying that "at least this gonna work…. The old one was crappy." Previous research found that when beginning designers make a decision about an idea they only focus on negatives or positive features of their ideas, but not both (Fischer & Bidell, 1998). I did not capture any evidence that they had weighed and balanced both positive and negative aspects of the decision point before/when making decisions. I acknowledge that children in this study did not always communicate their design decisions. Thus, it is possible that the same as other beginning designers, they did not fully engage in considering all aspects of the ideas when making their decision.

As children were making decisions during modeling and prototyping, some of their behaviors were similar to those that could be associated to testing. This process resulted in making decisions for modifying their design. In many instances, these children changed components of the rollercoaster without running the car on it. Most of the process happened in the children's mind. However, the non-verbal cues that children provided during design were the only evidence that showed this evaluation. These non-verbal cues included using their fingers to evaluate the size of pieces and spatially examining pieces of the components. It is possible that they ran mental simulations in their mind and imagined a sequence of events (Adams, et al., 2002), and envisioned how this component of the rollercoaster may work, similar to what informed designers do (Crismond & Adams, 2012). Interestingly, Temple Grandin, a famous autistic scientist, has mentioned in her book, *Animals in Translation*, that she tests her designs in her imagination before building them (Grandin & Johnson, 2009). A contributing factor to what Temple does is her exceptional visual-spatial skills. Because these children did not often communicate the process verbally, I cannot say for sure that they used a similar way of thinking as Temple Grandin does. However, it is possible that they also used their visual spatial abilities to test their designs, especially that visual special ability is considered to be autism's STEM-related strength.

Testing was observable when the children would run the car through the rollercoaster or components of the rollercoaster. I observed a pattern of testing an incomplete rollercoaster several times. Children would build a component and then test it. If it required modification, they would apply the changes and then continue building. This behavior of testing while prototyping has not been mentioned exactly in previous literature. However, it may be equivalent or similar to generating data about and possible explanations of the prototype performance (Crismond & Adams, 2012). Professional designers favor ways of doing testing that can get quick feedback and insights on their prototypes without conducting time-consuming more scientific experiments (Norman, 1996). In this study, instead of waiting to complete their prototypes and then testing, children tested while modeling and prototyping and received quick feedback on how they are designing. This formative assessment seemed to be very helpful for these children to optimize their design.

Children also tested their completed prototypes (i.e. rollercoaster) by running the car on the prototype and observing the performance. The first thing they were examining through their test was if the car traveled all the way from the beginning to the end and if the movement was smooth. If either aspect was not met, children had the tendency to retest their rollercoaster over and over again, without changing anything in it, until they found a flaw (or flaws) and/or came up with ideas to improve or redesign. Crismond and Adams (2012) stated that beginning designers conduct few or no tests on their prototypes. When they do, they do not conduct fair tests as they change multiple variables in their experiments which results in gaining little understanding of the solution's flaws. While the findings from this study uncovered mixed patterns of children conducting fair and unfair

tests on the prototype, children engaged in multiple cycles of testing before they decided their next step.
As children were testing, they observed the prototype's performance excitedly. However, during the retesting, their observation was more diagnostic, either focused or unfocused. In most instances, children made comments about the performance and what could be the cause and how it can be fixed. Sometimes, without saying anything, after a few rounds of retesting, they made changes to one aspect (i.e. what NGSS calls fair testing) or a few failure points (i.e. unfair testing) and observed the performance of the prototype again. These behaviors and actions during testing were similar to what Wendell et al (2017) observed amongst children of the same age testing their designs.

Running a test is always necessary for conducting diagnostic troubleshooting in design, and this study was not an exception. Troubleshooting was usually followed by improving the solution or an attempt to improve the solution. The same as testing, troubleshooting happened both during Solution Development and Optimization phases. During Solution Development, children engaged in troubleshooting the problems they faced within their design. Examples include when a component they made did not connect to the other parts of the rollercoaster or the car did not run on that part properly. They would engage in finding the problematic area, making decisions of what pieces would fit better, and finally fixing that part of the prototype. Troubleshooting during Optimization happened when the prototype was designed and built completely, but it did not perform properly. During Optimization, children engaged in finding the problematic area(s) and then tried to fix and improve the solution. In a few instances, children attempted to redesign the entire solution. However, parental involvement helped conduct more effective troubleshooting and improve the solution. The findings suggest that drawing the boundary between testing, troubleshooting and improving was not always possible, and engaging in these actions clearly overlapped with one another.

Crismond (2011) suggested a four-step procedure to conduct diagnostic effective troubleshooting which included: observing the overall performance, diagnosing the problem, explaining why the problem occurred and finally suggesting a remedy. Children in this study showed evidence of engaging in one or combinations of these actions, with no specific order. This is similar to the findings in a study my colleagues and I conducted to explore 7-to 11-year-old girls' engagement in troubleshooting during an out-of-school activity. In that study, we observed patterns of girls engaging in all four troubleshooting actions in a non-linear order when building their solutions (Ehsan et al., 2018). They showed evidence of frequently engaging in observing and naming the flaw, "but that will not be it,", but also acknowledging that they know how to fix, "I got this, I got the idea. See, look, check this out, Dad. Now it can totally fit." While not very often, in some instances the children in the present study engaged in sharing their explanation or cause-effect reasoning for why an error was happening and how it could be fixed. For example, in one instance, Tom identified the problem that the car falls off the track, and he then explained the cause by saying, "This one [pointing to the end track] will just make the rollercoaster fall off." Finally, he suggested two remedies. The first one was not designable with the existing material, "unless all the rollercoasters have them, them …[I] mean the wheels stick… Here. Something stops the car. Like the ones in real." The second one was something he could try, "Oh hey, we can put it backwards. We can put the car backwards." In many instances, parents facilitated conversations with their children to explain the cause and share their ideas to improve.

In many instances, children identified and fixed problematic areas by engaging in diagnostic troubleshooting. As children engaged in rounds of testing and retesting (or observing the rollercoaster performance), one of the strategies they used was to focus on parts of the rollercoaster as the car was running on them. This helped them narrow down their attention to possible critical parts and not get distracted by all the variables. This way they were able to find the problem and fix it. Seeing the rollercoaster as a whole system with sub-systems seemed to be the strength observed in all children. However, children were not always able to zoom out their attention and examine how the flaw they identified is influencing the performance of the rollercoaster as a whole. For example, in the last challenge, John focused on the end part of his rollercoaster. He ran the car several times and observed the performance, and noticed a problem related to a slide. However, he did not zoom out to see if the cause was rooted in a different piece before that slide (which it was). He replaced the slide and rested the rollercoaster, but observed the same problem happening which made him frustrated. However, when his mother prompted him to look to see what was causing the car to not travel smoothly before that slide, he was able to notice that both towers were the same size and that's why the car could not slip smoothly. While this behavior of zooming in is very similar to what designers do (Crismond & Adams, 2012), children needed facilitation to zoom out, examine the whole system and how the performance of the smaller parts influence each other. As children examined the performance of their rollercoaster or parts of their rollercoaster, I observed occasions that troubleshooting action was not effective, and it did not result in finding the flaw or finding the cause properly. Like behaviors associated with beginning designers, children had an unfocused way of viewing the performance of their rollercoaster. In those instances, children rushed to make several changes without focusing on the problem. This happened especially when children were frustrated and had tested and modified their rollercoasters several times. One obvious example was when Tom came back to the room and tested the rollercoaster that his father completed. Since he observed that the rollercoaster was not working again, he started making random changes to the rollercoaster without even focusing on what the problem was. While his father tried to guide him by providing directions and suggestions to find the cause, he continued randomly removing pieces until he gave up and left the activity completely.

When looking at children's design performance over all the challenges, I see that even in the well-structured challenges, children evaluated the success of their design based on the given criteria and also identified additional features. Children's examples showed their designs pushed them to alter their initial ideas and improve their solutions. This seems to be different than what Andrews (2016) observed in elementary students during their engineering tasks. She found that during easy design tasks, which featured more immediate success, children interpreted the success of their design based on the overall performance without describing factors that led to the workability of their design. However, I observed that all the children engaged in conversations describing why their design did or did not work, regardless of how many warm-up challenges the tried.

Looking at the last challenge, Letter Two, I can see children designed their solutions utilizing what they learned in the warm-up challenges and kept the additional features identified in those challenges. They evaluated their solutions using all the different factors, from the specified criteria to all other additional features. At times, they even considered science concepts in their design. The same as Andrews (2016)'s observation, in this challenge, children attended to multiple features and components in their design simultaneously. This behavior seemed to be a more sophisticated design approach compared to the warm-up challenges.

Confronting design failure is known to be a learning opportunity. Failures during design can lead to productive moments and inform future design work. Failures are considered necessary since "they are an essential feedback mechanism" (Lottero-Perdue & Parry, 2014, p.3). However, failure is not always welcomed among designers, especially young designers like children. In this study, similar to Lottero-Perdue (2017)'s findings, across all the challenges, children's responses to design failure were both productive and non-productive. Throughout the Solution Development, most of the time when they observed that something in their solution did not work, they acknowledged it (verbally and/or non-verbally) and kept working and focused on improving their design. As I said before when discussing troubleshooting, there were many moments that children identified a flaw in their design, and just randomly made changes to their design without planning. I did not capture any event where children ignored the identified flaw and continued working with the problematic part.

When their rollercoasters were designed, children's responses to the unworkability of their design were very different. In most of the occasions, they continued troubleshooting and improving their design, without showing any evidence of calling it a failure. Examples were seen after John and Tom completed their warm-up challenges. In challenge three, John observed that the car did not travel from the beginning to the end. While he was first satisfied with his design, because it had met the criteria, he kept improving his rollercoaster until it worked. I also see Tom's second solution, during the second challenge, made the car fall off the rollercoaster, and he just acknowledged that it did not work and engaged in fixing it. However, they were moments that Tom and Scott gave up and lost interest in continuing the activity. Tom stopped working on the last challenge and Scott did the same in the first challenge. While these are examples of non-productive actions in response to failure, they did not happen right away after children faced failure. In Tom's case, he engaged in rounds of troubleshooting-improving before he gave up, and Scott engaged in a conversation with his mother and then when he got very confused about his design, he decided to discontinue the challenge.

In terms of their identity and emotions towards failure (Lottero-Perdue, 2017), children behaved differently at different times. Tom was the only child who got very frustrated and left the room twice. Since the beginning until towards the end, he did not express any negative emotions or frustrations towards his design failures. However, towards the end he got very frustrated and gave up. He got frustrated after several minutes of troubleshooting and improving his solution. While at the beginning he did not take on a failure identity, after he left the room, he even aloud called himself, a failure, “I told you I can’t do anything. I am such a failure…… I can’t be an engineer.” I have to acknowledge that he had asked to come back the next day to complete the task as he was tired. Thus, probably he was not in his best mental mode at that time. On the other hand, Scott and John showed evidence of getting frustrated and expressed negative emotions over things that did not go the way they planned during the process of designing their solutions or after the solution was designed. However, I did not capture any evidence of taking on a failure identity.

Parents played an important role in facilitating the moments that children faced design failure, both effectively and ineffectively. For example, I observed that since Scott’s mother misread the design statement, her involvement misled Scott and further confused Scott in challenge one. As a result, Scott was not able to troubleshoot the problem and gave up on all warm-up challenges. On the other hand, John’s mother’s facilitation strategies, and even her disengagement from the activity, seemed to help John overcome those moments he observed that his rollercoaster was not working. In almost all of the challenges, John, with the help of his mother, continued design in an iterative process of idea generation, troubleshooting, revisiting the criteria and improving. In Tom’s case, his father’s prompting and guidance helped him to be persistent and resilient to failure to some degree, but finally Tom was not able to overcome his frustration.

Engineering design is a social process of negotiation and consensus” (Bucciarelli, 1994, p. 21) that relies on communication and making decisions among all parties involved in the project (Aurigemma et al., 2013; Bucciarelli, 1994; Jonassen et al., 2006). Design decisions are often made collaboratively rather than independently. Engineering design projects for young designers are no exception. K-12 engineering education frameworks have all emphasized the collaborative process of design (e.g. Moore et al., 2014a; Lachapelle & Cunningham, 2007). However, in this study, while in many instances parents facilitated their decision-making process, the children’s engagement in engineering design actions was often independent and they made many of their decisions individually.

Communication and teamwork are important aspects of engineering (Dym et al, 2005). They are necessary for children's engineering engagement and learning. In this study, the children have not always considered their parents and siblings (in case 2 and 3) as team members. While in many events, parents used "we" structured sentences and included themselves in different actions, the children referred to themselves as the one who was doing the activity. This finding is different than what previous research focusing on children and engineering design reported (e.g. Ehsan et al., 2017; Lottero-Perdue, 2017 & Wendell et al., 2017). Ehsan et al (2017) observed that children and their parents became teams and made progress towards their design goals through their collaboration. Similarly, Wendell et al. (2017) reported that much of the reflective decision-making happened in collaboration. This finding is not surprising given the characteristics of the participants being on the autism spectrum.

One interesting pattern that I observed was that as the challenges got more complex in structure, children's willingness to seek help from their parents and/or accept their help offers increased. Accordingly, their collaborations and teamwork also expanded. Their behaviors in earlier challenges were not surprising, given their difficulties in empathizing abilities (Baron-Cohen, 2009). However, their behavior in more challenging tasks is similar to the rationale and findings of the studies that use engineering-related activities to improve the social and collaboration skills of children on the autism spectrum (Albo-Canals et al., 2013; LeGoff, 2004). One possible reason is that they did not see the necessity of collaboration and communication with others when the tasks seemed more doable for them. However, at later challenges, they have possibly recognized the necessity of getting help, and therefore they attempted to collaborate with parents.

5.2.2 Effective Parental Strategies for Children's Engineering Design Engagement

Throughout the activity, parents were very involved and facilitated their children's engagement in engineering design. None of the parents were engineers or had STEM careers or higher education in STEM. Therefore, the strategies they used were not based on their STEM background and arose naturally as children were solving engineering problems. Some of these strategies happened to be similar to what engineering education literature recommends to educators and those that special education teachers use to engage students with autism in STEM. Certainly, I have to acknowledge that the same strategies that were effective at times, they were ineffective when implemented at other times.

Soliciting Information happened implicitly or explicitly in the form of asking prompting questions, asking for confirmation and seeking an explanation. Parents used these strategies when facilitating Problem Scoping, Solution Development and Optimization. Overall, prompting is a very common instructional strategy used in engaging individuals with autism (Ehsan, et al, 2018). Also, questioning was seen to be an effective strategy to support computational thinking of children during an engineering design activity (Ehsan et al., 2019; Rehmat et al., 2020).

During Problem Scoping, this strategy helped children delay building their solution right away. Parents asked the children prompting questions, both explicitly or implicitly, and helped them define the problem. They sometimes explicitly asked them to think about the problem statement and share their plans for how their solution should look like. At times, they implicitly prompted them to define the problem by asking what they think. This strategy is similar to what Lachapelle and Cunningham (2014) suggested for teachers to do when introducing the design problem. With this strategy, children summarized the design problem in their own words and showed their understanding of the problem. This strategy also seems to provide the same scaffolding recommended by Crismond & Adams (2012) for comprehending the problem statement. Throughout the challenges, parents helped children to revisit the problem's requirements by soliciting explanation and asking prompting questions. This revisit helped them expand the problem space which eventually helped with better solutions. The revisiting technique could be similar to "coupled iterations" suggested to educators by Crismond & Adams (2012) (based on Adams et al,, 2003 study). Parents implemented this technique naturally as felt needed and was not as systematic as described by Crismond and Adams (2012). However, the coupled iteration strategy shows to be an effective strategy to engage children in Problem Scoping.

During Solution Development, soliciting information was mostly used to help children generate ideas and plan to design their solutions. Parents asked their children explicit and open-ended prompting questions to help them brainstorm and generate ideas, and create plans for how to build them. This strategy was suggested by Lachapelle and Cunningham (2007) in their design trajectory.

The explicit and implicit prompts also helped them generate characteristics of the idea they were building. Prompting guided children to make decisions about pieces they were going to select and use.

During Optimization, soliciting information was used very often by parents. Explicit and implicit prompting was effective for the children when troubleshooting their problems. The prompts helped them observe and identify the problematic areas in their design. It also engaged them in thinking and having conversations about the remedy and evaluating the solution. One parent also solicited information through seeking explanation which resulted in evaluating the solution. If implemented in a more systematic way, the prompting strategy, along with different forms of guidance that adults can provide, can engage children in the four-step diagnostic troubleshooting technique that Crismond (2008) suggested (i.e. observe, diagnose, explain and remedy). Below, I revisit this.

Providing Guidance was a very effective strategy that happened in multiple ways including direction, suggestion, assessment, modeling and explanation. Through this strategy parents led the interaction purposefully to provide information and guidance to children. Providing direction is very similar to explicit instruction strategy/intervention being used for individuals with autism. While directing or explicit instruction is common management intervention for individuals with autism (Machalicek et al., 2007), it is also common for teaching them math and science (Ehsan et al., 2018). Providing suggestions also occurred very often and provided some scaffolding for children while giving them a space to learn and explore more independently. This strategy is similar to the facilitation strategy which was found to be effective to the role parents played during engineering design activities (Svarovsky et al., 2018; Ehsan et al., 2019). Providing explanations followed or was followed by other strategies like direction or suggestion. Explanations and suggestions are commonly used with student-directed STEM instruction as children with autism are asked to lead an activity, adjust their goals and evaluate their progress (e.g. Agran et al., 2006). While doing that they are provided with guidance that usually comes in the form of explanations and/or suggestions. Finally, parents also assessed children's design and/or did some modeling for them. Modeling was observed to be effective in previous research during engineering design activities (Rehmat et al., 2020; Johnston et al., 2019). Teacher-modeling is also a common instructional strategy being used to teach math and science to individuals with autism (Ehsan et al., 2018).

To facilitate Problem Scoping, parents directly asked their children to read the design statement. This is similar to the findings of the previous research, that parents often supervise and direct their children when they begin engaging them in engineering activities (Ehsan et al., 2019; Ohland et al., 2019). They then modeled what the problem was asking and provided explanation by summarizing and/or restating the problem. Providing explanations, which was often followed by prompting, helped children to comprehend the problem statement (Crismond & Adams, 2012).
During Solution Development, parents provided a fair bit of guidance. Providing guidance through suggestions and explanations (recapping the problem and plans) was an effective strategy to reengage children in their design. Reengagement usually resulted in generating ideas and prototyping. Sometimes, parents directly encouraged children to use a piece or select a component in their design. As children were prototyping their solution, parents also modeled how pieces go together or how they can attach pieces to their rollercoaster to follow their plans. Finally, parents engaged in assessing components of the prototype as children were building. The assessment was often very direct. The purpose of this assessment was to engage children in decision-making process about the workability of components of their solutions.

Parents facilitated the Optimization phase by providing guidance to their children. The guidance appeared in the form of direction, explanation, assessment and suggestion. Through this guidance, they sometimes modeled and encouraged employing diagnostic troubleshooting (Crismond & Adams, 2012) which resulted in engaging the four-step troubleshooting (Crismond, 2008) in no specific order. Parents guided their children to observe the performance of their prototypes and to identify the problematic areas. They would model these steps themselves or encourage children to do it by providing suggestions and/or directing statements. While parents sometimes sought for explanation from their children, they often explained why the protype was not working. They then provided suggestions (or prompting) for children to find the remedy and improve their solution. In very limited occasions, parents assessed children's design which led children to engage in reasoning and evaluating their design.

Assisting happened during Solution Development and Optimization. This strategy was implemented at different times and in different ways. They would offer help verbally, ask for permission to get hands-on or build a component for them without a heads-up. Parents were constantly there for their children and very involved in different aspects of their design and throughout the activity. However, they sometimes explicitly used an assisting strategy where they became an assistant to the child. One parent (John's mother) talked about this strategy in her interview, emphasizing that she wanted to be available for her son, but did not want to distract him from thinking. Therefore, she made sure to remind him she is there to help. Similar events happened as children were designing their solutions. Parents offered help verbally to ensure their children that they were available for them. They would wait for children to ask and/or invite them to help. They would also ask permission to help them build a component of their design. If they got permission to help, they would follow up with a suggestion and/or explanation or getting hands-on and build parts of the solution. When getting hands-on while assisting the children, parents either gave children the pieces they could use in their design or build a part of the rollercoaster for them.

During Optimization, parents engaged in the assisting role very similar to the ways they did when their children were designing solutions. However, the purpose of assisting was to identify the problem and improve it. Assisting was mostly hands-on; enacted by parents pointing to a problem, giving them the pieces that they needed to fix the problem or even fixing the problem themselves. The three children were different in terms of getting help and accepting assistance from their parents. John was more willing to accept his mother's help, and his mother was cognizant of when to offer help or to get hands-on. Scott and Tom were more reluctant to get help. Scott's mother was very involved and attempted to help very often, with or without a heads-up. She also got hands-on several times. This involvement made Scott frustrated and at times he did not allow his mother to assist. Tom showed to be the most independent child, but also the most talkative, among the three. His parents mentioned in their interview that he wants to be the lead at home and do thing independently. They also mentioned that he is very curious and shares his excitement with others. I also observed that Tom was very independent but would ask questions from his father and describe what he was doing. Given these characteristics, he did not welcome any help until he felt it necessity. On the other hand, his father used lots of prompting and suggestions, but never got hands-on without a heads-up. Especially in the last challenge that he got hands-on, he first asked permission to build the rollercoaster with him, which helped him stay engage in the activity even when he was very tired and frustrated.

Disengagement happened during Solution Development. During disengagement parents purposefully decided to disengage from the activity temporarily to allow their children to work independently. While disengagement can mean the times parents did not do or say anything, I am just referring to when parents disengaged from the activity per their child's request or by their own decision to respect their child's space and independence during design. This point came out of all parents' interviews in different ways, as they mentioned their intentionality in giving children a space to work, but also to be available if needed. Therefore, disengagement sometimes started by statements to offer help, and happened when offers of help were declined by the child. Disengagement as a parental role was observed in previous studies of my colleagues and I when focusing on children's CT engagement during engineering activities (Ehsan et al., 2019; Ohland et al., 2019).

During the Solution Development phase, parents would leave the pieces they had in hand, stop suggesting or offering help verbally and/or sit back and observe their children. Effective disengagement usually culminated with a response to children's help requests, questions or comments. It sometimes ended when the child was done with a task and was moving to a different task, which usually parents were cautious about when or how to re-engage. I also observed ineffective disengagement that even against the child's request, parents re-engaged quickly, provided comments or directions to children which caused frustration.

Affirmation was a very effective strategy across all of the engineering design phases, not only to facilitate engineering design engagement but also to motivate the children to continue the activity. Affirmation was observed coming in two different forms with two purposes: providing (1) encouragement, and (2) confirmation. Both strategies mediated children's engagement in engineering design.

Encouragement facilitated all design phases. Encouragement got children started with their design and helped them overcome their frustration and re-engage in the activity. When tasks were completed, parents cheered with them or used simple encouraging phrases like "good job". This encouragement looks like the rewarding system that usually works for all children including children with autism. At times, parents also reminded them of their abilities in similar activities like doing puzzles or playing with LEGO bricks, and telling encouraging statements to let them believe in their abilities. For example, they told them, “I have every faith that you can do it.” or “You got this.” This encouragement seems to be very similar to the parental support observed in previous studies of children’s engagement in STEM activities (Ehsan et al., 2019; Ohland et al., 2019; Rehmat et al., 2020).

Another form of encouragement that parents provided was referring to the children as engineers. They told them phrases like “you need to engineer this…”, or “like how engineers build/think…”. In an event that one of the children got frustrated, his mother reminded him that engineers also fail and it is okay to restart several times because this is what engineers do. This strategy of referring to children as engineers leveraged the engineering context of the activity and seemed to be very motivating for reengaging children in the activity. Similar patterns of encouragement were also observed in recent work focusing on teacher talk in a middle school classroom (Johnston et al., 2019). All parents talked about this during their interviews. They all mentioned that their sons acted like an engineer and did engineering, and this is what they were hoping for them to get out of this activity. One parent specifically said how proud she was of her son for being an engineer and learning that engineers fail over and over again until they succeed. Two of the children, Scott and Tom, mentioned that they were doing engineering and they can do engineering. Having an understanding of what engineers do is also mentioned as an important aspect of K-12 engineering which can eventually help children do better in their engineering activities (Moore et al., 2014a).
In all of the design phases, confirmation served as an immediate feedback to let children know what they were doing or saying was right. Confirmation helped children continue engaging in what they were doing. Usually confirmation was followed (or followed) by providing guidance or soliciting information. The immediate feedback following by prompting was also observed in previous studies focusing on children science and math learning (e.g. Knight et al., 2012). Additionally, confirmation also served as the concluding feedback on children’s design, before or after testing and evaluating.

Other Facilitation Strategies: Parents also used a *student of the child* strategy to facilitate the activity (Beaumont, 2010). While this strategy was not observed as practiced by parents very often, when it happened, it seemed to be an effective way to gain children’s attention, especially when children were distracted. Parents acted like they did not know how to do something and asked their children to show them how to do it. In previous research, this strategy was observed being effective to engage children in computational thinking during engineering activities (Ehsan et al, 2019; Ohland et al., 2019).

6. CONCLUSION, ASPIRATIONS AND IMPLICATIONS

6.1 Conclusions

In this study, I conducted a multiple case study to investigate the engineering design experiences of three children with mild autism during an engineering design activity. Given my theoretical underlying, I focused on (1) the individual level and their interactions with the environment; ways children engaged in engineering design phases based on their interactions with the activity, and (2) the more knowledgeable other; ways parents facilitated and scaffolded their children's engineering design engagement.

To investigate children's engagement in engineering design practices, this study responded to these two questions:

- What engineering design practices (i.e. Problem Scoping, Solution Development and Optimization) do children with autism engage in?
- How do they engage in engineering design practices?

This study helps expands our understanding of what engineering design can look like for children with mild autism, particularly as engineering design is considered to be a very iterative process with multiple phases and actions associated with them. The first main finding of this study is that these children (with mild autism) could engage in all of the engineering design phases. They were able to use their engineering thinking to build solutions to the engineering design problems given in this activity. Looking within and across all the challenges, I observed many similar instances of the children's actions and dialogues that could be associated with all three engineering design phases. Children engaged in problem definition and information gathering throughout the activity and in all the challenges. When developing the solution, they generated one idea/solution to each challenge, but constantly brainstormed features and characteristics of that idea. They also showed evidence of planning by discussing strategies and steps they were going to use to build the solution. They made decisions about selecting pieces to build their solutions as well as deciding what components and features of the idea should be included in the final solution. When modeling and prototyping, they mainly started by physically building their solution, but occasionally, they used gestures to model what their solution would look like. They never sketched their design. Finally, they engaged in design optimization not only when building solutions, but also while designing solutions. They tested and troubleshot the pieces used to build the solution. They improved the built solution by testing the performance and troubleshooting it. They also engaged in evaluation by sharing their reasoning about the workability of their solution. Finally, an important note is that in all three cases, the children's engagement in engineering design phases was non-linear and very iterative.

The second main finding is that I observed some differences in the children's engineering design engagement. For example, not all children tried all of the warm-up challenges, and only one completed all five challenges. The children's solutions to the last challenge, Letter Two, were completely different. However, they considered all of the criteria in their solutions. The children's engagement in different engineering phases were slightly different. For example, two of the children were more willing to share their plans and ideas aloud, while the third child only acknowledged that he had an idea but never shared what the idea was. Overall, children in this study met most of the expectations mentioned in the EiE trajectory for children of ages 7-10.

I also observed similarities and differences between the findings of this study with previous literature on engineering design. Many of the instances of the children's engagement in engineering design captured in this study were similar to what previous studies focusing on participants of the same age or older have observed. Some examples include additions to the context, engagement in Problem Scoping by expanding both the problem and solution space at the same time and engagement in all four actions of troubleshooting. The differences were mainly observed in the ways children generated and shared their ideas, communicated their plans with others, engaged in troubleshooting at the sub-system level and collaborated with their parents. The differences may be a result of their autism characteristics. Additionally, some of the behaviors these children engaged in were comparative to what experienced designers and engineers exhibit. Given the depth of the analysis in this study, I expect that these findings are not limited to these three particular children and these instances can be seen in other children with mild autism too.
On the other hand, I explored parental influences on children's engagement in engineering design practices. I responded to these two questions:

- What strategies do parents use to support their children's engineering thinking when they engage in an engineering task?
- How do these strategies help children engage in engineering design activities?

Given the theoretical perspective, I expected that social interaction with adults would be important. The findings of this study showed that while children were not socially interacting with their family members when they tried the challenges, their parents still played an important role in their design engagement. Parents used different strategies during the activity that supported and facilitated children’s engineering design problem-solving. These parents were not trained to do engineering or STEM with their children, and these strategies may have come naturally as they were helping their children throughout the activities or were adapted from their previous trainings for how to interact with their children in other contexts. However, some of these strategies were similar to what literature recommends for formal and/or informal educators in STEM education and/or special education. These strategies include soliciting information, providing guidance, assisting both verbally and hands-on, disengagement and being a student of the child. Parents used soliciting information and providing guidance very often and they were effective in engaging children in all engineering design phases. Assisting and disengagement were most effective during Solution Development. Affirmation was a very effective strategy across all of the engineering design phases, not only to facilitate engineering design engagement but also to motivate them to continue the activity.

One parent (Case 2) used the strategies in an order where she would be disengaged and give autonomy and freedom to her son to do the activity. As needed, she would provide facilitation with the least necessary involvement like asking promoting questions, providing explanations and suggestions. However, gradually she would increase her involvement to providing directions and assisting with building. This pattern of facilitation helped the child to be engaged in engineering design thinking, with the support and scaffolding he needed at times, and helped avoid and/or overcome his frustration at different instances. This pattern seems to be similar to the *Least to Most Prompt Strategy* (Neitzel & Wolery, 2009).that I considered when designing this activity and is being used when teaching STEM and other subjects to children. Since this parent had a career related to supporting individuals with autism, it may be possible that she was aware of this strategy and had already found it helpful to implement when interacting with her son.

As mentioned before, parents effectively used one or a combination of these strategies at different times. However, in certain circumstances, the same strategies did not seem to be very effective and further frustrated children. Additionally, at times, the same strategy that helps one child engage in an engineering practice did not help another one, given the child’s personality (e.g. being a lead or follower at home). While I believe these strategies can help other children with and without autism, effectively utilizing them requires considering children’s specific personalities.

6.2 Implications for Educators

The first implication of this study is the list of effective strategies used by parents. These strategies showed to be effective in engaging these children in engineering design and in many instances helped them overcome their frustration. Although these strategies were employed by parents in a lab-based setting, many of them are similar to the instructional interventions and instruction used in STEM and special education. Additionally, utilizing these strategies support the constructivists' point of view. Learners construct their own knowledge when they are in the center of the learning environment. However, adults’ scaffolding and facilitation help them move to the zone of proximal development where the learning could not be achieved if working independently. Therefore, I believe that formal and informal educators can adapt these strategies to other contexts, with children with or without autism. They can utilize strategies individually and/or a combination of them to facilitate children’s engagement in design.

When employing these strategies, formal and informal educators should pay attention to the specific characteristic of their learners. In this study, all three children were diagnosed with mild autism and showed similar patterns of behaviors. For example, too much involvement of the parents was not welcomed by any of the children. In many instances, children simply ignored parents’ suggestions, direction and promptings when they felt unnecessary. However, the involvement seemed to become ineffective when continued, as children showed disruptive behaviors such as discontinuing building their ideas, throwing a piece to show their unwillingness or verbally asking parents to stop talking. Similarly, getting hands-on and building the prototype without a heads-up seemed to be disruptive for children and caused frustration. I encourage educators to let children know that they are available to provide support and guidance, and if children permitted them, they get hands-on. In instances that children are spatially misusing the material, providing guidance by modeling (far away from the prototype) seemed more effective than changing something in the prototype. However, in events that children are too frustrated, and they seem to be quitting the activity, educators may want to get hands-on and build with children and/or provide explicit prompts to provide the sense of design success to them. However, they should employ this technique cautiously as children may react differently. In sum, I believe children can be engaged in engineering design more productively, when parents allow their children to lead the activity and let them know that their presence is to provide additional support. Thus, I encourage educators to play the role of facilitator, and not supervisors, to allow children to explore, make mistakes and learn from their mistakes until they succeed.

One recommendation for educators is to be flexible with using the strategies found in this study (i.e. Soliciting Information, Providing Guidance, Disengagement, Being Student of the Child, Assisting and Affirmation). Switching strategies was very common among all three parents and seemed to be very effective. Keeping in mind that one strategy can be helpful in an event but not in other events. For example, one parent turned a prompting question to encouragement and provided a design suggestion later. Another recommendation for educators is to remind children of their abilities by giving them concrete examples of their previous experiences. At times, this technique seemed to be particularly helpful when children got frustrated and had the fear of not being able to do a challenge. Parents would remind them of their strong abilities of similar activities like playing with LEGOs or doing Puzzles. One parent also reminded her son that he thought that LEGOs are difficult and now he has mastered them. Finally, aligned with previous literature (e.g. Moore et al., 2014), I recommend educators introduce children to engineering and the job of engineers. Let them know that engineers fail over and over again until they succeed. In this study, parents talked about engineers' failures throughout the activity and mostly when children encountered a problem. This conversation happened in the form of encouragement and helped children face failures more easily and reengaged them in fixing the problem. However, I believe that it may be even more effective if educators do the introduction prior to the activity and remind children of the role of failure in engineering when needed during the activity. One suggestion is to have a read-aloud or picture walk of books written for children to teach them about engineering. Many of them can be found in Purdue's INSPIRE Engineering Gift Guide.

6.3 Implications for Curators of Engineering Learning Resources

One implication of this study is the activity itself. In a systematic literature review that my colleagues and I conducted, we found no research-based engineering intervention for children on the autism spectrum (Ehsan et al., 2018). This activity was designed using an asset-based approach by considering theoretical perspectives that could enhance engineering design engagement of children, autism STEM-related strengths, and the EiE trajectory for designing resources. The theoretical considerations, using cognitive and social constructivist applications, have been discussed in the previous sections of this chapter. The main autism STEM-related strengths considered in this activity included aspects of building with physical objects, problem-solving and spatial reasoning. Additionally, many of the parameters of the EiE trajectory were used to design this activity. A few recommendations for using this trajectory are provided at the end of this section. Although the aim of this study was not to evaluate the activity and its components, the findings showed that all three children effectively engaged in engineering design phases in this activity. I believe the structure of this activity played a role in this engagement, and therefore can serve as a guide for educators and curriculum designers to design other engineering learning resources and activities. Below, I briefly present the main components of this activity. I also summarize the patterns I observed in regard to children's engineering design engagement. They are described thoroughly in Chapter 5.

1. The series of challenges ranged from well-structured to ill-structured
    - Children became familiar with the system of rollercoaster they were developing (Gero & Kannengiesser, 2004) and its functionality given the different materials they used.
    - The challenges provided children a chance to spatially and gradually explore material which better prepared them to scope the problem in the last challenge (Letter Two).
    - The challenges helped with gradually generating ideas and understanding the context of the problem before learning about the details of the last (and main) challenge---it could possibly help with their difficulties in not seeing the bigger picture of the problem and focusing too much attention to details given their weak central coherence (DSM-5, 2013).
    - Children considered more aspects of the problem gradually which helped with expanding the problem and solution space gradually.

2. The Least to Most Prompt strategy
   - Helped children re-engage in exploring materials and generating ideas by receiving different forms of hints.
   - (Note: not all children needed the hints)
3. The similar format and organizations of Warm-up Challenges
   - The challenges are written in the same organization where children first see the design challenge text, and then possible hints. The font in all the challenges are the same too.
   - All are numbered and have clear goals—this helped with their difficulties in transitions between activities as well as lack of structure.
4. Family-based intervention and the presence of a more knowledgeable other
   - Provided a safe place to avoid the rigidity and aloofness that can be observed in a team with new members (National Autism Center (NAC), 2009).
      i. For different contexts, I suggest having introductory activities to help children get familiar with people in their teams. This strategy has been previously used in LEGO therapy was approved to be effective to engage children in teamwork by research (e.g. LeGoff, 2004).
   - Helped with children's engagement in engineering design and overcoming frustration in overall (see chapter 5 and chapter 6-Conclusion).

Based on the findings of this study, I also suggest changes to the structure of the activity.

- Implementing the activity over a longer period of time and possibly multiple sessions: Children could spend more time on each challenge to explore more ideas and learn about the material. This could possibly help them with a more robust profound solution to the last challenge, Letter Two.
- Adding an unstructured, self-guided challenge to the activity. All three children were very excited about exploring the activity on their own. Two of the children spent some time designing a rollercoaster without considering the given criteria. The findings showed that they both were able to build a working rollercoaster and had fun building it. They also explored different ways they could use different pieces differently. They engaged in Solution Development and Optimization during the self-

guided challenge. I believe providing an exploratory opportunity for them to get the excitement out is valuable for not only children on the autism spectrum but all.

- Combining both ideas and based on the experience of Case 3-Tom, I suggest implementing a longer activity that provides a self-guided opportunity for children after warm-up challenges and before the last challenge. By then, they already explore the material and generated some ideas in mind. Having the self-exploratory may provide an opportunity for them to build their ideas without restricting their creation by the problem boundaries. This may help them to see their design abilities without being too focused and stuck with design criteria and constraints. Then, they can be given the last challenge where children have to now focus on details and design a rollercoaster considering the criteria and constraints.

Using the comprehensive EiE design trajectory was very helpful when designing this activity. As mentioned before, children in this study met most of the expectations mentioned for the ages of 7-10. Some of the strategies that parents used were similar to what EiE suggests. However, given the patterns observed in this study, I provide some recommendations for educators or curriculum designers when designing learning resources to support children with mild autism engineering design.

- EiE emphasizes that children at the age of seven should be able to balance trade-offs of up to four to five design requirements to ensure multiple valid solutions. Based on the findings of this study, working with five design requirements seems reasonable for children with mild autism. However, the limited instances of considering trade-offs observed in this study were facilitated and initiated and facilitated by parents. Therefore, curriculum designers and educators need to consider providing additional support for this process.
- EiE states that children should communicate their ideas, designs and solutions using different techniques including drawing, writing, discussion and presentations. This activity provided space for the two techniques including drawing and discussion. None of the children used drawing, even though two of them specified drawing as their hobby. One possible reason may be the limited time children had to do the activity. Therefore, given the importance of sketching, modeling and analyzing the ideas before building the

ideas, I recommend educators and curriculum designers to allocate a specific time and direct instruction for children to sketch their ideas. I acknowledge that further research is certainly needed to focus on this aspect of design for this population. Additionally, the extent to which children shared and discussed their designs varied depending on the child, the challenge they were problem-solving and parental involvement. Therefore, I recommend when assessing and judging children with mild autism' design decisions, conversations and discussion should not be the only element.

- EiE emphasizes collaboration in engineering design. At the age of seven, EiE suggests children work in pairs or teams of 3 on a shared Solution Development. EiE's expectation is that children work together on making design decisions at any phase of design. EiE also provides strategies for teachers to support design collaboration. However, when working with children with mild autism, I recommend considering and appreciating their unwillingness to interact with others unless they see the need. As discussed in the next section, further research is needed to explore engineering experiences of children with mild autism and how they collaborate with their peers with or without autism.

NGSS has also a set of standards that impose the expectation for the engagement of third to fifth grade students in engineering design. The standards are written without consideration of children with autism or other neurodiversity. The findings of this study suggest that children met these standards for the most part, but some differences were also observed.

NGSS Standard-3-5-ETS1-1: Can define a simple design problem reflecting a need or a want that includes specified criteria for success and constraints on materials, time, or cost.
The children's engagement in problem scoping was beyond the NGSS standard for 3^{rd}-5^{th} grades.

- Their understanding of the problem evolved gradually
- Treated design problems <u>not as simple</u> and well-structured but as ill-structured with many variables
- Paid attention to the given design criteria and constraints, also considered additional context

NGSS Standard-3-5-ETS1-2: Generate and compare multiple possible solutions to a problem based on how well each is likely to meet the criteria and constraints of the problem.
The children meet the expectations of NGSS when developing their solutions, however, their engagement was slightly different.

- Often generated one overall solution, with lots of characteristics
- Compared and made decisions towards selecting the characteristics
- Made their decisions based on the given criteria and those self-specified later

NGSS Standard-3-5-ETS1-C: Plan and carry out fair tests in which variables are controlled and failure points are considered to identify aspects of a model or prototype that can be improved.
The children's engagement in optimization was beyond the NGSS standard for 3rd-5th grades.

- Fair tests and unfair tests were both conducted
- Troubleshooting happened to identify the problematic area and suggesting remedies
- Design evaluation occurred against the given criteria and self-specified
- Improvement happened randomly, but often aimed to fix the problematic area

6.4 Potential Implications for Different Context

While this study was conducted in a lab-based setting with a particular age group, findings of this study may be transferred to other settings. The characteristics that the children exhibited in this study such as their unwillingness to ask/get help and work in teams with their parents (and siblings), their frustrations over failure and too much involvement of others may be seen in pre-college classrooms, higher education and in the workplace. These characteristics may become challenging for these individuals in different contexts. Thus, educators and curriculum designers should be aware of these characteristics and anticipate these characteristics, before engaging these learners in learning engineering (and other subjects where social interactions maybe important). While taking an asset-based lens can help educators see how some unique characteristics of individuals with autism can help them engage in engineering learning, being aware of the possible challenges can help them plan ahead of time and accommodate the needs of these individuals. To have an inclusive engineering education, educators may possibly need to adjust their pedagogical approaches and assessments to meet the needs of these individuals. One example is that teamwork is an essential part of many of the undergraduate engineering courses where students are evaluated based on their performance in teams and possible peer-evaluation. Thus, having a back-up plan for possible help for these individuals is important.

6.5 Aspirations for Future research

The goal of this study was to capture the engineering experiences of children with mild autism. Therefore, I aimed to provide a setting where children can engage in engineering design in a bounded activity, with minimal external distractions while also providing space and opportunities for family interactions. The activity was implemented in a university lab setting (the lab space for the INSPIRE Research Institute for Pre-College Engineering). Family members of the same household were welcome to participate in the activity. However, only in one case, the entire family came to the lab, in other cases one or two family members were missing. Therefore, the activity turned out to have a structure of dyads of parent-and child with mild autism, and not the entire family, which made my presence more visible. While this structure helped me achieve my research goals, future research should explore children’s experiences in more naturalistic family settings, such as at home and/or in museums. Additionally, this study captured the challenges and opportunities that children had given parental interactions during this activity. I anticipate differences in children’s experiences without my (or any researchers’) presence and with having siblings more naturally involved.

The findings of this study align with individuals with autism’s STEM interests and strengths, and further shows their strengths in engineering design. As we, the engineering education community, move towards being more inclusive and diverse, exploring more ways to include children (and adults) with autism and other neurodiversity conditions is needed. While the activity used and the parental strategies captured in this study are great resources to promote the inclusion of this population, more research-based resources are needed. Further research should explore children with mild autism’s experiences in engineering in different inclusive learning settings. Researchers need to further investigate how children engage in the same or different engineering design activities with their peers with or without autism in school while teachers facilitate the activities for the entire class. Previous studies have focused on peer mediations to help children with autism in inclusive settings (Mason et al., 2014; Kamps et al., 2017; Camargo et al., 2016). Thus, following those studies is necessary to see how different and similar those interventions can be used in the context of engineering. Future research may also examine the order of the strategies being used in different context to see if using the Least to Most involvement pattern is effective for engaging children in engineering. Researchers also need to explore teachers' and peers without autism's experiences during engineering design activities. This future research is particularly valuable and important since children's peers in school would be their future college classmates and colleagues. A more inclusive and diverse engineering community will be shaped when colleagues know how to work with each other, and this learning may be more effective if it starts in childhood.

Engineers apply science, math and other related content knowledge when solving engineering problems and designing solutions. The EiE trajectory also expects that children age 7-10 can take age-appropriate scientific considerations and mathematical calculations in their successful Solution Development. I observed some instances where children considered science in their design. Also, they engaged in very simple calculations and measurements when designing their rollercoasters. I believe the nature of the activity did not require more applications of STEM. Therefore, exploring ways and the extent in which these children can use, learn and apply STEM during engineering design is very important. I acknowledge that this exploration requires us to create activities that provide more opportunities for children to engage in STEM learning and application. This research is valuable as children with autism have difficulty learning STEM in traditional settings and with traditional practices (Hwang & Taylor, 2016; Kaweski, 2011).

As mentioned above, one important recommendation for future research is changing the setting and context of the study. For that, researchers and educators need to create engineering design opportunities appropriate for those contexts and settings. Thus, to be able to fully characterize engineering thinking of children with mild autism, I recommend taking design-based research approaches where researchers and educators collaborate with each other to design new integrated STEM activities, for different home, museum and in-school settings, and explore children with autism's engagement in those activities.

Another recommendation for future research stems from children's interactions with parents. At times, I observed that parents used we-structure conversation instead of you-structure. The we-structure dialogues enhanced a more collaborative experience for children. However, while it was beyond the scope of this study, I anticipate that closely examining the nature of child-parent dialogues may reveal findings on children's motivation, persistence, agency and the sense of collaboration. Therefore, future research should examine child-led and parent-led conversations and their responses and explore the opportunities they provide for children.

Finally, future research should continue mapping autism characteristics to engineering design behaviors. In this study, I observed evidence that children engage in engineering design in certain ways that may have possibly been a result of their autistic and systematized brain. The aim of this study was not to map out those characteristics to engineering phases and practices, but to capture evidence of their engineering design engagement. However, this future research is needed as it can add clarity to ways individuals on the autism spectrum do engineering. It can also serve as a guide for educators and researchers when taking asset-based approaches to design and facilitating engineering learning opportunities for these individuals.

APPENDIX A. PARENT GUIDE

This information was sent to parents before they attend the session. It introduces the activity and ways I expected parents to interact with their children.

Roller Coaster Challenge Guide

This activity is an engineering design activity. It starts with a short letter from the director of an amusement park. In the letter, the director states a problem and asks "engineers" to solve it. She suggests that the engineers start by completing a set of warm-up challenges to explore the materials that will be used for the challenge to learn how different pieces work together. After each family explores the materials, a second letter will be given to them. The second letter includes the criteria that should be considered for designing a roller coaster. Then, the family builds their own roller coaster.

Parent Guide

1. This is a family-based activity, but we encourage parents to let their children lead the activity while they, as parents, help facilitate the activity. Leading the design activity may include talking about the challenge and different ideas, planning the Design Solution , exploring materials of the kit and building the rollercoaster using the kit.
2. The main goal is to let the child have **fun** while using their thinking to build. Thus, it is fine if for any reason children decide to create their own challenge and build their own without using the given challenges.
3. It is up to the family to decide who wants to read the challenge set (the child with autism, the child without autism or the parent).
4. Parents, better than anyone else, know their children. They can understand what message the child with autism is conveying through her/his verbal and non-verbal interactions. We encourage parents to verbally clarify what children are saying while the researchers are video recording.
5. Parents can help understand what children are thinking by asking them questions and encouraging them to talk about what they are thinking if possible.
6. For warm-up challenges number 3 and 4, we ask that parents use the *Least Prompt* strategy. In this strategy, parents will use a prompt hierarchy ranging from least to most intrusive (written, partial visual, fully visual). Each prompt level should be accompanied with verbal prompting from parents.

   For example, the prompt first includes short written instructions that parents (or children) need to read. If the child with the help of other family members is able to build the structure that is asked, the family moves on to the next challenge. If they are NOT able to build the structure, the parents will provide the next level of prompting which is a picture of the material needed (labeled by P#2). If the family still is not able to build the structure, a shape of the structure will be provided (labeled by P#3), so the child can build the structure he is asked.

APPENDIX B. BUILD A ROLLERCOASTER ACTIVITY

Letter One

City Amusement Park

Dear Engineers,

My name is Hannah Noah. I am the director of the City Amusement Park.

Many kids came to the park. They were very happy and enjoyed the rides and games. However, they were sad that the park does not have a rollercoaster. They asked me if I can add a roller coaster.

Can you please help me?

I want you to design **a model for a roller coaster**. Use the box of materials provided to design the roller coaster.

Before you design the roller coaster, you should explore the materials you will use to create the model. Try the *Warm-up Challenges* to explore the materials.

At the end, my helper will take a photo of your model, and will send it to me. will then decide what design I want to use in my park.

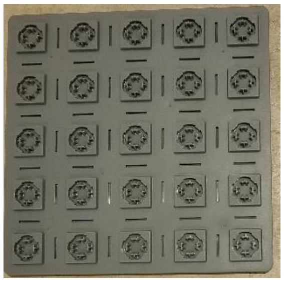
Thanks,

Hannah Noah

Director of City Amusement Park

Explore the materials in the box.

1. Gray Base



2. Coaster Car

3. Start Track

4. End Track

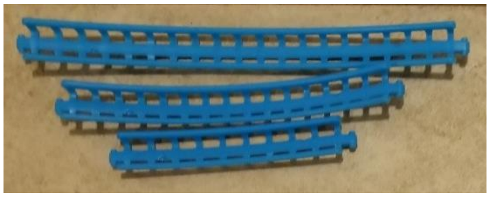
5. Black Post

6. Loop

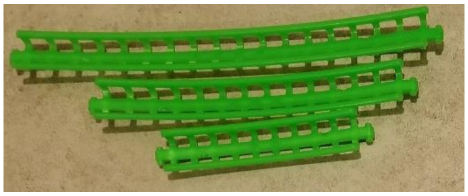
7. Curved Tracks

8. Tunnel

9. Blue Slide Tracks



10. Green Slide Tracks



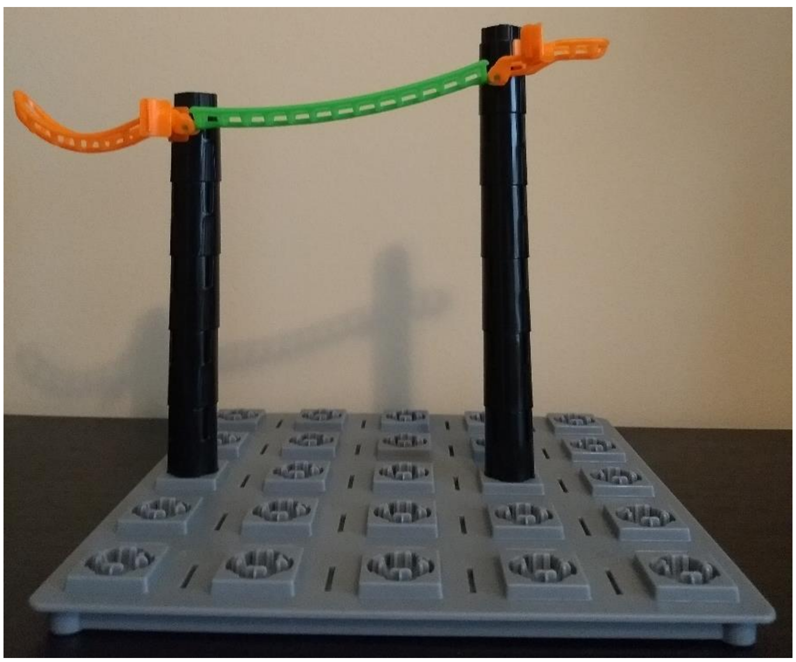
11. Orang Slide Tracks

Warm-up Challenges

Explore how the materials work!

Warm-Up Challenge 1. Build the roller coaster you see in the picture, and try it!

How many black posts does the Coaster Car drop down?



Warm-Up Challenge 2. Can you build a steeper roller coaster than the previous roller coaster you made?

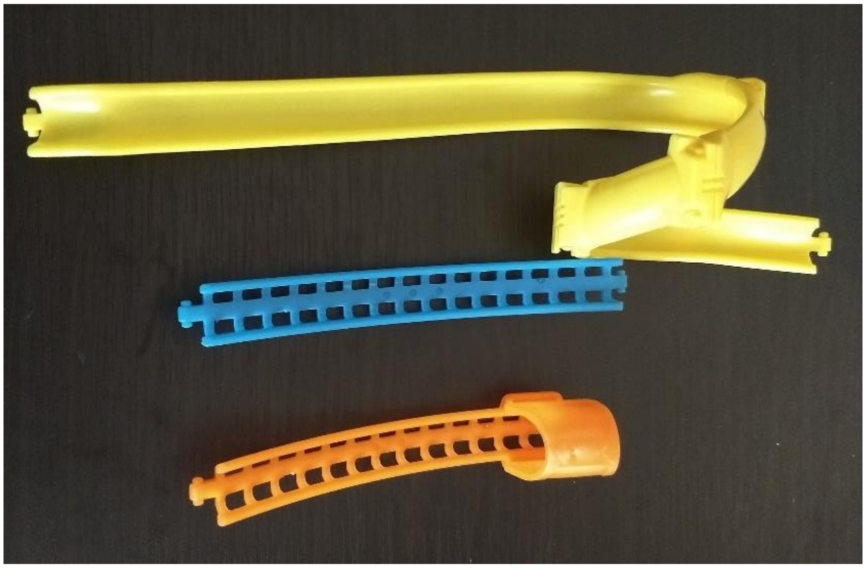
Prompt 1.

- Try other slide tracks

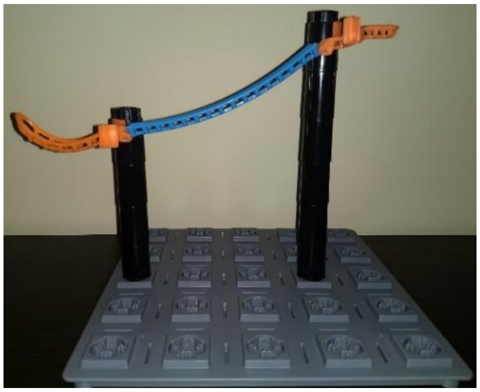
- Try a different number of black posts

In each roller coaster you make, can you **count** that how many black posts does the Coaster Car drop down?

Prompt 2. You can use one or more of these slides.



Prompt 3. You can build one or more of these rollercoasters. They are all steeper than the one in challenge 1.



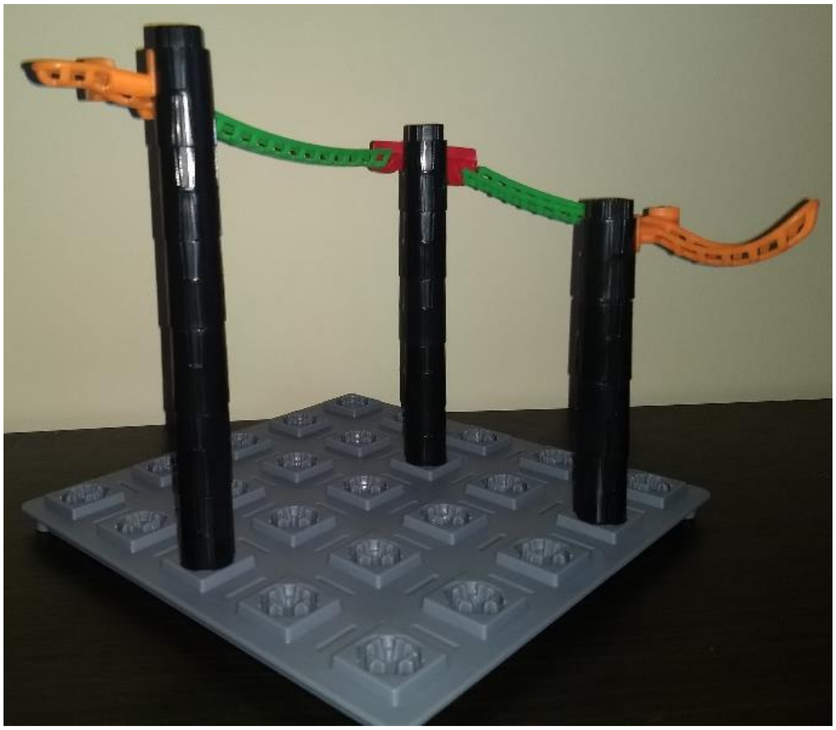
Warm-Up Challenge 3. Can you build a roller coaster that turns the coaster car before it stops?

Prompt 1.

- Use one curved track (red or blue)

Prompt 2. You can use one or more of these turn track.

Prompt 3. You can build one or more of these rollercoasters.



Last Challenge: Letter Two

Design a Roller Coaster Challenge

City Amusement Park

West Lafayette, IN, 47906

Dear Engineers,

Thanks for agreeing to design a roller coaster for my park.

Do not forget:

- Children have asked for a **very exciting** roller coaster. To make them happy, the roller coaster needs:
    - to start very high and end low.
    - to have a loop.
    - to pass at least one tunnel.

  What other features will make the rollercoaster exciting?

Imagine the **fastest, loopiest, and steepest** roller coaster you can, and try to build it.

- We have **a limited space** for the rollercoaster. Build the rollercoaster on the gray base.
    - All the black posts must be built on the gray base.
    - The roller coaster can go beyond the base.

Thanks,

Hannah Noah

Director of City Amusement Park

APPENDIX C. PARENT'S INTERVIEW

The Parent Interview Protocol used in this study is as below. This protocol was approved by IRB. I'd like to ask you a few questions about the things you did today as well as things your child may do at home or at school.

- Tell me about your impressions of the activity you did today. what did you like? Describe this experience of playing with your child, trying to solve a problem and building the solution.
- What do you think your child learned from this activity?
- What do you think your child's strengths were?
- What was challenging for your child in this activity?
- What did she/he like about this activity?
- How do you usually play together?
- Tell me about this experience of playing with your child? How was it different than /similar to your previous experiences of playing together?
- What is your child favorite toy/game/hobby?
- What is his/her favorite subject at school?
- What is engineering? What do you think about engineering and being an engineer?

APPENDIX D. CHILD'S INTERVIEW

The Child Interview Protocol used in this study is as below. This protocol was approved by IRB.

I'd like to ask you a few questions about the things you did today. I'm also going to ask a few questions about things you may have done at home or at school.

- So, can you tell me about what you did with your family today?
- What was your most favorite part? Why?
- What was your least favorite part?
- Is there anything you did not like about this activity?
- Have you done any similar activities anywhere else?
- What are your favorite toys? What are your favorite things to play with?

APPENDIX E. SURVEY

Date:

Please tell us how much you agree with the following statements:

		Strongly Disagree ⟷ ***Strongly Agree***				
	1 = Strongly Disagree 2 = Disagree 3 = Neutral 4 = Agree 5 = Strongly Agree	**1**	**2**	**3**	**4**	**5**
a.	I know how to help my child(ren) with his/her “designing, creating or building” ideas and skills.	☐	☐	☐	☐	☐
b.	I know how to help my child(ren) with his/her “designing, creating or building” ideas and skills.	☐	☐	☐	☐	☐
c.	I believe that learning engineering ideas and skills would be good for my child(ren).	☐	☐	☐	☐	☐
d.	I want my child(ren) to learn engineering skills.	☐	☐	☐	☐	☐
e.	I want my child(ren) to understand what engineers do.	☐	☐	☐	☐	☐
f.	I think it is necessary to learn engineering as early as possible.	☐	☐	☐	☐	☐

Please mark the frequency that you perform each of the behaviors listed below by checking the appropriate responses using the following scale provided.

	0 = In the past, but not recently, 1 = Never, 2 = Yearly, 3 = Monthly, 4 = Weekly, 5 = Daily	***In the past, but not recently*** **0**	***Never*** **1**	***Yearly*** **2**	***Monthly*** **3**	***Weekly*** **4**	***Daily*** **5**
a.	I watch TV shows with my child that has engineering topics in them (for example, Mythbusters, How Things Work, Design Squad, etc).	☐	☐	☐	☐	☐	☐
b.	I read books, stories, or articles about "designing, creating, and building" topics/issues with my child.	☐	☐	☐	☐	☐	☐
c.	I provide opportunities for my child to play with toys that allow them to "design, create, or build" things (for example, Legos or Blocks).	☐	☐	☐	☐	☐	☐
d.	I give my child some projects that he/she needs to use "designing, creating, and building" skills for.	☐	☐	☐	☐	☐	☐
e.	I visit science or children's museums with my child to improve their knowledge of "designing, creating, and building."	☐	☐	☐	☐	☐	☐

This set of questions helps us to understand whether or not we have included different types of people in our study. Like the rest of the survey, these questions are optional.

What is your gender?

☐ a. Male ☐ b. Female

Which grades are your children currently in? (Please answer this question with all of your children in mind both those on spectrum and typically developing children)

What best describes your household type?

- ☐ a. Married-couple, children living at home
- ☐ b. Married-couple, children not living at home
- ☐ c. Unmarried-couple, children living at home
- ☐ d. Unmarried-couple, children not living at home
- ☐ e. Single, children living at home
- ☐ f. Single, children not living at home
- ☐ g. Other ___________

Which of the following age groups do you belong to?

☐ a. Under 20	☐ d. 30 – 34	☐ g. 45 – 49	☐ J. 60 and above
☐ b. 20 – 24	☐ e. 35 – 39	☐ h. 50 – 54	
☐ c. 25 – 29	☐ f. 40 – 44	☐ i. 55 – 59	

Are you of Hispanic, Latino, or Spanish origin?

- ☐ a. No, not of Hispanic, Latino, or Spanish origin
- ☐ b. Yes, Mexican, Mexican Am., Chicano
- ☐ c. Yes, Puerto Rican
- ☐ d. Yes, Cuban
- ☐ e. Yes, another Hispanic, Latino, or Spanish origin

Which of the following describes your race? Please check all that apply.

- ☐ a. White
- ☐ b. Black, African-Am., or Negro
- ☐ c. Asian
- ☐ d. American Indian or Alaska Native
- ☐ e. Native Hawaiian and Other Pacific Islander
- ☐ f. Other ___________

Thank you very much for your participation. We appreciate your time.

Please complete by checking the appropriate box for each statement:

	1 = Definitely Disagree 2 = Slightly Disagree 3 = Slightly Agree 4 = Definitely Agree	1	2	3	4
1.	My child likes to look after other people.	☐	☐	☐	☐
2.	My child often doesn’t understand why some things upset other people so much.	☐	☐	☐	☐
3.	My child doesn’t mind if things in the house are not in their proper place.	☐	☐	☐	☐
4.	My child would not cry or get upset if a character in a film died.	☐	☐	☐	☐
5.	My child enjoys arranging things precisely (e.g. flowers, books, music collections).	☐	☐	☐	☐
6.	My child is quick to notice when people are joking.	☐	☐	☐	☐
7.	My child enjoys cutting up worms, or pulling the legs off insects.	☐	☐	☐	☐
8.	My child is interested in the different members of a specific animal category (e.g. dinosaurs, insects, etc).	☐	☐	☐	☐
9.	My child has stolen something they wanted from their sibling or friend	☐	☐	☐	☐
10	My child is interested in different types of vehicles (e.g. types of trains, cars, planes, etc).	☐	☐	☐	☐
11	My child does not spend large amounts of time lining things up in a particular order (e.g. toy soldiers, animals, cars).	☐	☐	☐	☐
12	If they had to build a Lego or Meccano model, my child would follow an instruction sheet rather than "ploughing straight in".	☐	☐	☐	☐
13	My child has trouble forming friendships.	☐	☐	☐	☐

14	When playing with other children, my child spontaneously takes turns and shares toys.	☐	☐	☐	☐
15	My child prefers to read or listen to fiction rather than non-fiction.	☐	☐	☐	☐
16	My child’s bedroom is usually messy rather than organized.	☐	☐	☐	☐
17	My child can be blunt giving their opinions, even when these may upset someone.	☐	☐	☐	☐
18	My child would enjoy looking after a pet.	☐	☐	☐	☐
19	My child likes to collect things (e.g. stickers, trading cards, etc).	☐	☐	☐	☐
20	My child is often rude or impolite without realizing it.	☐	☐	☐	☐
21	My child knows how to mix paints to produce different colors.	☐	☐	☐	☐
22	My child would not notice if something in the house had been moved or changed.	☐	☐	☐	☐
23	My child has been in trouble for physical bullying.	☐	☐	☐	☐
24	My child enjoys physical activities with set rules (e.g. martial arts, gymnastics, ballet, etc).	☐	☐	☐	☐
25	My child can easily figure out the controls of the video or DVD player.	☐	☐	☐	☐
26	At school, when my child understands something they can easily explain it clearly to others.	☐	☐	☐	☐
27	My child would find it difficult to list their top 5 songs or films in order.	☐	☐	☐	☐
28	My child has one or two close friends, as well as several other friends.	☐	☐	☐	☐
29	My child quickly grasps patterns in numbers in math.	☐	☐	☐	☐
30	My child listens to others’ opinions, even when different from their own.	☐	☐	☐	☐
31	My child shows concern when others are upset.	☐	☐	☐	☐
32	My child is not interested in understanding the workings of machines (e.g. cameras, traffic lights, the TV, etc).	☐	☐	☐	☐

33	My child can seem so preoccupied with their own thoughts that they don’t notice others getting bored.	☐	☐	☐	☐
34	My child enjoys games that have strict rules (e.g. chess, dominos, etc).	☐	☐	☐	☐
35	My child gets annoyed when things aren't done on time.	☐	☐	☐	☐
36	My child blames other children for things that they themselves have done.	☐	☐	☐	☐
37	My child gets very upset if they see an animal in pain.	☐	☐	☐	☐
38	My child knows the differences between the latest models of games-consoles (e.g. X-box, Playstation, Playstation 2, etc) or other gadgets	☐	☐	☐	☐
39	My child remembers large amounts of information about a topic that interests them (e.g. flags of the world, football teams, pop groups, etc).	☐	☐	☐	☐
40	My child sometimes pushes or pinches someone if they are annoying them.	☐	☐	☐	☐
41	My child is interested in following the route on a map on a journey.	☐	☐	☐	☐
42	My child can easily tell when another person wants to enter into conversation with them.	☐	☐	☐	☐
43	My child is good at negotiating for what they want.	☐	☐	☐	☐
44	My child likes to create lists of things (e.g. favorite toys, TV programs, etc).	☐	☐	☐	☐
45	My child would worry about how another child would feel if they weren’t invited to a party	☐	☐	☐	☐
46	My child likes to spend time mastering particular aspects of their favorite activities (e.g. skate-board or yo-yo tricks, football or ballet moves).	☐	☐	☐	☐
47	My child finds using computers difficult.	☐	☐	☐	☐
48	My child gets upset at seeing others crying or in pain.	☐	☐	☐	☐

49	If they had a sticker album, my child would not be satisfied until it was completed.	☐	☐	☐	☐
50	My child enjoys events with organized routines (e.g. brownies, cubs, beavers, etc).	☐	☐	☐	☐
51	My child is not bothered about knowing the exact timings of the day's plans.	☐	☐	☐	☐
52	My child likes to help new children integrate in class.	☐	☐	☐	☐
53	My child has been in trouble for name-calling or teasing.	☐	☐	☐	☐
54	My child would not enjoy working to complete a puzzle (e.g. crossword, jigsaw, word-search).	☐	☐	☐	☐
55	My child tends to resort to physical aggression to get what they want.	☐	☐	☐	☐

Note: This questionnaire is designed and published by a group of autism researchers. The reference is as below:
Auyeung, B., Wheelwright, S., Allison, C., Atkinson, M., Samarawickrema, N., & Baron-Cohen, S. (2009). The children's empathy quotient and systemizing quotient: Sex differences in typical development and in autism spectrum conditions. *Journal of autism and developmental disorders*, *39*(11), 1509.

APPENDIX F. CASE 1 NARRATIVE

Letter One & Challenge Zero. The researcher explained the activities and what the family has to do. Immediately after that and before reading the tasks, Scott asked the researcher about one piece (i.e. Tunnel), by saying, "how does the tunnel work?" (***Problem Scoping-Information Gathering***). Mom then asked Scott to read the letter first, "We have to read the letter first and see what they want" (<u>**Providing Guidance-Direction**</u>) and they both read it quietly to themselves (***Problem Scoping- Problem Definition***) Scott leaves the letter on the table, and nods excitedly saying, "I knew I'm gonna build something" (***Problem Scoping- Problem Definition***). Mom confirms nodding, (<u>**Affirmation-Confirmation**</u>) then asks Scott to explore the pieces (<u>**Providing Guidance-Direction**</u>) that were asked in Challenge 0, he jumps into the first challenge.

Challenge One. Scott reads the challenge (***Problem Scoping-Problem Definition***). He then chooses some pieces used in the model by looking at the picture given in the challenge (***Solution Development -Decision Making***). He then builds a prototype based on the given model (***Solution Development -Modeling/Prototyping***). He picks up some black posts, and builds two towers first, and then grabs the end track and put it on top of the longer tower [mistaken by the start track] (***Problem Scoping-Information Gathering***). Then, he says, "I need to get up [to get other pieces]", and then looks at the pieces to learn about the pieces until he chooses the ones he needs (***Problem Scoping-Information Gathering*** & ***Solution Development -Decision Making***). Mom asked, "how are you building this?" (<u>**Soliciting Information-Prompting**</u>), and Scott responds, "picture [referring to the picture on the task] (***Solution Development -Idea Generation***).

Scott is not building the rollercoaster on the gray base. Mom indirectly provides step-by-step directions/plans for Scott to get him to realize that he needs the gray base. However, Scott is building the rollercoaster independently without listening to the mom's comments. Thus, the mom directly prompts him.

> Mom: What does it say first? (<u>**Soliciting Information-Prompting**</u>) [passing the challenge to the child]
>
> Scott (quickly looks at it): I'm just going to say this that what I'm building works.

Mom: Okay. What is the first thing that you're supposed to get? (**<u>Soliciting Information-Prompting</u>**) That one (**<u>Providing Guidance-Direction</u>**) [Mom points to the gray base and gives it to him].

Scott: Oh, so that's what I can leave them on (***Problem Scoping-Information Gathering***).

Mom: Okay. What's the second thing? (**<u>Soliciting Information-Prompting</u>**)

Scott: [doesn't pay attention to Mom] Oh, wow, so I connect it (***Problem Scoping-Information Gathering)*** [while connecting the start track to the slide track]... that ... Okay done.

Mom: Okay. What's the second thing? (**<u>Soliciting Information-Prompting</u>**)

Scott: [talking to himself (inaudible)] done.

As the mom sees that he is done with planning and modeling the prototype, she asks questions that lead to the evaluation of the solution.

Mom: how many do we have [referring to the black posts on the tower]? (**<u>Soliciting Information-Prompting</u>**)

Scott: One, two, three, four, five (counts the number of black posts in the picture). One, two, three, four, five (counts the number of black posts used in the first tower) (***Optimization-Evaluation***).

Mom: Okay. This and this are connected to posts of themselves, though [she is referring to the start and end tracks that are each attached to black posts and she believes they don't count as black posts and he has to include one more. She takes the slide and one tower out]. They're connected to the start track and the end track. No count (**<u>Providing Guidance-Explanation</u>**). So, how many more would we need to make this six? (**<u>Soliciting Information-Prompting</u>**)

Scott: One (***Optimization-Troubleshooting***)

Mom: Okay. Okay, so how many are here? (**<u>Soliciting Information-Prompting</u>**) Count (**<u>Providing Guidance-Direction</u>**)

Scott: One, two, three, four (***Optimization-Evaluation***)

Mom: And we need to make six, (**<u>Providing Guidance-Direction</u>**) right? (**<u>Soliciting Information-confirmation/clarification</u>**)

Scott: Five. [As he is looking at the Figure given to him, he notices that he needed to include five not four black posts.] (***Optimization-Evaluation***)

Mom: Okay (**Affirmation-Confirmation**)

Scott: Six? so they both have to be six? [Realizes that a possible problem in the number of pieces he used building the towers] (***Optimization-Troubleshooting***)

Mom: Well, it says we need 12, so my guess would be they both need to be six (**Providing Guidance-Explanation**). [the mom is misleading the child as she has read the challenge incorrectly]

Scott: One, two, three, four, five, six [changes the design and counts] (***Optimization-Troubleshooting & Improving***).

Mom: Okay, (**Affirmation-Confirmation**) and then we need one start track, one end track (**Providing Guidance-Direction/Explanation**).

Scott: I already have both.

Mom: One blue slide track (**Providing Guidance-Direction/Explanation**). [Misleading the activity again as she is reading challenge zero, not challenge one.]

Scott: No, that's green (***Optimization-Evaluation***).

Mom: But honey…

Scott: Just let me try this out [Scott builds the towers with six posts and then grabs the green track and puts on top of the towers.] (***Optimization-Improving)***.

Mom: Okay (**Disengagement**).

Scott: Can you hand me the coaster?

Mom: Okay (**Assisting-Building**), did we finish this step [pointing to the first challenge]? (**Soliciting Information-Prompting**)

Scott: No, just let me do this hah. [gets frustrated]

Mom: Okay (**Disengagement**).

While Mom is helping her son to evaluate the solution, she has misunderstood the challenge herself. Scott's prototype is the same as what he sees in Challenge 1's picture, however, Mom is referring to challenge zero which is designed for children to explore the materials. Mom's misunderstanding of the challenge results in the child's confusion and later frustration. She directs design

Optimization by telling him what to do based on what she thinks is right and makes the child change the prototype. As a result, the child builds a rollercoaster that the start and the end track are located on the same size tower which doesn't work at the end.

Scott decides to test the rollercoaster he built (***Optimization-Testing***), but it does not work. He leaves the coaster car on the first tower. He pushes it slightly, but the car does not roll on the slide by itself. He thinks there is something wrong with the car. He grabs the car, looks at the car trying to figure out how to make it work (***Optimization-Troubleshooting)***

> Mom: maybe the bottom [referring to the coaster car to be used upside down] (**<u>Providing Guidance-Suggestion</u>**).
>
> Scott: Oh, Yes (***Problem Scoping-Information Gathering)***.

He leaves the car upside down on the rollercoaster (***Optimization-Testing***), and it does not move by itself either. Finally, he pushes the car himself to roll on the rollercoaster (***Optimization-Testing***). The car stops in the middle.
Mom and Scott have a conversation to find the problem and fix it (***Optimization-Troubleshooting & Improving)***.

> Mom: Maybe try turning it the other way to roll better (**<u>Providing Guidance-Suggestion</u>**).
>
> Scott: No, this is the end track (***Optimization-Troubleshooting***).
>
> Mom: Okay. No, no, no, I meant turning the car. Oh, you know what? There's a guy (**<u>Providing Guidance-Direction/Explanation</u>**). Does he have a face? (**<u>Soliciting Information-Prompting</u>**)
>
> Scott: No.
>
> Mom: Okay (**<u>Affirmation-Confirmation</u>**) So you can't tell which way he's facing (**<u>Providing Guidance-Explanation)</u>** [Mom's troubleshooting with her son.]
>
> Scott: Wait, don't these look like they're uneven? [pointing to the given picture (see Appendix B-Challenge One] Is this? (***Problem Scoping-Problem Definition*** & ***Optimization-Evaluation)***

Mom: You think so? (**<u>Soliciting Information-Prompting</u>**)

Scott: I'm just ...

Mom: [crosstalking] Okay, well, we have to follow this, (**<u>Providing Guidance-Direction/Explanation</u>**) okay? (**<u>Soliciting Information-Clarification</u>**) So, it says you're supposed to have a blue slide track, an orange slide track, and one medium and small green slide tracks, and one…(**<u>Providing Guidance-Direction/Explanation</u>**). [Mom is mistaken about the challenge they are solving]

Scott: I do not need the warmup. [Then he takes out both towers]

Scott takes out what he built and starts rebuilding something new by taking one black post out of one tower. He then moves the towers to another spot on the gray base and adds some black posts on top of it (***Solution Development - Idea Generation & Modeling****).*

Mom: Ha! (Mom realizes that Scott was doing challenge One not Zero) Do you want to count in the picture? (**<u>Providing Guidance-Suggestion</u>**) I think there's six here, and five here (**<u>Providing Guidance-Explanation</u>**). Wow, look what you have (**<u>Affirmation-Encouragement</u>**). How many is that [on your tower]? (**<u>Soliciting Information-Prompting</u>**)

Scott: Six and four. 10. [He then takes out the shorter tower and put it on top of the other one which now he one tower with 10 posts.]

Mom: Okay, no! Now you try to build the picture (**<u>Providing Guidance-Direction</u>**).

Scott: Mm-hmm (negative). [While knocking down the tower again and exploring other pieces.]

Mom: No?

Mom: Okay. So are you telling me you don't want to do any of the warmups? (**<u>Soliciting Information-Clarification</u>**)

Scott: Mm-hmm (negative).

During the troubleshooting conversation, Mom first referred to an error and suggested a remedy (turning the car) that Scott tried. Then, Scott found the error and shared it with the mom (uneven towers). However, Mom, who was still confused about the challenges herself, did not confirm what Scott said and suggested that they follow the guidelines for challenge Zero. This seemed to make Scott frustrated where he decided to stop working on Challenge One and instead move to the last challenge. Even when the mom realized that he had been working on Challenge One, he resisted rebuilding his solution for that challenge and worked on a different task.

Rest of Warm-Up Challenges. Since Scott decided to skip the warm-up challenges, Mom encouraged him to read through the challenges, to make sure they are not missing any points. He agreed. However, while Mom was reading the challenges, Scott was exploring different pieces and building a new rollercoaster. Mom initiates conversation with Scott that leads to scoping the problem and generating ideas.

Mom: Okay. Can we read through them, though, just so that if there are any secrets that we miss or any hint? (**Providing Guidance-Suggestion**) [She starts reading through the challenges.]

Mom: Okay. Can you build a steeper rollercoaster than the previous rollercoaster you made (Challenge 2)? You make it steeper, so bigger angle? (**Providing Guidance-Explanation**) She then shows the steeper by her hands (**Providing Guidance-Explanation**). Yes? (**Soliciting Information-Confirmation**)

Scott: I can. [He responds while looking at the pieces. He attaches a start track to one black post and puts on the gray base (***Solution Development - Modeling/Prototyping***)]

Mom: Okay. Let's try other slide tracks. Try a different number of black posts.

Scott does not respond to Mom and he works on prototyping his new idea. He grabs a green track and attaches it to a start track.

Mom: Isn't that the start? (Soliciting Information-Prompting)

Scott: Yes.

Mom: Aren't you learning at school about gravity? (Providing Guidance-Other)

Scott: Yeah. It's going to have to go up, and then up, and up, and up, and then down (showing his hands spinning and coming down) (*Solution Development -Idea Generation*)

Mom: Okay, but if that's the start, it's going to be really hard to start low, (Providing Guidance-Explanation) don't you think? (Soliciting Information-Prompting) [Mom helps with the inclusion of science.]

Scott: But how are the people going to get all the way up? (*Problem Scoping-Problem Definition*)

Mom: I think we can just pretend that they start all the way at the top (Providing Guidance-Suggestion)

Scott: Okay. It's an underground rollercoaster (*Solution Development -Idea Generation*).

Mom: There you go (Affirmation-Confirmation). Or it's a rollercoaster, like the one that we did in Tennessee where you have to go up the mountain, and then the rollercoaster goes down the mountain (*Problem Scoping-Information Gathering*) (Providing Guidance-Explanation).

Scott: With no stop to kill anyone (*Solution Development -Idea Generation*).

Mom: Mm-hmm, no brakes (Affirmation-Confirmation) (*Solution Development -Idea Generation*).

Scott: Daddy said that there were brakes, so with brakes! (*Problem Scoping-Information Gathering*)

Mom: Yeah, you didn't let me use that, and they were under your hands.

Scott grabs some other black posts and builds a longer tower with the end track and places it on a different corner of the gray base and then attaches the start track to the lower track, and finally attaches a slide. He moves the tower to the center (***Solution Development - Idea Generation & Modeling***). He is using the start track as if it's the end track, and the end track as it's the start track.

Mom: Can you build a rollercoaster that turns the coaster car before it stops? (**<u>Providing Guidance-Other</u>**) [reads Challenge 3]

Scott: That turns it. I mean this one. Umm. [Points to a turn track and then grabs it and attaches it to the green slide] (***Problem Scoping-Information Gathering & Solution Development -Idea Generation***).

Mom: Mm-hmm, it sure does (**<u>Affirmation-Confirmation</u>**).

Mom: Okay, so now we ... Can we read the actual request? (**<u>Providing Guidance-Other</u>**)

Scott: Yeah (and adds some black posts to a corner (***Solution Development -Idea Generation & Modeling***)

Letter Two. Mom reads the letter to Scott. Although Scott is focusing on building his own rollercoaster, he makes some comments such as “you have already read that”, “oh no you didn't" and “I have an idea”. Mom then stops reading the letter word by word and summarizes the rest (**Flexibility**), “Children have asked for a very exciting rollercoaster. To make them happy, the rollercoaster needs to start very high and end low. I think you're doing very well. To have a loop and to pass at least one tunnel (***Problem Scoping-Problem Definition***).”

Scott continues working on his rollercoaster, and starts sharing his idea, “So change of plans is going to...”. However, Mom interrupts his conversation a few times (**Providing Guidance**) She says, “See these lines there? the tunnels go in it (**Providing Guidance-Explanation**).” Scott gets frustrated and screams, “Stop!”, and continues working on his rollercoaster (***Solution Development -Modeling/Prototyping***). Mom disengages as she stops providing suggestions and asking questions (**Disengagement**).

After a few minutes of Scott working on his rollercoaster by adding and removing pieces (***Solution Development -Decision-making & Modeling***), Mom attempts to suggest an idea, but turns it to an affirmation (**Flexibility**), “Up at the top. Umm, I mean that sounds kind of cool” (**Affirmation-Encouragement**). Scott nods and then talks about his ideas using his words and gestures: “It's going to go all the way ... it's going to go down ... this needs to be the start (pointing to the taller tower with the start track)... and then it's going to go down, down, down, down, down, down, down (***Solution Development -Idea Generation***).” Mom nods and approves by saying, “okay” (**Affirmation-Confirmation**). Scott continues, “It's going to go really far down (***Solution Development -Idea Generation***)” The mom looks at Scott, and then says, "It's okay" (**Affirmation-Confirmation**). Scott, without paying attention, says, “And that's the start, and then it's going to go whoop, and then it's going to make a sharp turn ... turn ... and then it's going to fall in, and then it's going to go (***Solution Development -Idea Generation***).”

As Scott is working on building his rollercoaster, while deciding on what pieces to use (***Solution Development -Decision-making & Modeling***), Mom reads the letter, “Let me finish reading the letters. There are some other specifications in the letter. What other features will make the rollercoaster exciting? [She then switches to just summarizing the rest of the letter.] Imagine the ‘fastest, loopiest, and steepest’ rollercoaster you can, and try to build it. We have limited space for the rollercoaster, so build the rollercoaster on the gray base. All the black posts must be built on the gray base. So all the black posts have to be on the gray base, and the rollercoaster can go beyond the base” (**Providing Guidance-Explanation**). Then she points to the material guide and says, “here is the materials and there’s a loop too” (**Providing Guidance-Explanation**).

While Mom is reading the letter, Scott is adding pieces to his design following what he described and he also makes some changes to the existing towers he made before (***Solution Development - Idea Generation & Modeling***). He misused the end track instead of the start track [pattern of misusing the material was observed]. After Mom stops reading the letter, Scott engages in understanding the challenge and planning accordingly, “Am I going to have to use all of the black posts? (***Problem Scoping-Problem Definition)*** To reach the limits, so it’s going to have to go all the way up [showing a few black posts to be used on top of one tower]. Then yes. I need all of them [blocks] (***Solution Development -Idea Generation***)”. Mom let Scott decide by saying, “you are in charge (**Disengagement**)”, and she sits back with her hands down.

Scott continues building his model (***Solution Development - Modeling***), but occasionally takes out what he builds and makes a new piece (***Solution Development -Decision-making & Modeling***). He builds a structure including a tower attached to a slide and a turning track, but takes it all apart as he says, “No this not gonna work.” He then restarts working on that part. Meanwhile, Mom directs him on how the rollercoaster should be built, “rotate it that way”, “push it harder”, or “use another slide” (**Providing Guidance-Direction**). Scott follows some of Mom’s directions but ignores others.

As Scott is building his rollercoaster, he identifies a problem that parts could not be attached. He says aloud, “but that will not be it” (***Optimization-Troubleshooting***), and takes out a tall tower and the small tower with the end track on it (***Optimization-Troubleshooting & Optimization-Improving***) He then builds a tower with three posts and puts it on top of another tower that has only one post **(*Optimization- Improving*)**, but very quickly he removes it (***Optimization-Troubleshooting***) and says, “I have to do the curve. The loop.. (***Optimization-Troubleshooting & Problem Scoping-Problem Definition***)" and then grabs the loop and rotates it to see how it works

(***Problem Scoping-Information Gathering***). He tries to attach the loop to the start track which is very low, and Mom reminds him, "Now, remember gravity!" but he ignores his mom, and says, "Ahh". Mom continues, "I don't think that works with gravity" (**<u>Providing Guidance-Assessment: Inclusion of science</u>**). However, Scott ignores his mom and continues attaching the loop which it breaks apart. He gives the loop to Mom and she assembles it (**Assisting-Building**). He looks at his model and then gets the coaster car and tests the parts of the model he already has (***Optimization-Testing***). After testing, Mom suggests a remedy, but Scott disagrees and continues adding to his model:

> Mom: But this is probably where it should end because you'll get a lot of gravity (**<u>Providing Guidance-Explanation</u>**).
>
> Scott: It's worked.

He adds a red [left] turn track to another tower at the corner (***Solution Development -Idea Generation & Modeling***), and realizes a problem, "Wait, no, that's the wrong way" **(*Optimization-Troubleshooting*).** He attempts to fix the problem by taking the red turn track out and adding the blue one [right turn] **(*Optimization-Troubleshooting & Improving*)**. Then, he describes the reasons of the change which includes remedy plans, "I need it to face it this way because it's going to have to elevate this way down, down, down, down, down **(*Optimization-Troubleshooting*)**, and then go to the loop, and then the end, but there will be a tunnel." **(*Solution Development -Idea Generation*)**

However, Mom disagrees with his plan and directly suggests another plan, "Well, you have to start with a loop, sweetie." (**<u>Providing Guidance-Direction</u>**) Scott shakes his head in disagreement and Mom continues, "Let me see a black piece and see if I can get this in here" (**Assisting-Building**) Scott says, "Just give me a minute" and adds a tunnel to his model (***Solution Development -Idea Generation & Modeling*).** He then looks at his design and moves some parts of the model (***Optimization-Troubleshooting & Improving***). He seems satisfied with his model (which the criteria are met), but Mom disagrees:

> Scott: Yay, this might actually work. Might be able to. They are just going to hit the top of the tunnel. Where did that little car go?" (**Optimization-Evaluation**)
>
> Mom: Okay, this tunnel can't... This can't (<u>**Providing Guidance-Assessment**</u>).
>
> Scott: It'll be fun when hitting the top. Trust me, [It] works. That's the idea. [He puts the coaster car aside without testing the rollercoaster] (**Optimization-Evaluation**)

Scott engages in adding to his model without touching the tunnel section. He grabs a green slide that is connected to the start track and connects it to a curve track (***Solution Development -Idea Generation & Modeling***). Mom then encourages a change to happen, and he shows some reasoning when making decisions.

> Mom: Use the shorter ones [referring to the slide tracks]. You can use a shorter one here (<u>**Providing Guidance-Direction**</u>). Here, let me assist you (**Assisting-Building**). [She helps him to find a small slide track.]
>
> Scott: It needs to be really short.
>
> Mom: Well, there's a bunch of different lengths here in the green, and there's a few different lengths here in blue (<u>**Providing Guidance-Explanation**</u>), and I don't know what these are, but you probably do (<u>**Soliciting Information-Prompting**</u>) (<u>**Student of the Child**</u>). [Puts all the material closer to the child]
>
> Scott: Slide-tunnels [he points to the tunnel part of the slide.] (***Problem Scoping-Information Gathering***). [and then he explores the rest of materials] (***Problem Scoping-Information Gathering***)

Mom hands him a small slide track (**Assisting-Building**)

> Scott: This is not going to connect. It's just a slide (***Solution Development - Decision Making***).
>
> Mom: Let's think together. What's our plan again? (<u>**Soliciting Information-Prompting**</u>)
>
> Scott: I don't know. I just need it to something here [inaudible], but it doesn't. The pink ones do. I do not think that they belong on this. Nope (***Solution Development - Decision Making***).
>
> Mom: Okay. You do what you want to do (<u>**Disengagement**</u>).

Scott works on his roller-coaster (***Solution Development -Modeling/Prototyping***), and then tests that part (***Optimization-Testing***). And shouts, “Yes, yes, yes! It goes through the tunnel! Yay. It goes through the tunnel.” (***Optimization-Evaluation***)

Mom directs the next step in the plan, but after he disagrees, she disengages from the activity by not doing and saying anything, until the child talks to her. She then re-engages by providing confirmation and continues by encouraging Scott to identify a problem in the design (the location of the tunnel). Mom tells him, “Okay, so now we need to build, going around here.” (<u>**Providing Guidance-Direction**</u>) Scott disagrees by nodding. Mom responds, “Okay, whatever you want to (<u>**Disengagement**</u>**)** Scott works on his design for a few minutes and then says aloud, “A little bit shorter. Right (***Optimization-Testing & Troubleshooting***) Umm. I have to name it too.” Mom shows the excitement and says, “Oh, do we? Okay. Super Crazy?” (<u>**Affirmation-Confirmation**</u>) Scott says, “nope!” Mom changes the conversation and points out to a problem, “You know, this thing [tunnel]’s moving here. So maybe we need to take it out.” (<u>**Providing Guidance-Direction**</u>) However, Scott ignores her again. They engage in the conversation below as Scott argues why that is not a problem.

> Scott: No! It's the Leaning Tower of Pisa and moves (He makes a connection to the real-world experience)
>
> Mom: Yeah, it kind of is (<u>**Affirmation-Confirmation**</u>).
>
> Scott: Wait, no, this is going to be the Leaning Tower of Pisa Future Rollercoaster.

Mom aims to reengage her son to do the building and keep him on track. She says, “I was thinking maybe we could just use a longer [Tunnel]. Okay. I think we need a longer.” (<u>**Providing Guidance-Suggestion**</u>)

> Scott: Pisa Tower?
>
> Mom: Yes. I like the name (<u>**Affirmation-Confirmation**</u>). Going back to this (<u>**Reengaging the child**</u>). I think we need a longer one here (<u>**Providing Guidance-Suggestion**</u>).
>
> Scott: Okay. Let’s try to move the tunnel (***Optimization-Troubleshooting***).

Then he takes out the tunnel and moves it to somewhere (***Optimization-Improving***), which the mom disagrees with where he placed it but does not provide any explanation.

> Mom: Nope (Providing Guidance-Direction).
>
> Scott: It won't go anywhere else
>
> Mom: Okay (Affirmation-Confirmation).
>
> Scott: But something's really slowing it down [referring to the slide that goes under the tunnel) (*Optimization-Troubleshooting*).
>
> Mom: I think this piece [referring to the slide which goes under the tunnel] needs to be lower because I think it's just too tight here. So get a longer, big piece [Tunnel] (Providing Guidance-Suggestion) (*Optimization-Troubleshooting*).

She grabs a bigger tunnel to make the changes (<u>**Assisting-Building**</u>). Scott raises his voice and does not let his mom make any changes, and he then provides explanation.

> Scott: Oh, no. What are you doing? I think it'll be fine. It's going to go down really lower. This is going to be low (***Optimization-Evaluation***) [makes changes to his rollercoaster] So now this piece is elevated [the tower before the tunnel] so that it'll go down (***Optimization- Improving & Evaluation***).

He then engages in revising his design. He takes one black post out of a tower so the slide goes lower (***Optimization-Troubleshooting & Improving***). He attaches the green slide to a turn track but realizes that the slide cannot attach to the other black post (***Optimization-Troubleshooting & Improving***). He looks at a blue track and put it side by side the green slide that is attached to the rollercoaster, and says, "Wait, does it ... oh, no. Blue [slide track] won't fit (***Optimization-Troubleshooting***)" Thus, he drops the blue track and takes out the green slide (***Optimization-Troubleshooting***). He then makes changes to that part of his design, but keeps the rest the same (***Optimization-Improving***). After he makes changes to that part, he tests his rollercoaster (***Optimization-Testing***), but the car gets stuck between the tunnel and slide which makes Scott retest it two more times (***Optimization-Testing***), and then he says, "no" which may indicate that he recognizes that what the problem is (***Optimization-Troubleshooting***).

Mom suggests trying it without the tunnel, “maybe we can try without it and just see how it goes without the tunnel” (**Providing Guidance-Suggestion**). However, Scott reminds his mom of the criteria, “I need to have one” (***Problem Scoping-Problem Definition***). Mom reassures him that he can put the tunnel in later, “I know (**Affirmation-Confirmation**) It is just for the sake of testing this. It will work believe me.” (**Providing Guidance-Explanation**) He agrees with Mom and tests the design without the tunnel again, but this time from the start point (***Optimization-Testing***). Because he is using the end track instead of the start track, the car needs an extra push. The car gets stuck in the middle of the track. He looks at the slide and says, “this piece was popping up” (***Optimization-Troubleshooting***). He fixes that part and tried one time (***Optimization-Testing & Troubleshooting***). The car travels all the way to the last part he made.

Mom encourages him and makes another suggestion for remedy (**Providing Guidance-Suggestion**), “Nice. I have an idea. For the tunnel, if we take this piece out and move this down one, it'll go right in the tunnel” (***Optimization-Troubleshooting & Solution Development -Idea Generation***). Scott disagrees and says, “I found a hack. I think that it will be best if we do it right here” (***Optimization-Troubleshooting & Solution Development -Idea Generation***). He then chooses the big tunnel and compares it with the small one and attaches it to his model (***Optimization-Troubleshooting*** & ***Improving***). Mom confirms by saying, “Okay” (**Affirmation-Confirmation**). He tests the rollercoaster again, and shows his satisfaction by saying, “Aw yeah! Certainly, that it will not hit the guy. It didn't hit the guy! It didn't hit the guy.” He then starts adding more details to the design (***Solution Development -Idea Generation & Modeling***). He adds the bigger tunnel on the gray post (***Solution Development -Idea Generation & Modeling***), and with his Mom’s help (**Assistance-Hands-on**), he gets the loop attached to the gray base (***Solution Development -Idea Generation & Modeling***). He then asks, “Wait, do you think we need to build up some elevation, so it will go up” (***Solution Development -Idea Generation***). Mom shakes her head and says that she does not know (**Disengagement**).

Mom changes the conversation after a couple of minutes that Scott has focused on one part of his rollercoaster by saying, “Okay, now we're going to have to use all the black posts (misunderstanding the criteria)” (**Providing Guidance-Suggestion**). Scott does not respond to Mom but refocuses on other parts of his design. He builds multiple new components by adding and removing pieces (***Optimization-Troubleshooting*** & ***Improving & Solution Development - Idea Generation & Modeling/Prototyping***).

He continues silently working on his design until gets stuck at some point and he cannot add to his design. He gets frustrated and shows his frustration by hitting on the table. Mom encourages him and says, “We got this.” And, “I think you’re doing a fabulous job.” (**<u>Affirmation-Encouragement</u>**). Scott disagrees and says, “No. I really don’t. I think I should just screw it and restart.”

Mom agrees with his decision of redesigning but also suggests that they do not use the loop in their next design, “Okay, maybe we can restart. Should we just get rid of the loop all together?” (**<u>Providing Guidance-Suggestion</u>**). Scott, however, insists that they should use it because “they asked us.” He generates a new idea for how to use it while taking off the pieces and relocating them. He keeps some pieces on the gray base and tells the researcher that he is going to restart because "it wasn’t working.” (***Optimization-Troubleshooting*** & ***Improving***)

While Scott is taking pieces out, Mom suggests that he can reuse the pieces he built. This involvement is however frustrating for Scott.

> Mom: Oh, no. It was fine. It doesn’t have to be in those holes just perfectly (**<u>Providing Guidance-Explanation</u>**). Keep it there (**<u>Providing Guidance-Direction</u>**).
>
> Scott: No. No, no, take that. Stop it!
>
> Mom: okay.
>
> Mom (a few seconds later): Oh, was I supposed to take this piece out? (**<u>Soliciting Information-Confirmation</u>**)
>
> Scott: No. No, no, no, don't take the blue pieces off [with frustrations].

As Scott is recreating his solution (Im.2), he engages in exploring material with the help of his mom (***Problem Scoping-Information Gathering***).

> Mom: What's the difference between the blue pieces and the red pieces [turn tracks]? (**<u>Soliciting Information-Prompting</u>**) I can't figure it out (**<u>Student of the Child</u>**).
>
> Scott: The red pieces elevate up. The blue pieces elevate down.

He builds a part of his new rollercoaster using a loop and he tests it, "it's not making it." (***Optimization-Troubleshooting***) Mom says, "I wonder why? (**<u>Soliciting Information-Prompting</u>**)" They both agree that the loop needs a re-assembly (***Optimization-Troubleshooting***). They take it out, and it breaks. Scott gets frustrated and says, "Okay. Now we can't do it anymore. SHHH."

Mom asks for help from the researcher. The researcher tries to assemble the loop but realizes that the piece is broken. She tapes it and returns it.

Scott puts the loop back in the same place as it was. Mom starts brainstorming aloud (***Solution Development -Idea Generation***), but Scott stops her. As a result, Mom disengages, "okay. I will just let you work." (**<u>Disengagement</u>**)

He engages in prototyping by choosing, adding and removing pieces silently (***Solution Development -Idea Generation, Decision-making & Modeling & Optimization-Troubleshooting*** & ***Improving***). He creates a rollercoaster. Meanwhile, Mom asks Scott, "do we want a shorter one there? Or do you want a longer one?" (**<u>Soliciting Information-Prompting</u>**) Scott does not respond but implements a change by taking out the short one and builds a taller tower (***Optimization-Troubleshooting*** & ***Improving***). A few minutes later, after Scott used the small tunnel, Mom asks, "You got the tall one?" (**<u>Soliciting Information-Prompting</u>**) This comment prompted Scott to remove the small tunnel and add the bigger one, "yeah. It didn't make it the other time [referring to the time he used the small tunnel]." (***Optimization-Troubleshooting*** & ***Improving***)

After he builds another rollercoaster that met all the criteria (having a loop, a tunnel and start high, end low), hee tests the rollercoaster (***Optimization-Testing***). The car runs out of the loop. Mom and Scott try a couple of times (**Assisting-Building**), and the loop does not work (***Optimization-Testing & Troubleshooting***). Scott tells the researcher, "it's all about the loop. It is broken"

(***Optimization-Troubleshooting***), and he gets upset. The researcher encourages him to test the rollercoaster from the point right after the loop, acknowledges his design looks great and the problem is the loop, and assures him that the loop in the real world would work. Scott says, "so I pretend that the loop works." Mom suggests another solution, "or another option is just to get rid of the loop altogether" (**<u>Providing Guidance-Suggestion</u>**). Scott prefers to stick to the criteria, "But then I won't get the extra points....... Don't touch it Mom." (***Problem Scoping-Problem Definition & Solution Development -Decision Making***)

He takes some moments exploring the material by comparing the length of the slides available with the ones he has already used (***Solution Development -Decision Making***). He then shares his new ideas by asking the researcher, "So in theory, it also would have... if that was going the opposite way, it would also have the metal thing that makes it drag all the way up?" (***Solution Development -Idea Generation & Problem Scoping-Information Gathering***). Mom continues, "Yeah, he wanted to start high, go low, then go high again. There's no way" (**<u>Providing Guidance-Explanation</u>**). Researcher suggests that they can write a note back to Hannah and provide more explanation. Scott says, "oh yeah. Like those pulleys and gears (***Solution Development -Idea Generation & Problem Scoping-Information Gathering***)." Mom cross-talks, "Good (**<u>Affirmation-Encouragement)</u>** It needs the pulley system" (**<u>Affirmation-Confirmation</u>**).

Scott adds pieces to his design and removes some others (***Solution Development - Idea Generation, Decision-making & Modeling & Optimization-Troubleshooting and Improving***). As he is attaching a piece on a tower closer to the loop, the loop and towers around it drop down. This makes him frustrated so that he loudly says, "No." Mom reacts immediately, "it's okay... You got this... You know this goes in easy" **<u>(Affirmation-Encouragement)</u>**, and she physically helps to rebuild that part (**<u>Assisting-Building</u>**) (***Optimization-Troubleshooting***). However, as she was building the loop again, another piece drops that makes Scott even more **frustrated**, "And now that piece popped out. Aahh." (***Optimization-Troubleshooting***). Mom engages in finding the problem, "This is a little too long, so it's leaning and falls off." (***Optimization-Troubleshooting)*** (**<u>Providing Guidance-Explanation</u>**). Scott disagrees, "it's fine. Just leave that piece … It's fine. It's more toward the Leaning Tower of Pisa. That's my plan." (***Optimization-Troubleshooting & Evaluation***)

As he gets engaged in prototyping and building his solution, Mom provides information for using different materials. He explores the materials per Mom's suggestions. However, when mom gets hands-on to make some changes physically, he prefers his mom to disengage.

> Mom: That blue one all the way far would fit perfectly. The other one (**Providing Guidance-Explanation**).

Scott picks the blue track and compares it with the slide he already used.

> Mom: Is it? (Soliciting Information-Prompting)
>
> Scott: It's actually a bit longer (*Problem Scoping-Information Gathering*).
>
> Mom: It's way longer (Providing Guidance-Explanation).
>
> Scott: Wait. These two are the same size [while comparing a green slide with the existing one] (*Problem Scoping-Information Gathering*).
>
> Mom: [grabs the green one] just look at this (Providing Guidance-Explanation)
>
> I can replace it (Assisting-Offers).
>
> Scott: I have it under control (refuses to get help)
>
> Mom: Look at me [tests the rollercoaster] (Assisting-Building).
>
> Scott: I said, I have it under control. I have it under control.
>
> Mom: Okay (Affirmation-Confirmation).

After a while, Scott builds a rollercoaster that starts high and ends low. It has a loop and a tunnel. Mom asks him if he is done. He elaborates on his idea which broadens the context of the solution.

> Mom: Are you done? (Soliciting Information-Prompting)
>
> Scott: I need to try to switch them to go that way (up). Then they can go up again... but there isn't a switch (using his fingers to illustrate his ideas) (*Solution Development -Idea Generation*).
>
> Mom: What do you mean? (Soliciting Information-Prompting)

Scott: There is no giant switch.

Mom: Why don't we build it and then we can explain it's going to use the same track twice? (Providing Guidance-Suggestion)

Scott: I'm gonna write a long letter.

Scott continues building his rollercoaster (***Solution Development -Modeling/Prototyping***). Mom makes another suggestion and gets hand-on quickly where Scott disagrees.

Scott is exploring different turn tracks and chooses one (***Solution Development -Decision Making***) and attaches one to one slide (***Solution Development -Modeling/Prototyping***) and then takes it out (***Optimization-Troubleshooting)***. Mom suggests that Scott can use another turn track (**<u>Providing Guidance-Suggestion</u>**) and tries to attach it (**Assisting-Building**). Scott does not allow her, and says "SHHH" aloud, making his mother stop. Mom says, "I am here to help" (**Assisting-Verbally**). And Scott continues building his rollercoaster without getting any help from his mom. Suddenly and after a few unsuccessful attempts, he acknowledges that the activity is frustrating.

Scott: This is much more frustrating than it needs to be.

Mom: Well, you found LEGOs really frustrating before you knew how to use them, too (**<u>Affirmation-Encouragement</u>**).

Scott: Yeah (and continues working on his design).

Without testing his rollercoaster, Scott informs his mom and the researcher that he is done. While Scott says that he has done his best job, his mom believes that he is frustrated and that is why he is quitting. She tries to make her son continue building by suggesting new ideas, encouraging him to redesign using an engineer as a metaphor and reminding him of the criteria.

Mom: Did you do your best job? Did you follow the instructions? (**<u>Soliciting Information-Prompting</u>**)

Scott: I did my best job.

Mom: No, I think you got frustrated, and you want to quit. Can I make a suggestion? (**<u>Assisting-Verbally</u>**)

Scott nods meaning no.

Mom: Can I make a suggestion? (**<u>Assisting-Verbally</u>**)

Scott: Yes.

Mom: Why don't we take this piece completely out (**<u>Providing Guidance-Suggestion</u>**) (***Optimization-Troubleshooting & Solution Development -Idea Generation***). since it doesn't work very well (**<u>Providing Guidance-Explanation</u>**) (***Optimization-Troubleshooting***), and you can just go back to what you were originally building because that was beautiful (**<u>Affirmation-Encouragement</u>**).

Scott: No it wasn’t (playing with different pieces randomly).

Mom: Yes, it was (**<u>Affirmation-Encouragement</u>**) You know, engineers go through this all the time. They build something, and then it doesn't work, and they have to go back to the drawing board, but you shouldn't quit (**<u>Providing Guidance-Explanation</u>**).

Scott: I’m done!

Mom: Okay. You didn’t use all the black pieces (**<u>Providing Guidance-Assessment</u>**)

Scott: Yeah, I have to use all the black pieces? (***Problem Scoping-Problem Definition***)

Mom: Okay, do you remember what the letter said? (**<u>Soliciting Information-Prompting</u>**) That all the black posts must be built on the gray base. So the way I read that is you have to use all the black posts (**<u>Providing Guidance-Explanation</u>**) (***Problem Scoping-Problem Definition***).

Scott: Okay. Black ones will be used. [He built a very tall tower using all the unused black posts, and placed it in the middle.]

Given the similarities Mom sees between Scott’s current design and what he first described as a solution, Mom uses this opportunity to encourage his son to build his first idea, by saying, “Wow. You know how cool that would’ve been? (**<u>Affirmation-Encouragement</u>**) Do you want to start it up there and just go on around the little spin-y thing?” (**<u>Providing Guidance-Suggestion</u>**) Scott disagrees and says, “Um, No. and that’s most of the black pieces. I can’t build anything else.” Mom says, “okay. It's his job. He called it done. Are you sure? 100%? Because when you're done, we leave. Okay.” Scott changes his mind and while taking out some of the black pieces from a tower, he says, “That’s it. I’m going to start doing.” Mom asks for clarification, “that’s it, you mean you're done or…" (**Soliciting Information-Clarification**). Scott shakes his head and takes out pieces [a non-verbal sign that he is continuing to work on this]. Mom suggests that they take a picture of the version they already have (**Affirmation-Encouragement**). He gets excited and says, "and then I'm going to go back to the beginning." Mom responds, "yes, and this way they [pointing to the researcher] will have multiple versions of your work. You're doing great buddy!" (**Affirmation-Encouragement**). Scott agrees.

In this scene, Scott is frustrated that his design is not working and he decides to give up. Mom helps him overcome his frustrations, by encouraging him to build a new idea. She reminds him of his first idea by describing the idea in more detail. After he decides that he will be restarting again, Mom reassures Scott that his first design will be saved (photographed) and sent to the stakeholder. Scott starts taking out some of the pieces, and Mom makes a suggestion to take the problematic piece away (i.e. the loop), "do you want to get rid of this yellow thing?" (**Providing Guidance-Suggestion**) and then she points to the researcher and she says, "But he was really on his way to something really awesome, but then he wanted to use the yellow thing, and I think it just messed him up" (**Affirmation-Encouragement**). Scott says, "because it's part the thing (***Problem Scoping-Problem Definition/reflection***)." Mom continues, "Well, and it kind of threw him off his game a little bit. I'm going to put the loop back (**Assisting-Building**). We don't like the loop." Scott reacts, "No. Wait. I think I'm good. I can do it myself." Mom still tries to help, and she offers to, "just tell me how many pieces of what you want, and I'll give them to you." (**Assisting-Verbally**) Scott says loudly, "No". Mom then takes a piece and attaches it to a tower (**Assisting-Building**). Scott reacts louder this time, "Weeeeee. Stop" and he knocks the entire design down except for the end track, and stops working.

Mom disengages for some minutes, and then attempts to reengage her son, "Okay. Are we going to stop at the end then? (**Soliciting Information-Prompting**)." Scott shakes his head, and says, "Nope". He then uses two tall towers with the turn track and the slide that he previously used and places it at one corner (***Solution Development -Modeling/Prototyping***). Mom takes a piece and says, "But where was this supposed to be placed? It falls off." (**Soliciting Information-Prompting**) This involvement makes Scott angry, which he makes a noise to stop Mom. Mom says, "Okay. I'm just trying to help (**Assisting-Verbally**)". Scott refuses the offer, "Don't."

In this scene, mom’s direct and consistent involvement makes Scott frustrated, especially when the involvement is hands-on and without previous notice. Even if the facilitation question helps Scott to reengage, he still strongly reacts to his mother’s involvement, and finally, he refuses to take any help.

As Scott is building his new rollercoaster, he takes out some pieces several times without saying anything and replaces them after exploring different pieces (***Problem Scoping-Information Gathering***), comparing the pieces and choosing one (***Solution Development -Idea Generation, Modeling and Decision Making***). Mom says, “Do you know what you want to build this time?” (<u>**Soliciting Information-Prompting**</u>) He confirms, “the one I said I will.” (***Solution Development -Idea Generation***). At this point, he has explored and used all of the different pieces (***Problem Scoping-Information Gathering***). During this time, he uses his fingers and imitates the motion of the roller-coaster car and says, “Oh. Don’t need that” (***Optimization-Troubleshooting***). He takes that part out and adds something new (***Optimization-Troubleshooting & Improving***). He builds a part of his rollercoaster, with some towers and several slides, and then he decides to change the structure of his design. He says, “Ahh no” and he removes the entire structure and leaves it at another corner (***Optimization-Troubleshooting & Improving***). Mom encourages him, by saying, “You are so smart (**Affirmation-Encouragement**). See that? The gray base is clue, and if that's the same length as that one, it's going to fit going that way (<u>**Providing Guidance-Explanation**</u>). That's really smart.” (**Affirmation-Encouragement**)

As he is building his new rollercoaster, he runs out of some pieces. He acknowledges that “ darn it, there’s not more blue pieces like that. It’s ruined! (***Optimization-Troubleshooting***)” But then he starts comparing other slides with the blue slide track that he needs, and finally chooses a couple of slides (***Solution Development -Decision Making***). As he is building the towers and attaching them together by the slides, Mom facilitates the solution design planning.

> Mom: How many of these you want it go back there [pointing to the towers]? How high?” (<u>**Soliciting Information-Prompting**</u>)
>
> Scott: Six [Counts the towers he already has].

Mom: Okay, now keep in mind that if we're going to go higher, we might need a longer one ... just so you know (**<u>Providing Guidance-Suggestion</u>**).

Scott: Oh yeah. [he then removes the tower to be four]

Mom's explanation encourages Scott to make some changes to his design (***Optimization-Troubleshooting & Improving*** & ***Solution Development -Idea Generation***). He shortens all the towers by one post, then attaches the turn tracks and the slides he selected before to the turn tracks. However, he realizes that that the slides he selected before do not fit this new design with shorter towers (***Optimization-Troubleshooting***). He looks for a remedy for this problem, "Now if that goes up by one, then this one also has to go up by one. So I need one, two, three, four [as he counts the first tower]. So One, two, three, four, five. [He collects five black posts and makes a tower with them] (***Optimization-Troubleshooting***)" He then adds the longer tower and a turn track (***Optimization-Improving***)." However, after this change, he realizes that only one of the slides can be attached and not the other ones. He says, "What? What? [he leaves the slide that cannot be attached] (***Optimization-Troubleshooting***). Mom directs him to try other slides, "Well, what color is this one? How about other colors?" (**<u>Soliciting Information-Prompting</u>**) He engages in comparing the slides side by side and by placing them close to the two towers, and he finally chooses the ones he needs and attaches them (***Optimization-Troubleshooting & Improving*** & ***Solution Development -Decision Making***). After that he shows his satisfaction for the design by saying, "This is what I was originally going with. This is fun, and I bet Abby [his sister] would love it!"

As Scott is attaching the slides to his rollercoaster, Mom asks him about his plan for building the rest of the rollercoaster. She engages in a conversation with his son and helps with the design.

Mom: Keep in mind, honey, you can move this [model], too (**<u>Providing Guidance-Explanation</u>**).

Scott: No, no, and then you're making me dizzy (while the mom is rotating the model).

Mom: There you go. You can see your model now. Okay, so now do you want some of these black ones? Where do you want me to put them? (**<u>Soliciting Information-Prompting</u>**)

Scott: umm.

Mom: Like that [She builds a long tower] (**<u>Providing Guidance-Modeling</u>**). Okay. So do you want to go to here? Or do you want to go to here? (pointing to two short towers at the corners) (**<u>Soliciting Information-Prompting</u>**)

Scott: Here because, obviously, it's going up here and then here (showing with his hands where the rollercoaster will go)

Mom: How many do you want? (**<u>Soliciting Information-Prompting</u>**)

Scott: One, two, three, four, five, [he counts the other towers], so six and seven [he decides based on the patterns of the previous towers.] (***Solution Development - Modeling/Prototyping and Decision Making***).

Mom: But did you count the one on the bottom? (**<u>Soliciting Information-Prompting</u>**) There's six. Tell me if that works.

Scott: One, two, three, four, five, six.

Mom: Seven.

Scott: Yep. [grabs a slide and attach it to the first one]

Mom: Okay (**<u>Affirmation-Confirmation</u>**).

Scott: [While grabbing another slide to attach to the next tower], Wait, no ... I just have to test it. [He tests that parts of the rollercoaster he already has built (Ts)]

Mom: Okay, the longer blue one's right there (**<u>Providing Guidance-Direction</u>**).

Scott: But it's breaking (***Optimization-Troubleshooting***).

Mom: It's not breaking. It's just ... it's been bent. Somebody bent it. It'll be fine because we'll just let her know that we want new construction, not bad construction. And this is just a model, they will use the good material when they want to build it (**<u>Providing Guidance-Explanation</u>**).

Scott: I want this one to be sent to them (shows his satisfaction with this design). At least this is gonna work. The old one was crappy (***Solution Development - Decision Making; Optimization-Evaluation***).

Mom: It’s okay. They will love both of them (**<u>Affirmation-Encouragement</u>**) What’s next then? (**<u>Soliciting Information-Prompting</u>**)

Scott: Both? Ha? [He then builds a tower and attaches a slide and a turn track to it. (***Solution Development -Modeling/Prototyping and Idea Generation***). He then tests the entire rollercoaster that he has (***Optimization-Testing***).]

Mom: Nice! Let’s see what else you are thinking to add! (**<u>Affirmation-Encouragement</u>**)

As he is progressing on his rollercoaster, he adds tunnels to his rollercoaster (***Problem Scoping-Problem Definition & Solution Development -Modeling/Prototyping***). He places the first tunnel with one leg on the gray base and the other leg out of that. He then seeks confirmation from Mom and the researcher. Mom confirms by referring to the problem statement (Letter two) and repeats what was written there (<u>**Affirmation-Confirmation**</u>). As Scott gets the confirmation, he rotates the design and adds the second tunnel (***Solution Development - Idea Generation & Modeling***), and then he describes his idea, "Because that one's right there, this one's right here (***Solution Development -Decision Making).***" Mom encourages him by saying, "Nice, (<u>**Affirmation-Encouragement**</u>) it's like the tunnel into the unknown (<u>**Providing Guidance-Explanation**</u>). And Scott points to the second tower and describes his idea with more detail, "And then you come out of the unknown (***Solution Development -Decision Making***)."

As he goes to build another slide, he realizes that he has run out of the slides. He says aloud, "Oh, no, there's not another." And he tests some others slides to see if they fit (***Optimization-Testing, Troubleshooting & Improving*** & ***Solution Development -Decision Making***). Mom then engages in a conversation with him with a suggestion.

> Mom: Yep, I think we're out of the long ones (<u>**Affirmation-Confirmation**</u>). Well, you know what you could do is only go to here [closer tower], and then maybe go around this one [the tallest tower in the middle] (<u>**Providing Guidance-Suggestion**</u>) (***Optimization-Troubleshooting***).
>
> Scott: I cannot really do this well (***Solution Development -Decision Making***).

While Scott does not follow Mom's suggestion directly, he uses the characteristics of that idea and generates his new idea. The idea is slightly different than Mom's suggestion. He creates a tower next to the last tower that adds a slide with the correct length (***Optimization-Troubleshooting*** & ***Solution Development -Decision Making, Modeling & Idea Generation***). And then he describes his idea again:

> Scott: Oh my gosh, this is so terrifying. If you go like that and look down ... and if you look down, this is going to be a couple ... like 25 feet. Maybe even a couple 25 feet.
>
> Mom: It should be fun (<u>**Affirmation-Encouragement**</u>), but what are we looking for now?

Scott nods his head, and moves the longest tower in the middle, adds a start track to it, and adds a slide. He says with excitement, “and we are done!”, and he tells his mom to test it, “You get the honor. You helped me. I couldn’t have done it without you.” (***Optimization-Testing)***

Mom pushes the car to test the rollercoaster (**<u>Assisting-Building</u>**). It stops after the first slide. Mom pushes it one more time. and then at after each of the slides it stops and the mom has to pushes (**<u>Assisting-Building</u>**). Finally, Scott pushes the car to the end track. At every spot that the rollercoaster stops, Scott says, “Oh no (***Optimization-Troubleshooting***)” After the testing is over, he acknowledges that he has an idea for remedy, “We got to switch that (***Optimization-Troubleshooting***).” Mom encourages him, by saying, “Okay, Uh, somebody’s got an idea” (**<u>Affirmation-Encouragement</u>**). Scott starts by moving a couple of the towers around and then removes some black posts from each one (***Optimization-Improving***). As he makes the changes, he points out some possible problems that he predicts (***Optimization-Troubleshooting***), such as “Oh, no, that's ... no. Oh, I think we're getting too low” or “I do not know if the tunnel will be possible”. He accordingly and immediately makes the changes (***Optimization-Improving***).

When he is over with improvement, he describes his solution. “I'm making it go faster. My goal is to make it go all the way without hitting ... without any stop, even for soda. Don't stop for soda this time.” (***Optimization-Improving***). Then he tests his solution (***Optimization-Testing***), but the car stops right before the end track. He notices the problem, and they both engage in finding a remedy.

> Scott: We forgot to change this pink [referring to the slide] (***Optimization-Troubleshooting***).
>
> Mom; [Hands him a small slide track] (**<u>Assisting-Building</u>**) Maybe this would work (**<u>Providing Guidance-Suggestion</u>**). You may even need to move this over and that there (**<u>Providing Guidance-Suggestion</u>**).

Scott gets the slide and compares it with the slide he was using before (***Solution Development - Decision Making***), and looks to see which one fits there. Mom also grabs a new slide that has a tunnel attached to it. She compares it side by side with the beginning slide and asks her son if they can switch the slides on the rollercoaster with the one she has, by saying, “Do you think we can switch this with that?” (**Soliciting Information-Prompting**) Scott agrees by nodding and Mom removes the slide and attaches the new slide with tunnel (**Assisting-Building**). However, she notices that the length of both were not the same. Mom tells her son, “I can’t do it. You just have to move this out.” (**Providing Guidance-Direction**). After few minutes of not paying attention to what Mom said, he moves one of his slides which causes him to move some other parts of the structure he made (***Optimization-Troubleshooting & Improving***). Mom attempts to engage physically and help with building (**Assisting-Building**), but Scott disagrees and loudly says, “No it’s fine.” They attach all the new pieces and make the changes, then Scott says, “Don’t touch it until I test it. If you do not want it to be end, do not touch this.” Mom nods and leaves the pieces (**Disengagement**).

He then looks at Researcher and expresses his satisfaction, “We have made the alternative roller-coaster. It’s the all-time rollercoaster. If this is real life, I’m going to go, Yippie!” (***Optimization-Evaluation***). He then tests it and while testing it, he evaluates his design. The first time the car stops is at the point that slide was bent previously, so he says, “Obviously, that wouldn’t happen” and Mom confirms. The car, however, stops in other spots, given the design problems including the height of the slides, and he acknowledges that, “in the real life, these would happen though.” The mom says, “It would be going fast enough that it would just shoot him down there” (**Providing Guidance-Explanation**).

They then describe the solution to the researcher which leads him to add a new element to his rollercoaster (***Optimization-Improving***).

> Mom: And it's based on the Leaning Tower of Pisa, which is why everything's a little off (**Providing Guidance-Explanation**).
>
> Scott: It's the Leaning Tower of Pisa Extravaganza. Oh wait. This is the Tunnel of Mysteriousness (***Solution Development -Idea Generation***). This-- So it could be pitch dark inside of the tunnel, and then you could come out right there. [He adds a tunnel and points to it]. I prefer rainbow colors not darkness. This is much much better [referring to his solution].

Finally, he writes his name and the rollercoaster's name "Leaning Tower of Pisa Extravaganza" as his signature and lets the researcher photograph the solution.

APPENDIX G. CASE 2 NARRATIVE

Letter One. The family reads the letter quietly (***Problem Framing*-a**). While neither Mom nor John talked about the letter and the proposed problem, they engaged in Problem Scoping through exploring material. Mom facilitates her son's engagement by asking him to find the pieces and what each piece does. Mom looks at the kit guide that has named the pieces with their images and asks John to find each piece. Mom points to one of the pieces, and asks her son: "Do you know how we can use the tunnel?" <u>**Soliciting Information-Prompting**</u> John rotates the piece and then says, "I know how," and he grabs the gray base and demonstrates how he can use this piece (***Problem Scoping-Information Gathering).***

Challenge Zero. In this challenge, he was asked to explore material by collecting different pieces that could be used in the next challenges. With Mom's request, he picked up all the pieces and gave them to his mom. They explored what each is by briefly talking about them. For example, he grabbed the yellow loop and they talked about that being like "a giant slide" (***Problem Scoping-Information Gathering***)

Challenge One. Challenge one was a well-structured design task. The child received a model of a rollercoaster and was asked to build it using the kit. Mom hands the challenge to John and says, "Here is what it says." (<u>**Providing Guidance-Direction**</u>) John looks at the problem (***Problem Scoping-Problem Definition***). John loudly says, "I know how to do this," and then looks at the picture carefully (***Problem Scoping-Information Gathering***) and quickly grabs two black posts and places them on two sides of the gray base (***Solution Development - Modeling/Prototyping***) Then, he counts the number of black posts he needs for each tower by looking at the tower (***Problem Scoping-Problem Definition***). He builds two towers at both sides with the same distance shown in the picture (***Solution Development -Modeling/Prototyping***) He looks for the start and end track and chooses an orange slide based on their color (***Problem Scoping-Information Gathering***), but is slightly different in shape. He tries to attach one but he cannot (***Optimization- Troubleshooting***). Then he rotates it and looks at the picture carefully and then at the pieces he has in his hand and he realizes he chose a wrong piece, by saying "Oh, wait."

(***Problem Scoping-Information Gathering & Solution Development -decision-making & Optimization- Troubleshooting***) And Mom confirms, "Ummm!" (**Affirmation-Confirmation**) He then picks up the right two orange pieces, the start and end tracks, (***Problem Scoping-Information Gathering & Solution Development -decision making***), places them next to the picture and whispers, "here." (***Problem Scoping-Information Gathering; Solution Development -decision making***) He is trying to attach the start track but he cannot as he is holding it upside down. Mom says, "correct just rotate it." (**Provide Guidance-Directions**) Without saying anything, John looks at the pieces again and rotates one and is able to attach it (***Problem Scoping-Information Gathering & Optimization-Troubleshooting)*** He then quickly grabs the end track and attaches it to the other tower he built (***Solution Development - Modeling***) He suddenly realizes that he has misused them, which he has attached the start track to the shorter tower, and attaches the end track to the longer tower. He says, "hah" and switches them (***Optimization-Troubleshooting)*** As he picks the pieces, Mom constantly encourages him by saying phrases like "good job" "well-done" and "yes!" (**Affirmation-Encouragement**)

John grabs a green slide track and attaches it to the start track (on the first tower) (***Solution Development -Modeling/Prototyping***). He tries to attach it to the end track (on the second tower) but realizes that the slide is small to be attached to both towers (***Optimization-Troubleshooting***) Then, John grabs another green slide and attached it to the end track and tried to put both slide tracks together (***Solution Development -Idea Generation & Optimization-Improving***). He tries to connect them together, but he cannot. Mom offers help without any physical involvement which resulted in the conversation below:

Mom: Let me know if you need any help." (**<u>Assisting-Verbally</u>**)

John: I think that should be orange (referring to the green track on the pictures) (***Optimization-Troubleshooting***).

Mom: Orange? What do you mean? (**<u>Soliciting Information-Prompting</u>**)

John: I think that should be large (***Optimization-Troubleshooting***).

Mom: Ohh. Yes. But we have large, medium and small of the green (**<u>Providing Guidance-Explanation</u>**)

Mom grabs a larger track and gives it to him (**<u>Assisting-Building</u>**). He tries it but he cannot attach it either as the track is larger than what it should be (***Solution Development - Modeling/Prototyping***). Then, he moves the end tower one square (***Optimization-Troubleshooting & Improving***) He attaches the large slide to the start track. But he cannot attach the slide to end tower (***Optimization-Troubleshooting***) [Because he rotated the tower while moving it]. He looks at the tower, and whisper, "oh, it was upside down," and he fixes it. Mom cheers and says, "You got it, god job." (**<u>Affirmation-Encouragement</u>**) Mom suggests him to test the design (**<u>Providing Guidance- Suggestion</u>**) He tests the rollercoaster and it works (***Optimization-Testing***). Mom cheers for him (**<u>Affirmation-Encouragement</u>**) John turns to the researcher and explain, "I couldn't do it the same as the picture, but I moved the tower to the next spot and worked. I think they used a wrong slide here." (***Optimization-Evaluation & Reflection***) John identified a criterion for his problem that the rollercoaster should be built with the exact pieces provided but also the same numbers of pieces. He engaged in information gathering as he carefully gathered information he needed to build the same roller coaster as the given model such as the needed pieces (e.g. same shapes and numbers) and exploring how each piece works with the other ones.

Challenge Two. John gets excited about his achievement in the first challenge, and shows his willingness to build another rollercoaster. He says, "I'm gonna build the master one now," (***Problem Scoping-Problem Definition***) and grabs the loop and tries to assemble it (***Problem Scoping-Information Gathering***) Mom gives him the challenge and tells him that he has to work on the challenges first (**<u>Providing Guidance-Direction</u>**). John reads the challenge (***Problem Scoping-Problem Definition***) and says "Okay". He starts building a new solution using the rest of the rollercoaster he built previously. He takes out the slide and builds another tower in the middle of the two other towers he has (***Solution Development -Idea Generation & Modeling***) He takes two pieces, a turn track and a slide, compares them together, and see which one could be attach to the tower (***Solution Development -Decision Making***). Mom facilitates the activity by initiating the conversation:

> Mom: Do you know what you have to do? (**<u>Soliciting Information-Prompting</u>**)
>
> John: Steeper (***Problem Scoping-Problem Definition***)
>
> Mom: Do you know what steeper is? (**<u>Soliciting Information-Prompting</u>**)
>
> John: Yes [He then illustrates what steeper means by putting his hands in an angel and moving from high to low and making the sound of a crashing airplane.] (***Problem Scoping-Problem Definition***).
>
> Mom: [while nodding, bends her arm into an angle (**<u>Providing Guidance-Modeling</u>**)] Yes, (**<u>Affirmation-Confirming</u>**) it needs to have an angle (**<u>Providing Guidance- Explanation</u>**)

She then adds two more posts on top of the first tower (**<u>Assistance-Hands-on</u>**) John adds the end track to the first tower and keeps the other two towers untouched (***Solution Development - Idea Generation & Modeling***) While mom is watching his son, she tells him, “Maybe you can add two more posts on this tower.” (**<u>Providing Guidance- Suggestion</u>**) John does not react, which the Mom says, “You do what you want. Don’t just listen to me (**<u>Disengagement</u>**) I am here to help (**<u>Assistance-Offering</u>**)” and she puts her hands off the table and watched her son. John takes a start track and puts it on top of the tower the mom just built and added two posts (***Solution Development - Idea Generation & Modeling***)

John then explores different slides by taking them one by one and putting them side by side to check the length. He finally chooses one slide. (***Problem Scoping-Information Gathering & Solution Development -Decision Making***). He attaches the slide to the start track. The slide just gets halfway through to get to the end tower . He then attaches the end track to the other tower (***Solution Development -Modeling/Prototyping***) He attempts to attach the slide to the second tower, but he cannot since the slide is short. He leaves the slide on the table (***Optimization-Troubleshooting***) He starts exploring other slides (***Problem Scoping-Information Gathering***). He compares the length of the few other slides by putting them side by side, and then placing them next to the towers (***Solution Development -Decision Making***) Mom gives him a small slide (**<u>Assistance-Hands-on</u>**), and he holds it next to the slide and then suddenly says, "ha" [probably a sign of a thought coming to mind] (***Solution Development -Idea Generation***) He adds the smaller slide to the end tower, and leans it on the middle tower. He tries to lean the other slide on the middle tower too, (***Solution Development -Idea Generation***) however, the slide is shorter to get to the middle tower. He then puts the two slides on top of each other and decides where to move the middle tower (***Optimization-Troubleshooting***). He moves the tower one square towards the start tower and leans both the slide on top of it (***Optimization-Improving***) Again, he tries to connect both slides, but they do not get attached (***Optimization-Troubleshooting***) Therefore, he removed the shorter slide and moves the third tower (the shortest one with the end track) closer to the first tower and adds one post to on top of it the tower and connects the slide to the end track (***Optimization-Troubleshooting & Improving)***

In this scene, John was exploring different slides to see how he can create a steeper rollercoaster. While he never articulates the purpose of the middle tower he created, he seemed to be wanting to attach one slide from the start tower to the middle and then the one from the middle to the end tower. As he was exploring the slides, Mom gave him one small slide, and he used it without checking if it has the appropriate length or not. This made him have to go undergo some other changes to his design. However, finally, he decided to create a one-slide rollercoaster, but a steeper one.

By the researcher's request, John tests his rollercoaster within which the end and start track were misplaced (***Optimization-Testing***). In his first attempt, the car falls off the track. He tests it a few times after, but the result is the same (***Optimization-Testing***). He then looks at the car, cleans the car and tries to find the problem within the car (***Optimization-Troubleshooting***)

Mom initiates conversation to find the problem, "why did it fall out, John?" (**<u>Soliciting Information-Prompting</u>**) John, who is attempting to redesign, answers, "Maybe, it needs a loop?" Mom directs John to fix the current prototype instead of building a new one. She suggests an idea by saying, "Should you switch these two tracks [referring to the start and end track]?" **<u>(Providing</u>**

Guidance-Suggestion) John agrees and quickly fixes the problem (***Optimization-Troubleshooting***), and then tests the rollercoaster which works (***Optimization-Testing***) Mom says, "Good job dude! (**Affirmation-Encouragement**) How many posts it goes down? (**Soliciting Information-Prompting**)" John says, "two."

*Challenge Three***.** The challenge provided an open-ended problem: "Build a rollercoaster that turns the car before it stops." John gets challenge three, and he reads the challenge aloud (***Problem Scoping-Problem Definition***) and looks at his mom, nodding his head and putting his hands on his face [signs of frustrations]. Mom says, "you can do it." (**Affirmation-Encouragement**) Mom refers him to the first prompt given in the task and says, "Okay one blue one red (**Provide Guidance-Explanation)** You can figure out what you want to build (**Affirmation-Encouragement**)"

John looks at the turn tracks (***Problem Scoping-Problem Definition***) and tries to connect them all together (***Problem Scoping-Information Gathering***) Mom says, "they don't go together." (**Proving Guidance-Explanation**) John gets frustrated, saying, "I can't do this." However, mom helps him to engage in the activity.

> John: Oh no, this is a challenge.
>
> Mom: That's a challenge (**Affirmation-Encouragement**) Yes, but you can do it (**Affirmation-Encouragement**)
>
> John: No. that's a challenge, I can't do it.
>
> Mom: I have every faith in the room that you can. You have Master LEGO skills that can play in here. You can! Let's do it together (**Affirmation-Encouragement**)

Then John reengages in the activity and looks at the two turn tracks that he has in hand. He grabs different slide tracks (***Problem Scoping-Information Gathering***) and sees which one can be attached to the turn track (***Solution Development -Decision Making***). Then takes out all the pieces in his previous design except for the two towers. He then grabs the end track and attaches it to the longer tower (***Solution Development -Modeling/Prototyping***) Mom stops him.

Mom: think for some minute John (**<u>Providing Guidance-Direction</u>**)

John: What?

Mom: Is this the end or start? (**<u>Soliciting Information-Prompting</u>**)

John: Oh yeah, the end [and he fixes the problem] (***Optimization-Troubleshooting & Improving***)

He moves both towers across the base and then builds the third tower in the middle of them (***Solution Development -Idea Generation & Modeling***) He attaches the turn track to the middle tower and to a slide, and then attempts to connect all the other towers to this tower. He tries a few slides, by putting them next to the towers and deciding if they fit or not (***Solution Development - Decision Making***). He then adds two black posts to a tower and removes the slide and the turn track (***Solution Development -Idea Generation, Modeling and Decision Making***) He attaches a longer slide to the turn track and to the first tower (***Solution Development -Idea Generation, Modeling***) He then asks help from Mom.

John: Can you help me? (***Collaboration***) There you go never mind… No I need, We need something to hold this [pointing to the slide that is attached to the turn track and should be attached to the middle tower] (***Solution Development -Idea Generation***).

Mom: I don't think this works this way, dude [pointing to the turn track that is flipped] (**<u>Providing Guidance-Explanation</u>**)

John: Never mind. This holds it (and leans the turn slides on the tower).

Mom: Turn it around, it is the other way round (**<u>Providing Guidance-Direction</u>**)

Mom hands John a different turn track (**<u>Assisting-Building</u>**) John looks at it, rotates it and replaces it with the other turn track (***Problem Scoping-Information Gathering; Solution Development - Idea Generation and Modeling & Optimization-Troubleshooting***)

John sees that the slide+turn track is still unstable as it is leaning on a tower without being attached to it (***Optimization-Troubleshooting***). John moves it in a couple of ways but still finds it unstable (***Optimization- Troubleshooting***) He looks at his mom, and she says, "You need another piece"

(**Providing Guidance-Direction**) He builds another tower next to the middle one to play as another hold for the tracks (***Optimization- Improving***) He pushes it softly (***Optimization-Testing***) but finds it unstable again, so he asks his mom to hand him more black posts (***Collaboration***). He then makes the tower longer (***Optimization-Troubleshooting & Improving***). He finds it more stable and nods and leaves that part. He then adds another slide to the turn tack and connects it to the end track (which is already connected to the last tower) (***Solution Development - Modeling/Prototyping & Idea Generation***).

He tests the rollercoaster (***Optimization-Testing***). The car turns but doesn't get to the end. He tested a few times, but then says, "Oh, I know why" (***Optimization-Troubleshooting***) He goes back to fix it by moving one tower, and says I think this should hold it (***Optimization-Troubleshooting & Improving***) He tests it again and finds the same problem (***Optimization-Testing*** & ***Troubleshooting***) Mom disengaged from the activity by saying, "umm…" and she sits back so John can find the problem (**Disengagement**). He tells the researcher that, "well, it turned before it stopped, and it's so close to the end, so this counts [as the solution]." (***Problem Scoping-Problem Definition & Optimization-Evaluation***) He, however, keeps working on it, "Oh wait, I have an idea (***Optimization-Troubleshooting***) He removes one post from the end tower which lowers the slide (***Optimization-Improving***) He tests the coaster car travels all over the rollercoaster (***Optimization-Testing***) Mom cheers for him (**Affirmation-Encouragement**)

Letter Two. Challenge four was when the child received the second letter from the director of the amusement park. The challenge was ill-structured and open-ended with three specified criteria and two constraints. Mom hands the letter to John and asks him to read it aloud (**Providing Guidance-Direction**) He looks at the letter very briefly and says, "Challenge accepted! I know what to do." (***Problem Scoping-Problem Definition***) Mom then reads the letter and shares some main points of the challenge with her son, "Hey, they are asking you to start very high and end low." (**Providing Guidance-Explanation**) John says, "and a loop and a tunnel." (***Problem Scoping-Problem Definition***)

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John explores the material and selects the loop and a tunnel, (***Problem Scoping-Information Gathering & Problem Definition***) and he says, "I don't think I can do it. Mom can you help me with this, I don't think I can do it." (***Collaboration Requested***) Mom nods and says, "You can do it and I'll help you buddy." (**Affirmation-Encouragement**)

John knocks down what he built in the previous challenge, Mom says, "John, all the posts have to be on this gray thing. But the rollercoaster can be bigger (**Providing Guidance-Explanation**) [modeling it by her hands] (**Providing Guidance-Modeling**)" John responds, "Ha, Okay" (***Problem Scoping-Problem Definition***).

After hearing what Mom says, he puts some posts on the gray base and asks, "can it be this short? (***Solution Development -Idea Generation***)*"* Mom says, "Yes, it can be as high or low as you want, so it's fine." He then starts building a tall tower and attaches it to the start track (***Solution Development -Idea Generation & Modeling***) And then builds a smaller post in the middle and then a small one all in a row. He then attaches a slide track to the start track and with a red turn track (***Solution Development -Idea Generation & Modeling***). He keeps attaching pieces and removing them. Meanwhile, Mom makes some suggestions about the pieces that he can use such as, "this green one maybe?" or "This [piece]?", (**Providing Guidance-Suggestion/Direction**) but he ignores what mom suggests. Therefore, she disengages from the activity temporary and provides space to John to work (**Disengagement**)

He grabs the loop to attach it, but he drops the loop and it breaks. Mom suggests, "Do you want me to fix it?" (**Assisting-Building**) which John refuses. As he is assembling it, he drops it one more time. He gets frustrated and says, "AHH" and takes it from the floor. Mom says, "you are doing great (**Affirmation-Confirmation**) don't get frustrated, buddy. Let me know if you need my help." (**Assisting-Verbally**) After a couple of minutes, John asks his mom to fix it (***Collaboration***), and she assembles it (**Assisting-Building**).

As mom is assembling the loop, she tries to encourage John to think about a plan and possible ideas, but he does not respond to any of them at the beginning, "Do you have a picture in your head on how you want to build it?" (**Soliciting Information-Prompting**) and "You can also draw your idea, do you want to?" (**Providing Guidance-Explanation**) Instead, John asks the researcher, "do you have a spare [Loop]?" Mom says, "Even if they don't, we will make this." He responds, "No, it says a loop, we need a loop." (***Problem Scoping-Problem Definition***).

After she assembles the loop and gives it to John, she asks his previous experiences and he starts responding to Mom.

> Mom: Think about all the rollercoasters that we have been on (**<u>Soliciting Information-Prompting</u>**)
>
> John: They always go up and then start very high. And then [go] fast." (***Problem Scoping-Problem Definition & Information Gathering***)
>
> Mom: But if you're starting high up already.
>
> John: But It says you can start very very high (***Problem Scoping-Problem Definition*)**
>
> Mom: It just says, you have to start very high and end very low. So, if you start the loop and then you twist it using the turns. So I am just thinking…
>
> John: I have an idea. [He puts several black posts on top of each other and creates a very tall tower.] (***Solution Development -Idea Generation***)
>
> Mom: This is too high (**<u>Provide Guidance- Assessment</u>**)

John makes it smaller without saying anything (***Solution Development -Decision Making***) Then he grabs the loop and attaches it to the long tower with the start track which falls down immediately. Then, he looks confused and looks at Mom. Mom tries to reassure him of his abilities.

> Mom: No worries. You can do it. I know you can (**<u>Affirmation-Encouragement</u>**)
>
> John: No I cannot.
>
> Mom: Let's think together first. How about we build the loop and then see what kind of support it needs. Because we want to build it completely high up (**<u>Providing Guidance-Explanation</u>**) Can I [help]? (**<u>Assisting-Building</u>**)

Mom then attaches the loop to model what she means, and then she takes it out (**<u>Providing Guidance-Modeling</u>**)

John: Put it back. [he seemed to be liking Mom's idea.]

Mom: Okay.

She attaches the loop again. And then reads the criteria aloud.

Mom: they wanted us to do it high and a loop and to have a tunnel (**<u>Providing Guidance-Explanation</u>**) What should we do next kiddo? (**<u>Soliciting Information-Prompting</u>**) And you kiddo need to do something. I am doing all the work myself.

Child: No, I am helping Mom.

He then grabs a slide track and attaches to the loop and asks Mom to give him another slide track (***Solution Development -Idea Generation & Modeling***). Mom hands him a slide, and then suggests, "I think you may need another turn piece, what do you think?" (**<u>Providing Guidance-Suggestion</u>**) He places a tunnel on top of a slide track, but then follows Mom suggestion and says, "oh yeah. That's a good idea. Can you give me a black post?" (***Solution Development -Idea Generation & Modeling***) He continues building the roller coaster.

After a few minutes of building and having a conversation with Mom, his rollercoaster starts very high and comes down and has a turn track at some lower levels. John attaches the loop backward (down to up). Mom tells him, "do you think this works?" John says, "yes." She then says, "Think if you have ever seen a loop in a park." (**<u>Soliciting Input-Prompting</u>**) John, a few minutes later says, "Like a giant slide?" (***Problem Scoping-Information Gathering***) Mom says, "Yes, this does look like a giant slide. Do you think that a giant slide can go down to up? It needs gravity, it can't" (***Problem Scoping-Information Gathering***). John looks at the loop and tries the car in it which doesn't move (***Optimization-Testing & Troubleshooting***). He agrees and takes the loop out (***Optimization-Troubleshooting & Improving***)

John attempts to attach the loop again and it falls down. Mom laughs. This makes him frustrated which he says loudly, "Come on. And it's not funny." Mom says, "Wait, wait! Should we support this…" (**<u>Assisting-Building</u>**) and starts building something. John looks at what his mom is doing and says, "I have an idea. I can do it." Mom disengages (**<u>Disengagement</u>**)as John is adding/removing pieces to the loops (**<u>Solution Development -Modeling/Prototyping</u>**)

After a few minutes of building, Mom says, "I am thinking that we need to make this higher, then higher and then higher. And…" (**Providing Guidance-Suggestion**) John disagrees, "Almost done. It looks good to me." Mom says, "okay, agree! Let's make some final changes only," They both make some minor changes to the rollercoaster (**<u>Solution Development -Modeling/Prototyping</u>**) John says looking at the researcher, "we're done I think. It starts really high, it ends really low, then loop and tunnel." (***Optimization-Evaluation***) Mom suggests that they test it to see if it works. John tests it (***Optimization-Testing***) and they see that the car stops in the middle of its way (***Optimization-Troubleshooting***) John looks at his mom and says, "I think I know why." (***Optimization-Troubleshooting***) He adds some black posts around the rollercoaster (***Solution Development -Idea Generation & Modeling***) and explains his new addition.

> John: If it falls down this keeps it. It is safe (Problem Scoping- Problem Definition; Solution Development -Idea Generation & Optimization-Evaluation)
>
> Mom: Is this going to solve the problem? (<u>Soliciting Information-Prompting</u>) I think we need to make everything higher (<u>Providing Guidance-Suggestion</u>)
>
> John: Nope. Why?
>
> Mom: Okay coming back to the original problem, I think we need to make this higher, then this higher to make this higher, because we need to use gravity. [referring to the towers one by one] (<u>Providing Guidance-Suggestion & Explanation</u>) (Optimization-Evaluation)
>
> John: No. I think we need to make this higher. [referring to the middle tower]

He takes apart the loop and pieces in the middle and adds black posts to the middle tower. He then grabs and looks at the loop, and says, "That's it." And then leaves all the stuff on the table. Mom, however, builds the part with the loop that previously made him frustrated, and then she guides John using her gestures, "what do you think would happen if it turns this way and then goes wider? You know what am saying?" (**<u>Providing Guidance-Suggestion & Modeling</u>**) This question reengages John and he moves some of the pieces following Mom's suggestion (***Solution Development - Idea Generation &*** **Modeling/Prototyping**)

While John is working on his prototype, Mom takes out one of the towers and starts describing (**<u>Assisting-Building</u>**), "I wonder John, what if we move this to here…" John cuts Mom's conversation and says, “No. That looks good there. No, Leave it!” (***Solution Development - Decision Making***) Mom adds one piece to the tower and leaves it where John asked. Mom asks prompting questions which help John stay engaged in the activity, as he tries different pieces on the prototype (***Solution Development -Idea Generation, Decision-making &*** **Modeling/Prototyping**) He moves all the pieces one row back and then Mom moves a short tower closer and asks, “How do you think we can connect these things?” (**Soliciting Information-Prompting**) He looks for a slide that can be connected to the pieces and attaches it (***Solution Development -Decision-making &*** **Modeling/Prototyping**) He then looks at the material, grabs a tunnel and says, “they need a tunnel.” and adds it to the rollercoaster (***Problem Scoping-Problem Definition & Solution Development*** **-Modeling/Prototyping**) John looks at the rollercoaster thinking. Mom points to the parts that are not connected, and says, “What pieces do you think can be used here?” John takes out the long tower and move it one square (***Solution Development - Modeling*** & ***Optimization-Improving***) Mom encourages him, “oh, right.” (**Affirmation-Confirmation**), and she takes out one black post under the loop and says, “Maybe if we make it shorter here.” (**Assisting-Building & Providing Guidance-Explanation**) and John tries to connect them together (***Solution Development - Modeling & Optimization-Troubleshooting***) while Mom thinks that the piece does not fit there (**Providing Guidance-Explanation**) He insists that it does, but moves one more tower to connect them (***Solution Development - Modeling & Optimization-Troubleshooting***) Finally, he asks the researcher for help, “We are very close to be done, but this one piece doesn’t connect to the whole things.” (***Optimization-Troubleshooting***) The researcher adds a very small slide and connects them together. Mom asks, “snap these final pieces together.” (**Providing Guidance-Direction**) He does and he shouts, “Done!”

Mom and Researcher encourage him to test his rollercoaster. He tests it and it works the first time (***Optimization-Testing***) Mom cheers, “Well-done!” (**Affirmation-Encouragement**) He tries another time and the car stops in the middle (***Optimization-Testing***) He looks at Mom confused. Mom says, “the first time went all the way.” He tries one more time and again the car stops in the middle (***Optimization-Troubleshooting***) Mom says, “Why?” and then he says, “Whatever. The first time counts,” and he anxiously tests the rollercoaster several times. Mom reassures him, “It counts for sure, and that’s a victory and high five for that (**Affirmation-Confirmation**) But isn’t going the second, third, fourth and fifth time?” John raises his shoulders and says, “I don’t know.”

Mom asks him again that, “Why do you think it didn’t work the second time? (**<u>Soliciting Information-Prompting</u>**) Let’s play with it. Run it again.” (**<u>Providing Guidance-Direction</u>**) At this point they both become very hands-on and try to move the pieces and put them back, and try the rollercoaster so they can understand what the problem is (***Optimization-Troubleshooting***) They run the car on the rollercoaster and still does not work. John says, “maybe it’s something wrong with the car itself?” (***Optimization-Troubleshooting***) Mom agrees (**<u>Affirmation-Confirmation</u>**) John takes the car turn it around and checks it (***Optimization-Troubleshooting***) Mom then gets the car and checks and blows in it and says, “right (**<u>Affirmation-Confirmation</u>**) Maybe dirt doesn’t let it run?”(**<u>Providing Guidance-Explanation</u>**) John takes back the car and runs it on the rollercoaster but it stops again (***Optimization-Troubleshooting***) He gets disappointed and says, “The first one counts. That’s it.”

Mom says, “Come and watch again to see what’s going wrong.” (**<u>Providing Guidance-Direction</u>**) and John comes closer to see (***Optimization-Troubleshooting***) Mom runs the car on the rollercoaster, and points to where it stops, “See it stops here.” (**<u>Providing Guidance-Explanation</u>**) She then pushes the car from the point that has stopped and the car goes to the end, (**<u>Providing Guidance-Modeling</u>**) and asks, “What do you think?” (**<u>Soliciting Information-Prompting</u>**) while she is running the car on the rollercoaster again (**<u>Providing Guidance-Modeling</u>**) John says after a couple of minutes, “ I think this needs to be lower.” (***Optimization-Troubleshooting***) He then lowers a tower with one piece (***Optimization-Improving***) and then says, “Here you go. I think it works now.” Mom responds, “do you think so?” And then he tests the rollercoaster which stops at a different point now. They both look at each other and mom encourages him to try again (**<u>Providing Guidance-Direction</u>**) He runs the car one more time and still does not work.

He starts thinking aloud, “I think I know what. Car?” (***Optimization-Troubleshooting***) he grabbed the car and played with it. Mom asks him to pass the car. She then says, “We need to know… Why do you think it worked the first time?” (**<u>Soliciting Information-Prompting</u>**) Mom then encourages John to look at the rollercoaster again. “We need to find out why it’s not working now,” mom says (**<u>Providing Guidance-Suggestion</u>**) As John is looking at his rollercoaster and testing it again, mom removes a part and places it back (**<u>Assisting-Building</u>**) and says, “maybe this is not plugged in, correctly.” (**<u>Providing Guidance-Suggestion</u>**) Then says, “Okay. Try it.” (**<u>Providing</u>**

Guidance-Direction) He tries and still does not work. The car stops in the middle again. They then turn the rollercoaster to see what the problem is. Mom says, "this way we may find the problem if we look at it from this side." They both keep moving some of the pieces and put them back and run the car. They collaboratively try to find the problem (***Optimization-Troubleshooting***) They do not add any new pieces to the rollercoaster, but just trying to fix they already had.

Finally, Mom looks at the researcher and says, "I am getting frustrated myself. I don't know why this is not working." The researcher suggests that they may use another slide track and she gives it to them. They both show their excitement and then Mom asks, "where do you think we should put it?" (**Soliciting Information-Prompting**) John looks at the slide and points to a small slide in the middle of his rollercoaster where the car stopped on many times (***Optimization-Troubleshooting***) Mom says, "Okay!" and she attempts to fix it (**Assisting-Building**) he takes the slide back and to do it himself. (***Optimization-Troubleshooting & Improving***) He removes the small slide and then attaches the other slide. He tests it by pushing the car very gently. The car stops there again. (***Optimization-Testing***) Mom points to the towers and says, "I think there is something wrong with this." (**Providing Guidance-Explanation**) John pushes the car another time harder, and the car runs to the end track (***Optimization-Testing***) Everyone cheers (**Affirmation-Encouragement**) He says, "Now it did it." and tries again in which the car stops (***Optimization-Testing***) Mom says, "You know, I think it's how the car rolls." (**Providing Guidance-Explanation**) John responds, "Oh that's what is happening?" (***Optimization-Troubleshooting***) He tests it again and harder and it works. And he says, "You know what. I think it is working. It's just the car that is not working sometimes. I'm done." (***Optimization-Troubleshooting & Evaluation***) Mom says, "Do you think this is the end?" (**Soliciting Information-Prompting**) He runs the car again hard enough that the car travels all the way to the end, and then says, "It has all the things you asked [pointing to the researcher] and the car sometimes works. It looks good. It's good. Done." (***Optimization-Evaluation***) While mom is still testing the rollercoaster, she acknowledges that, "You did really good boy." (**Affirmation-Encouragement**)

APPENDIX H. CASE 3 NARRATIVE

*Letter one & Challenge Zero***.** Dad asks Tom to read the challenge (**<u>Providing Guidance-Direction</u>)** and Tom starts reading, "Oh, my name. My name is Hannah. I am the director of city amusement park. Many kids come to the park. They were very happy, and enjoyed the rides and games. However, they were sad that the park does not have a rollercoaster. They asked me if I could add a rollercoaster. Can you please help me? I want you to design a model for a rollercoaster. Use the box of materials provided to design a rollercoaster. Before you design the rollercoaster…material as you will use to create a model. Try the warm-up challenges to explore the materials." (***Problem Scoping-Problem Definition)*.** Tom pauses and looks at the materials [possibly he is aiming to explore the materials], but Dad encourages him to read the rest of the letter, "Go on." (**<u>Providing Guidance-Direction</u>)** He continues, "At the end, I hope you will take a photo of your model and send it to me. We will then decide what design I want to use in my park." (***Problem Scoping-Problem Definition***)

He then looks at the researcher and says, "Umm. Wait, wait, wait. So, I'm actually building a real rollercoaster? (***Problem Scoping-Problem Definition***) The researcher confirms that he is building the model for a rollercoaster, using this kit. He gets very excited and asks again, "But they are actually going to build it? Oh." (***Problem Scoping-Problem Definition)***

As Tom gets so excited about the authenticity of the activity, Dad engages him in the task, by having a conversation with him.

Dad: What do you think, Tom? (<u>Soliciting Information-Prompting</u>)

Tom: That's cool.

Dad: Yeah? (<u>Affirmation-Confirmation</u>)

Tom: That's something I didn't know (*Problem Scoping-Problem Definition)*

Dad: Yeah. Let's build this then!

Dad: Okay. So before we jump into the actual challenge, we have some warm-up challenges. It says to get to know the material (<u>Providing Guidance-Explanation</u>) You want to read the first one there, Tom? (<u>Providing Guidance-Direction</u>)

Tom: What? .... I was thinking I could start this at the very top. Start the thing at the very top (Solution Development -Idea Generation) [As he is saying this, he also grabs a few black pieces and a start track, and attach them together.]

He builds a tower with two black posts, attaches it to a start track and then adds more black posts to that (***Solution Development -Modeling/Prototyping***) Then his sister, Anne, reminds him that he has to do the warm-up challenges, which he ignores. His dad suggests him to do the warm-up challenges. Dad realizes that Tom is excited about building a real rollercoaster and the ideas he has. Thus, Dad allows him to ask questions and express his idea, but then asks him to do the challenge.

Dad: Can you start by going through these steps, Tom? (<u>**Providing Guidance-Suggestions**</u>)

Tom: Hold on just one second. I think I know what I'm going to do with the design (***Solution Development -Idea Generation***) [He attaches the long tower that he built to the gray base.]

Dad: You do? (<u>**Soliciting Information-Confirmation**</u>)

Tom: Yeah. I have a fair idea of what it's going to .. (***Solution Development -Idea Generation***)

Dad: What's it going to look like? (<u>**Soliciting Information-Prompting**</u>)

Tom: [Using his gesture and language to describe his idea.] So, this is going to go down here a little bit. There can be loops, I guess (***Solution Development -Idea Generation***) Would people usually like loops? (***Problem Scoping-Information Gathering)*** [As he is exploring the loop by rotating them and checking how it can be attached to the other pieces.] (***Problem Scoping-Information Gathering***)

Anne: Yes. I would.

Dad: Yeah. Most people like loops (<u>**Affirmation-Confirmation)**</u>

Tom: But I'm not even going to ride on this. I'm not going to ride my own rollercoaster, I guess..

Dad: That's fine (<u>**Affirmation-Confirmation**</u>) You can just engineer it (<u>**Affirmation-Encouragement**</u>)

Tom: Yeah. I don't think engineers really ride their own.

Dad: I'm going on that rollercoaster with Anne (**Affirmation-Encouragement**)

Tom then attaches the pre-built tower with a few black posts and a start track to the gray base. He places a loop side by side tower and compares their sizes (***Solution Development -Decision Making***) Then, he takes out two black posts from the tower and pushes the rest on the gray base. He thinks aloud, "Out these two." (***Solution Development -Idea Generation & Prototyping***) He then repeats the side-by-side comparison of the loop and the tower, and thinks aloud, "Start with two. Yeah, it's got to be two." (***Solution Development -Idea generation***)

Dad then engages him to what he is asked to do (i.e. warm-up challenges), "Hey, before we dig in and start going at it, this is our warm-up challenge. So this is our first challenge, Tom. Can we do it?" (**Providing Guidance-Explanation)** Tom just responds by, "Ha" and continues exploring the material and checking how the pieces can work together (***Problem Scoping- Information Gathering***) He then points the loop, and thinks aloud again, "Oh, I see where this is supposed to go." and then takes out the loop and the black posts and adds a bigger tower closer to the first tower (***Solution Development -Idea Generation & Prototyping)***

Since Dad's suggestions for doing the challenges did not work, he uses direct language.

Dad: Can you find me one gray base?" (**Providing Guidance-Direction)**

Tom: What?

Dad: Can you find me the one gray base? (**Providing Guidance-Direction**)

Tom: I got it, right here (***Problem Scoping-Information Gathering***)

Dad: Good job (**Affirmation-Encouragement**) How about 12 black posts? (**Providing Guidance-Direction**)

Tom: What?

Dad: Where's the 12 black posts?

Tom: Those. [pointing to the black posts.] (***Problem Scoping-Information Gathering***)

Dad: Yeah.

Tom: These are like black posts, right here. [He gets up and shows his dad a black tower and then takes a part a couple of black posts]

Dad: How about, what's a one start track?

Tom: What?

Dad: One start track, and one end track.

Tom: [He does not respond to Dad’s question. He adds a small pink track to the start track.] This should go here (***Solution Development -Modeling/Prototyping & Idea Generation***)

Dad: Where's the start track for the rollercoaster?

Anne: Start track.

Dad: ... with start.

Anne: Start track. [points to the start track.]

Tom: How will I get it [the pink slide track] to stay like this, though? Do I need to attach more and more? (***Problem Scoping-Information Gathering***) [Tom without paying attention to his dad and sister, continues thinking about his design.]

Dad: Well, hold on a second. Do you ...(Providing Guidance-Direction)

Tom: I've got this. [He removes one black post from the second post and tries to add another pink slide to it.]

Although Tom did not show interest in listening to his Dad’s directions, Dad continues to ask him questions related to the challenge. He reluctantly responds to his dad.

Dad: Can you find me a blue slide track? (Providing Guidance-Direction)

Tom: What?

Dad: Can you find me a blue slide track?(Providing Guidance-Direction)

Tom: Wait. Okay, I don't know how I'm supposed to work on this, though. [He cannot attach the pink slide to the black post on the second tower (***Problem Scoping-Information Gathering)]***

Dad: I'll tell you now (<u>**Assisting-Verbally Verbally**</u>)

Tom: Do I believe like something ...[he gets up and looks at other pieces of the kit to see if he can find something that can be attached to the tower (***Problem Scoping-Information Gathering***)]

Dad: Where's one medium and small green slide tracks? (Soliciting Input-Prompting) [Dad does not pay attention to what Tom is looking for and asks a question to reengage him in the challenge.]

> Tom: I don't know what you're referring to. That's the thing. [He gets a turn track and moves the second tower to another point on the gray base (***Solution Development -Modeling/Prototyping***)]
>
> Dad: Right here. This is a medium. And this is small. [Pointing to the slides.] (**Providing Guidance-Modeling**)
>
> Tom: Oh. Oh, okay, I got it now. (***Problem Scoping-Information Gathering***)
>
> Dad: And, you found the one loop, right? The yellow one? (**Soliciting Information-Confirmation)**
>
> Tom: What? [Tom keeps working while Dad is asking him questions. He attaches a turn track to the pink slide. Then he tries to reach the second tower (***Solution Development -Modeling/Prototyping***)]

Challenge One. Dad realizes that he already knows the material, therefore, he asks him to do challenge one. Dad is being flexible in the strategies he uses to engage his son in the activity. He first suggests but then directly asks him to do what the challenge has asked.

> Dad: Can you build (**Providing Guidance-Suggestion**) ... So, read this step. I think you know where all the pieces are (**Providing Guidance-Direction**)
>
> Tom: That's not what ... [Thinking aloud as he is trying to attach the turn track to the tower. He then realizes that his dad asked him something.] What?
>
> Dad: Can you read step number two, what it says? (**Providing Guidance-Direction**)

He leaves what he was building and reads the challenge.

> Tom: Step number two. Build the rollercoaster you see in the picture. Ha?" (***Problem Scoping-Problem Definition***)
>
> Dad: There you go. So let's build the rollercoaster that you see in the picture (**Providing Guidance-Explanation**) [Dad rephrasing the statement for him] [It seems that through different ways and strategies, Dad is helping him with understanding the problem]
>
> Tom: All right. So take all this down now.

He removes some of the pieces from the design he had built, and reuses some parts of the structure for his new design (***Solution Development -Modeling/Prototyping & Decision Making***) He thinks aloud while understanding what he needs to build the picture and planning to build it, "So let's do this. Then I'll need a higher one. Or I think this was the actual ... Actually, a little, just a little bit lower. This is... Down here. So, two spaces. It's actually this. So then I will continue with it. Now

I just need two spaces.” (***Solution Development -Idea Generation & Modeling***) He shortens one of the towers and then adds another tower while counting how many spaces he needs in between the two of them (***Problem Scoping-Problem Definition; Solution Development -Modeling/Prototyping***)

Then, Dad realizes that he has placed the tower on a wrong spot. He points to the tower on the gray base and asks, "Where's this one located at? (**Soliciting Information-Prompting**) Tom responds, “Huh?” Dad points to the tower in the picture this time, “Where's that one located at [pointing to the tower in the picture]? (**Soliciting Information-Prompting**) Tom realizes this time what his dad is asking and he acknowledges the problem and attempts to fix the problem, “The ... Oh. That one's right there.” (***Optimization- Troubleshooting***) He moves the tower and places at the same place that it should be located according to the picture (***Optimization-Improving***) He then continues building the rollercoaster. He gets a green slide track and attaches it to the start track (***Solution Development -Modeling/Prototyping***) He then attempts to attach the slide to the second tower, but realizes that he cannot, "Wrong thing." (***Optimization-Troubleshooting***) and looks a for another pieces. Without looking at the picture again, he gets the end track that is already attached to a black post and attaches it to the second tower. And finally attaches the green slide to the end track (***Solution Development -Modeling/Prototyping***) Dad encourages him by saying, "There you go. Good job." (**Affirmation-Encouragement**)

Tom gets the coaster car, "All right.. And then, I do this." He then acknowledges that he is going to test it. "Now, I know how to test this, Dad, don't get me wrong. I've got to take this. I fling it like that." He then pushes the car on the rollercoaster but it does not work, because both towers have the same height (***Optimization-Testing***) Dad asks a question to indirectly prompt his child to find the problem.

> Dad: Is it working? (Soliciting Information-Prompting)
>
> Tom: Oh, wait. I'm too tall (*Optimization-Troubleshooting*) [He takes out one black post of the tower.] All right. Like that. Now I just get that out. Still not finished, I think (*Optimization- Improving)*
>
> Dad: There you go (Affirmation-Confirmation)

Tom then tests the rollercoaster and it works, and Dad praises him, “Good.” (**Affirmation-Encouragement**) Tom gets distracted again and talks about the real rollercoaster that he is building. He says, “Oh, I get it. I get now why they're giving me $25, because I build it for the actual amusement park. I thought it was just because I have Asperger's, and ... Yeah, that's why.” Dad reengages him with a question, “So they ask you a question there at the end, (**Providing Guidance-Explanation**) don't they?” (**Soliciting Information-Confirmation**) Tom answers the question (about the number of black posts) very quickly.

*Challenge Two***.** Dad passes the second challenge to his son, and says, “Another warm-up challenge for you.” Tom looks at the paper and reads it and while pointing to the start tower, says "Oh Steeper (***Problem Scoping-Problem Definition***) So should I put this one up on here. Up one more, higher (***Solution Development -Idea Generation***)" Dad responds, “Yeah, it says a steeper rollercoaster (**Affirmation-Confirming & Providing Guidance-Explanation**) Think about it (**Providing Guidance-Direction**)” Tom then immediately starts describing his ideas and prototyping. The conversation below happens between Dad and Tom.

> Tom: Oh, oh. Yeah, yeah. I got this. Man, there's going to be like, there's going to be like. Actually, I don't think we'll ... It probably will only be …umm… one more. Here we go, like this. Dad, this. This is longer. [While the slide is attached to both start and end track, he breaks the start tower. He adds a black post to the tower and puts the rest back in place. The start tower is now longer.] (***Solution Development -Idea Generation***)
>
> Dad: Is that steeper? (**Providing Guidance-Assessment**)
>
> Tom: Yeah. It's one more. It's one more (***Optimization-Evaluation***)

Since Challenge gives a hint to try other slides, Dad refers to that and reminds his son.

> Dad: It says, try the other slide tracks (**Providing Guidance-Explanation**)
>
> Tom: What?
>
> Dad: What's a slide track? You talked about slide tracks, right? (Soliciting Information-Prompting)
>
> Tom: What, what? Oh, those? [pointing to the slides] (***Problem Scoping-Problem Definition & Information Gathering***)
>
> Dad: What you got here, what's a slide track?
>
> Tom: The blue thing.
>
> Dad: And the orange ones.

Tom: Yeah, okay.

Dad: They're all slide tracks. [pointing to all the slides on the table.]

Tom tests his rollercoaster (***Optimization-Testing***). It works. He retests it and says, “Oh, look at this. Look how fast this one goes. It’s exciting” (***Optimization- Evaluation***) Dad uses this moment as a learning opportunity for his son, and asks, “Goes faster, why does it go faster?” (**<u>Soliciting Information-Seeking Explanation</u>**) Tom responds immediately, “Well, because it's steeper, and more like ... More taller (***Problem Scoping-Information Gathering***) So that one [probably referring to the first design] slows down more. If I were to add more, it'd go down way, way, way faster.” (***Solution Development -Idea Generation***)

Dad encourages Tom to try building a faster rollercoaster by asking, “You going to try that [the idea his just articulated]?” While Tom looks at his rollercoaster and points out to the height of the first tower, he says, “I don't think it will let me do another one.” (***Solution Development -Decision Making***) He then models what he means by breaking the start tower and pointing to the part he could possibly add a piece (***Solution Development -Decision-making & Idea Generation***) Dad asks another question, "Can we figure out a way?" (**<u>Soliciting Information-Prompting</u>**) While Tom is listening to Dad, he adds a black post to the start tower and is able to attach the slide to the end tower (***Solution Development - Idea Generation & Prototyping***) He then acknowledges that he is going to do what Dad wanted, “Oh, I get it. This.” He then decides to add another black post to the start tower to make a steeper rollercoaster, “Trying that. That makes it even more steeper, it's like ..” (***Solution Development - Idea Generation***) At the same time Dad asks "How can we do it even steeper?"(**<u>Soliciting Information-Prompting</u>**) Before Tom answered Dad’s question, they notice that the slide cannot reach the end tower any more as the start tower has gotten longer. Tom, says, "Oh." (***Optimization-Troubleshooting***) Dad follows up and asks, "how can we fix that?" (**<u>Soliciting Information-Prompting</u>**) Tom reassures his dad that he knows how to fix it, "Don't worry. I got this. I guess we'd better take one more off. I guess we got to take one more off. Guess. " and he takes one off and fixes the rollercoaster (***Optimization-Troubleshooting & Improving***)

Dad again tries to encourage him to use other slides as mentioned in the hint.

Dad: Could we try another, something else?” (**<u>Soliciting Information-Prompting</u>**)

> Tom: No, because this one's the longest [slide]. And the higher I go, the steeper it gets. So, it's going to be wasting the outside [inaudible]. It drops out. I got this. Not like that time [that the car fell off.] (***Solution Development -Decision Making***) Dad, look at this. Whee! That's steep and fast. [He tests his rollercoaster several times.] (***Optimization-Testing***)

While Dad makes sure that he praises his work, he still tries to get him use other slides. "That's steeper, yes (**<u>Affirmation-Confirmation</u>**) Can we get ..." But Tom is too excited about his steep rollercoaster, and he keeps pushing the car on the rollercoaster. "Hey, look. Wait, wait, wait, let me try it. It goes as fast as a finger snap." And Dad confirms by, “Yeah, that is fast.” (**<u>Affirmation-Confirmation</u>**) He pushes the car very hard that the car runs out of the track. "Oh, no. I pushed it too hard." (***Optimization-Troubleshooting***) His sister, Anne, warns him that he should not push it hard because somebody's going to get hurt on that ride.

Again, Dad re-engages by asking a question, "Do you want to do what they asked you to do?" (**<u>Providing Guidance-Suggestion</u>**) Dad waits until Tom responds as Tom is testing his rollercoaster excitedly, and then he follows up with an explanation, “They gave you a hint, here. [showing the challenge text to him]” (**<u>Providing Guidance- Explanation</u>**) Tom reads it aloud and then asks, “Try other slide tracks. Like a smaller one?”. “Probably” says Dad. Tom engages in the activity and says, “Oh, how about this” while comparing a small slide side by side to the other slide he has and then put it back (***Solution Development -Idea Generation & Decision Making***) He continues his reasoning, “I don't think there is any bigger. Oh, yes there is [seems to be looking for a longer slide] (***Problem Scoping-Information Gathering***) Then he decides to build a new rollercoaster, “This is, get up, be fun.” He takes out all the slides and tracks attached to the towers. He now has two black towers on the gray base. He says, “All right. Now let's make it this way, way higher. Way, way, way, way, way higher. Maybe three or two more [black posts to make the towers longer] (***Solution Development -Idea Generation***)

At this point he starts asking questions from his dad, but Dad let him make decisions by disengaging from the activity for a while. He is sitting on a chair close to Tom with his hands off the table. While he was not engaged in building or decision-making process, he supported Tom by his confirmation.

Tom: Which one do you think? (Solution Development -Idea Generation & Decision Making) Dad, should I do two or three more? (Solution Development - Idea Generation & Decision Making)

Dad: You do what you think you can make (<u>Disengagement</u>). I'm sure you can make it (<u>Affirmation-Encouragement</u>)

Tom: Okay. I'm going to take three (Solution Development - Decision Making)

Dad: Okay (<u>Affirmation-Confirmation</u>)

Tom: This probably won't work, but let's try it anyway. [And he tries his ideas.]

He adds three more black posts to the Start tower and tries to attach the slide. But he sees that the slide does not reach the end track as it's short. He realizes that, "All right. No, it doesn't fit." (***Optimization-Troubleshooting***) He decides to remove some more black posts, "All right, let me just get ... Take off some more (***Optimization-Improving***) Now we can try it." He puts the slide next to the start track this time without attaching it (***Solution Development -Decision Making***) and finds out that it is still short for the distance between the two towers, so he drops the slide (***Optimization-Troubleshooting***) He looks for another track, "Still not ... There even longer ones than these? (***Solution Development -Decision-making*** & ***Optimization-Troubleshooting***) Oh yes there is, there is. That's about as high as it'll go. I think. It's about as high as it will go. This will work. I know it (***Solution Development -Decision-making*** & ***Optimization-Evaluation***) [He attaches the longer slide to both tracks (***Optimization-Improving***)] All right, so like this."

He then looks at his dad, "Oh, great, here we go, Dad. Whoa! Whoa!" Dad supports him by celebrating with him, "Whoa!" (<u>**Affirmation-Encouragement**</u>) He then tests it (***Optimization-Testing***) The car goes very fast but at the end it falls off from the end track.

Self-Guided Challenge: Free Design. As Tom faces another problem with his rollercoaster, he engages in expanding the problem space and accordingly coming up with new ideas for how to fix the problem. First, he adds to the context by providing an idea that he cannot build himself but can help prevent the problem he is facing. He says, "This one [pointing to the end track] will just make the rollercoaster fall off. Unless all the rollercoasters have them, them …[I] mean the wheels stick." (***Solution Development - Idea Generation & Optimization-Troubleshooting***) Dad helps him elaborate on his idea, "What is this wheel stick you're talking about? What do you mean by that?" (**<u>Soliciting Information-Prompting</u>**) Tom points to the back of the car and says, "Here. Something stops the car. Like the ones in real." He then asks Researcher, "Do they do that on rollercoasters? The wheels stick to make it safer? Like pulls it over?" (***Solution Development - Idea Generation*** & ***Problem Scoping-Adding context***) Researcher responds, "That's an option too, I think. Pretty safer. If you want, you can put a note for her and we will share that with [crosstalk]"

He but cross talks as he thinks he found a solution and says, "Oh hey, we can put it backward. We can put the car backward." (***Optimization-Troubleshooting***) referring to his new idea for solving the problem. He tests it but the car runs out of the track again and he says, "Shoot. I thought it would stop. We need the little things [wheel sticks he was talking about it before] here." (***Optimization-Testing & Troubleshooting***)

Dad tries to help him find the problem and solve it. Thus, he engages in conversation with his son to encourage him test the rollercoaster and observe how the car travels on the rollercoaster.

> Dad: what it the problem and How could you make it go ... You're running into a problem, right? (**<u>Soliciting Information-Prompting & Confirmation</u>**) The car ...
>
> Tom: Yeah, it keeps falling (***Optimization-Troubleshooting***)
>
> Dad: So, how can we solve that? (**<u>Soliciting Information-Prompting</u>**)
>
> Tom: This ...[He tests it again and it does not fall which confuses him] Now it's stronger. I didn't change anything. I am probably going to change it now. It probably... No. What I'm saying is, it probably didn't change anything. [He keeps testing his rollercoaster and the car safely lands on the end track.]
>
> Dad: That it? Is it solved?
>
> Tom: Did. That's close. See, look. It is working. Oh no it didn't this time (***Optimization-Testing***)
>
> Dad: Oh.
>
> Tom: Yeah, I messed that one up. I messed that one up, see? It usually does it, though. But it does turn it around. That's why sometimes it doesn't work, but most of the times … (***Optimization- Troubleshooting***) Besides, not going to be as fast as it is right now, will it? Yeah. I think it shouldn't be very fast. That's the problem (***Optimization-Troubleshooting***)

Since he now has an answer to why the problem is happening, Dad encourages him to use other slides. Dad wants Tom to follow all the challenges one by one. However, with a new slide in mind, Tom decides to make a rollercoaster of his own and not following the challenges.

> Dad: So now you why. Can you examine this one [showing an orange slide with tunnel], and see how that one works?
>
> Tom: Huh? It's like a big tunnel. Like they do at the water slides, you know? (Problem Scoping-Information Gathering)
>
> Dad: I'm not sure how it works (Acting like a student of the child to help him figure out the slide works.)
>
> Tom: We could also make this a water slide. Yeah? [looking at his dad and the researcher] (***Solution Development -Idea Generation***)
>
> Researcher: We can tell Hannah, maybe if she's interested in that, that's a good idea. I like it.
>
> Tom: We can make a rollercoaster and a water slide. So, this, the first one I'm going to make is obviously a rollercoaster. And the next one's going to be a water slide (***Solution Development -Idea Generation***)
>
> Researcher: Okay. Yeah. Try it (<u>**Affirmation-Confirmation**</u>) That should be fun (<u>**Affirmation-Encouragement**</u>)
>
> Tom: Yeah, let's do that.

He starts looking at the material and thinking aloud saying his plans. “First, I need the ..” (***Solution Development -Idea Generation***) while taking out takes out the end tower and the green slide. Dad tries to convince him to follow the challenges, "Can you try this one challenge a little? Can you see if that ... How that works on there." (<u>**Providing Guidance-Suggestion**</u>) Because Tom does not show any interest in what he is saying, he paraphrases what he said earlier, "Can you see if it [the orange slide with tunnel] fits on there? (<u>**Providing Guidance-Suggestion**</u>)

> Tom: Yeah. One second, though. I'm just making my own rollercoaster now.
>
> Dad: Okay. See if you can get that piece to fit to it (<u>**Providing Guidance-Direction**</u>)

Tom gets the orange slide (orange slide with tunnel), He rotates it and tries to attach it to the start track. He then asks for more information about the piece (***Problem Scoping-Information Gathering***)

> Tom: Well look, it's a tunnel. But what do these tunnels do? (***Problem Scoping-Information Gathering***)
>
> Researcher: What do you think? (**<u>Soliciting Information-Prompting</u>**)
>
> Tom: Oh. Well. Okay. I'll try it.

He attaches it to the start track. He then takes another similar slide and tries to attach it to the other slide. Meanwhile he describes his idea and what he aims to do (***Solution Development -Idea Generation & Prototyping***) He cannot attach them together, so he leaves the second one on the table, and asks for help from his dad, “All right, which one?” Dad, however, instead of responding to his son's question, he tries to reengage him to the challenges, “There's a question down here” (**<u>Providing Guidance-Explanation</u>**)

Tom is not willing to stop what he is doing. He ignores what his dad said. He gets up and looks at all the material he has, and grabs a turn track and says, "Here's something I can do now." (***Solution Development - Idea Generation***) and attaches it to the orange track (***Solution Development - Modeling/Prototyping***) As Dad asks him to look at the challenges, he tells him to wait until he is done with his design. And he continues, "How do I get these [the orange track and turn track] to stand up, though? (***Solution Development -Decision-making & Idea Generation***) Do I just let them rest in peace on the thing, or does it ...Do I just let them rest in peace on the thing? " Then his orange slide comes off the start track. He tries to reattach the orange slide to the turn track, but he cannot. He gets frustrated and says, "Aah, Dad.” Dad offers to help. "Let me see." (**<u>Assisting-Verbally</u>**) Tom does not let him help. He attached some pieces together. He then grabs the tower he made in the previous challenge, makes it longer and put it on the gray base (***Solution Development -Modeling/Prototyping***)

He is unsure of what he has to do next. He thinks aloud about the problem and how to fix the problem, “So if I just let it ... So I just build something up, and just let it stay like this. [leaves the turn track leaning on the tower] Does that work? Or, is there some sort of trick? You have to connect them to this [the tower]? I don't know, Like this. Do we just let it do that, I guess? I don't know how to fit it on there.” (***Optimization- Troubleshooting***) Dad tries to provide an explanation but Tom stops him with his next step, “So, this turns here. And so, do you think we can...” (**<u>Provide Guidance-Explanation</u>**) Tom says, “Oh, wait, wait, wait, wait, wait. Let's see if it stands still. It does stand still." (***Optimization-Testing***) But he does not seem convinced to continue his design with that, and thus, he asks Researcher for more information, “Excuse me, is there something that I need to connect right here?”

Before Researcher responds, Dad redirects the subject and encourages him to do the challenges, " Maybe if you look at the guide and do the last warm-up challenge you will figure it out,” **Provide Guidance-Suggestion)**. Tom gets distracted from building, looks at the challenge and responds to the challenge question “in each rollercoaster, you can count how many black posts does the post.... I know it’s easy. It will drop down three.”

Dad praises him and says, “Good job. I think this is done and you can do the next challenge.” (**Affirmation-Encouragement & Provide Guidance-Suggestions**)

Tom who was in the middle of building his idea, he engages in evaluating his design, “Well it did turn. Still has problem.” (***Optimization-Evaluation***) Thus, he continues figuring out how to move on with his current design and how to solve the problem of connecting the tower to the turn track, and asks, “I'm just wondering, how do I fit this on here? Ah!” (***Optimization-Troubleshooting***) He then goes back to his design and changes a part (***Optimization-Troubleshooting & Improving***) He then tests is the two pieces work together which they do (***Optimization-Testing***)

Dad who is now frustrated that his son is not moving to the next challenge, models for him how he can continue designing by attaching other things and explains, “Because what happens is, is you put this over here. [moves the second tower.] And then you start adding on to this side, and then we'll start connecting down here. And so, you see what I'm saying? So, we'll come down here, and he'll rest up on this one, right?" **(Providing Guidance-Explanation & Modeling**). Tom excitedly says that he is willing to build Dad’s idea (***Solution Development -Decision-making & Idea Generation***) Dad, however, says, “Well, let's do this first, so we can get there. And then you're going to build your own.” (**Providing Guidance-Direction**) Tom disagrees and starts building a new tower based on what his dad suggested and lean the turn track on the tower. (***Solution Development -Modeling/Prototyping & Idea Generation***) Dad provide a confirmation and disengages from the activity by moving a bit further from the table (**Affirmation-Confirmation & Disengagement**)

As Tom is building he faces some problems that makes him very frustrated. These problems include falling apart the structure he builds, pieces not attaching to each other, and pieces not reaching the next piece. In these instances, he shows his frustration by words (e.g. It's hard, God. Come on." and gesture (e.g leaving the pieces on the table, putting his hands on his face). However, he does not give up the work and continues deciding which piece to use, attaching and removing pieces, and moving parts of the built structure (Solution Development -Idea Generation, Prototyping & Decision Making) At times, without using the car, he also tests the parts of the structure to see if they work together (Optimization-Testing) which these testing events lead to finding a new idea and adding/removing pieces. At the same time, both Dad and Ann are disengaged from the activity and just watching what Tom is doing.

Finally, Tom loudly announces that he is going to test it and that it works (***Optimization-Testing***) "Let's try it now. Oh, look. This is actually right." Before he tests, Dad gives Tom suggestions that makes him confused, "Can you use the stopper [end Track]?" (<u>**Providing Guidance-Suggestion**</u>) Since Tom looks confused, he follows up, "Can you try to make a curve?" Then after a few moments of silence (a sign of Tom's confusion), Dad uses points to the areas he is refering to and repeats his questions, "Can you use a stopper over there, to have stop …" (<u>**Providing Guidance-Suggestion & Modeling**</u>)

Dad's suggestions encourage Tom to complete his structure before he actually tests it. He engages in adding turn tracks and other pieces that can be attached to each other and make a rollercoaster (***Solution Development -Idea Generation & Modeling/Prototyping***) He looks for a pink slide but he cannot find one, therefore, he uses a green slide which is bigger. He acknowledges that he made the right decision, "This thing will have to do. Yes. Still works." (***Solution Development -Decision Making***) However, shortly after he realizes that he cannot attach the slides to the tower. He has not yet realized that he can attach the turn tracks to the towers. He asks his dad in frustration, "The How do I do this?" Dad who has been mostly disengaged to give his son the room to work independently, responds immediately, "What? What's the problem?" (Soliciting Information, Prompting) Tom points to the slides that he connected it together, "I don't get this. It's just falling apart. I have to figure out how I connect this. It won't connect." (Solution Development - Troubleshooting) Dad uses this moment to direct him to the warm-up challenges, "You want to read the warm-up challenge? It might help you." Tom accepts his dad suggestion, reads the challenge but does not find it helpful, “Yeah, that didn't help or anything. That didn't help, or anything helps?” He then takes apart the slides and turn tracks, and takes down all his rollercoaster.

Dad comes closer to his son. and give him the second prompt for this challenge. “Okay. You may want to take a look at this.... Okay, let's take a look at this, and see.” (<u>**Providing Guidance-Direction**</u>) As Tom looks at the hint, Dad continues by, “Well, we know what pieces are being used, right? See if we can get any idea from this.” (Providing Guidance-Explanation) Tom realizes about how to attach the turn track, “Wait. So ... So, the curve do this? I guess? The curves do this.” (***Problem Scoping-Information Gathering***) He gets a turn track and is trying to attach it to a black tower there as he sees that in the picture. However, he attaches it in a wrong way. Dad tries to get the piece from him and show him (Assiting-Hands-on offer) Tom does not let him. He tries himself but it does not work, “Wait, wait, wait. You put the curves here, and these two. Dang it!” (***Problem Scoping-Information Gathering***)

As Tom gets very frustrated, Dad provides another suggestion. He points to another tower, “What if you put the curve right here, in this one?” (<u>**Providing Guidance-Suggestion**</u>) But find Tom not looking at him and is still trying to attach the turn track in a wrong way, “Ah, It's not even going in there.”. He gets a turn track from the table and a tower and directly models it for him. “Here. Let's put the curve.” (<u>**Providing Guidance-Modeling**</u>) He then gives a tower to Tom, so he can also try it. Tom gets excited. While trying to copy Dad and attach the turn track on the tower, “How did you do that? Uh Like that!” (***Problem Scoping-Information Gathering***) And then he looks at the start track and sees the pattern between the way the turn track and start track can be attached to the towers, "Ah, this is how this connects here?" (***Problem Scoping-Information Gathering***)

Tom then decides to build a new rollercoaster and starts building (***Solution Development -Idea Generation & Prototyping***) Meanwhile, Dad prompts him by some questions and confirmation which leads to Tom’s decision-making process of choosing the right piece and understanding how they connect to each other (***Solution Development -Decision-making & Problem Scoping-Information Gathering***) While Tom is building Dad asks him, “Do you want to use a blue one, or do you want to use a longer one?” (<u>**Soliciting Information-Prompting**</u>). Tom responds that he thinks the blue one should work (***Solution Development -Decision Making***) Dad provides confirmation, “You are Right. I think it should work" (**Affirmation-Confirmation**)

He attaches the blue to the start track. He then checks the distance between the current small tower on the gray base and the long tower that the blue and start track are attached to it (***Solution Development -Decision-making & Prototyping***). The blue track cannot reach the black tower. He moves the tower to the longer track. He then gets a turn track and attaches it to the blue track. As the turn track does not get to the tower, he removes it and attaches it to the tower (***Solution Development -Decision-making & Prototyping***) He then tries to attach it to the blue track which does not attach. “I don't get this. This is what confuses me. Think I will need to put this on there first thing. But that doesn't work.” (***Optimization-Troubleshooting***)

As Tom is confused, Dad directs him to look on the base in the picture to see, “Where they have the towers on the base. The picture.” (**Providing Guidance-Direction**) Tom refuses following dad’s suggestion, “Wait, wait, wait. No I got this.” Then he gets another turn track to attach it to the slide which he cannot. He gets frustrated and throws the turn track on the table. Dad directs him to the base one more time by asking him, "Look at the base. How many black ones do you have on the base?" Tom is so frustrated that continues attaching the blue slide to the two towers without paying attention to what his dad is saying. As he pushes to the towers, one of the towers comes out. Overwhelmingly, he shouts, “Oh my God.” Dad calms him down using different strategies:

> Dad: It's okay. But why are you determined to use a blue one?' (**Soliciting Information-Prompting)**
>
> Tom: Because!
>
> Dad: If it doesn't work, why should you use it? It's okay, it's all right (**Providing Guidance-Explanation**)
>
> Tom: My God. Need to get this. Ah! Does everything have to be a problem? [As he is pushing the blue track to be attached to the second tower.]
>
> Dad: Tom, you almost had it. Keep trying (**Affirmation-Encouragement**)
>
> Tom: My God!
>
> Dad: You want me to help you? (**Assisting-Verbally**)

Tom: Yeah, sure.

Dad: I understand what you're talking about (**Affirmation-Confirmation**). This is tough to do. Let me show you something.

He moves to the other side of the table and compares some tracks with each other. He gets a slide he needs. He then takes out the towers and moves them a little bit and attaches the slide to both towers while they are off the base.] (**Providing Guidance-Modeling**)

Tom: Oh, I get it. I have to do that (**Providing Guidance-Explanation**)

Dad: It was tough to do. It went in.

Tom gets the towers from Dad but the slide comes out again. he gets upset and says, “No, no, no, no, no, no. I think there was something else.” Dad directs him to the picture again and tells him, "Look at the picture. How many black ones are there?" (**Soliciting Information-Prompting**)

Tom says angrily, “Nothing ever works for me. All right. All right.” Finally attaches them together (***Solution Development -Modeling/Prototyping)***

Dad prompts him to continue, "What could be next?" (**Soliciting Information-Prompting**) After a few minutes of silence, Dad directs him again to look at the picture, "What are they doing?" (**Soliciting Information-Prompting**) As he has calmed down now, he finally looks at the picture and realizes that he could build the same rollercoaster.

Tom” Oh. I didn't know I was supposed to copy off of that.

Dad: You don't have to copy exactly off of that. You can get an idea of how it works (**Providing Guidance-Explanation**)

Tom: Okay. So, then I can just do this with another one right here? [While he is grabbing another turn track and tries to attach that to the first turn track.]

Dad directs Tom to look at the picture if he is misusing a piece. He asks him, “Do they have that like that? (**Soliciting Information-Prompting**) You don't have to copy exactly like but... You want to be able to get on from this challenge. You want to be able to move on from this challenge. Do what you want then.” (**Providing Guidance-Explanation**) And this conversation leads to the conversation below as Tom brainstorms and plan for his new idea.

Tom: Okay. [He then drops the turn track and attaches a small slide to the turn track] I just got a great idea of what I could do just for this (***Solution Development -Idea Generation***)

Dad: You did?

Tom: Mm-hmm.

Dad: As you were working, you figured out a great idea? Great! (**Affirmation-Confirmation**)

Tom: Yeah. Say like here, I twist each one of those. See? (***Solution Development -Idea Generation***)

Dad: And, we need a stopper for it, right? (**Providing Guidance-Suggestion**)

Tom: Yeah. Oh, wait, wait, wait, wait, wait.

Dad: We need a stopper. What do you mean?

Tom: Yeah, I want to use that one slide, make it to the very bottom. And then the stopper (***Solution Development -Idea Generation***)

Dad wants Tom to wrap up this challenge by following the prompt and encourages him to get done with this challenge and get to the next challenge. "Let's just get past this challenge, and then you can do whatever you want to." Tom disagrees and continues working on his own plan for designing the rollercoaster.

Tom is now trying to attach the second slide to the third tower. He has attached a turn track to the third tower, but he realizes that the slide doesn't get to the tower. Learning from his previous experience, he adds one black post to the tower to make it longer and then re-attaches the turn track (***Optimization-Troubleshooting & Improving***) Tom is looking for more pieces to make his rollercoaster bigger by adding more towers. However, Dad who is frustrated that Tom does not wrap up his, passes an end track to indirectly encourages him to wrap up this challenge. He says he got this and puts the end track aside.

Tom gets frustrated as he has built more towers but can attach them to as he planned. He thinks aloud and asks questions like, “How am I supposed to twist this?”, but he does not allow Dad to help him. He generates ideas and try them and quickly decides that they do not work.

Dad: Here, why don't you show-

Tom: I got this. One second. Oh, great idea. I just need another thing, a switch (***Solution Development -Idea generation***) Wait, no, that's not going to work (***Optimization-Troubleshooting***)

Tom: I had to retry. Dang it! [and then the tower suddenly breaks] Do I really have to restart all the work I'd done?

Dad: If it's too steep .. (**<u>Provide Guidance- Explanation</u>**)

Tom: Let's try this, I guess. Although knowing it won't work. It obviously won't. [While he is disappointed, he is trying it, and he does not allow his dad to help (shows his persistence and indecency.)]

Dad: Try another block, Tom. I think you need one more black one if this slide you're using (**<u>Provide Guidance- Direction & Suggestion)</u>**

Tom: I'll just do this smaller one (***Optimization-Troubleshooting***)

Dad tries to encourage him to wrap up this challenge, so he can move to the last challenge. He shows him how he can just complete his rollercoaster. Because Tom has not read the problem at the beginning, he is not sure what has been asked to do. Therefore, in the middle of the activity, both parents engage in explaining the problem to him and what he is asked to do in the challenge (**<u>Provide Guidance- Explanation</u>**)

Dad: Hey, Tom?

Tom: Yeah?

Dad: If you just put this-[End track] here

Tom: I got this. I'm good.

Dad: I understand. But if you just add this piece on, right here at the end, you'll be done with this challenge, and you can move on and build whatever you want. [The dad is trying to help him understand the problem.]

Tom: What do you mean?

Dad: There was [crosstalk 00:28:56]-

Tom: Yes, I want to put this at the end. Don't worry.

Dad: But all she wants you to do is go around a curve right here.

Tom: What?

Dad: So if you can go ... What was the goal?

Tom: What do you mean?

Mom: She wants to see if you can build the rollercoaster first.

Dad: Can you build a rollercoaster that turns the coaster car before it stops, remember?

Tom: What?

Dad: So that would look like the picture. [crosstalk 00:29:18]-

Tom: Oh, I get it. So then I would need this?

Dad: This picture right here.

Tom: Wait, wait, wait, wait. I need this [slide], and then this [slide]?

Dad: Look, look at the picture. What we're talking about is the picture. So, here you start, come down, you got that. It goes around the curve. What piece is this? The green piece. Now, it's a green piece. Is there a blue piece? [showing the picture to him]

Tom: Yes, I know it's something similar to that. I just don't want to copy the whole, where they place it. Everything of where they placed. This is going to be my design at the end. I just don't want to do it exactly how something is [crosstalk 00:29:54].

Mom: Her thing is, she doesn't want you to build your own design until she can see that you can do what it's asking you to do first (<u>**Providing Guidance-Explanation**</u>) You need to prove that you can build what she's asking you to do first.

Dad: Just like a boss would at work.

Mom: Yeah. And once you show her, you can do the round thingy. Then you can build whatever you want. But right now, you're not showing her you can build the round thing.

Tom: What do you mean by round thing? (***Problem Scoping-Problem Definition***)

Dad: This one right here (<u>**Providing Guidance-Modeling**</u>)

Tom: This is going to be my design, I'm telling you. And this is going to be my design, on that one. But I'm just remixing it, just a little bit. So yes, this is my remixed version of that design. Now it's time to test.

Dad: Okay, test it out (<u>**Affirmation-Confirmation**</u> & <u>**Providing Guidance-Direction**</u>)

Tom then goes back to complete his rollercoaster, and then he adds a tower and track to his design and looks for other pieces. He keeps adding and removing pieces (***Solution Development - Idea Generation, Prototyping and Decision Making***). Tom asks Dad to pass him a turn track while he could just complete his rollercoaster by the end track. Dad reminds him, “Here's one, too. I thought you were going to add this piece [End Track], and show her that you're done, so you can start your own design.” Tom responds while attaching the turn track, “But I'm not done yet, though. I'm almost done, though. I now need a small one of these [tower] (***Solution Development - Idea Generation***) and then done.”

His sister Anne comes next to him and reminds asks him, “What are you doing, Tom?” He responds without looking at him, “Thinking.” She asks, “Is that a water slide, Tom?” (***Solution Development - Idea Generation***) Tom responds, “No, not yet. My water slide will be next (***Solution Development - Idea Generation***) Make the adjustment on it (***Solution Development - Modeling/Prototyping***) All right. It's really hard to build with Legos, but it would be very easy if I actually built this in real life, right? Really hard to do with Legos, however.” Anne asks him to call her when he is doing the water park.

He gets frustrated again as he is not able to attach the slide to the other tower as the slide is smaller than the distance between the two towers. After some think-aloud, he finally asks Dad, “"how to do this.!" But he does not wait for an answer. He engages in making decisions in which slide he needs to use, since he has moved the towers. He tries the first one and then tries another one. Since none of them works, he starts exploring other slides. Then his dad suggests, “How about smaller one.” (<u>**Providing Guidance-Suggestion**</u>) Tom accepts Dad’s suggestion and uses the small slide that Dad suggests. He then wants to use the turn track but realizes that he needs another tower.

> Tom: Wait, but I can't just have it go straight down.(***Optimization-Troubleshooting***) I could add another one [a tower] down here. [He adds a tower and makes some other changes.] (***Optimization- Troubleshooting & Improving***)
>
> Dad: Okay, do you want to end it now, so we can move on to the next challenge? (Providing Guidance-Suggestion)
>
> Tom: Yeah. Yeah, just center the thing. Now I'm going to show it right here. Well, this is going to be my design. Next, I'm going to make the water slide design (***Solution Development -Idea Generation***) [And then he welcomes help from his dad and adds the last tower, attaches the slide and adds the end track.]

Everyone cheers for him (***Affirmation-Encouragement***) He says, “Now, let’s just try my rollercoaster.” Dad says, “Excellent. This excellent. Let’s do it.” (***Affirmation-Encouragement***) Everyone encourages him to test his rollercoaster, and suddenly he says that he has to name his rollercoaster. He asks others to suggest names. He disagrees with other’s names. And starts suggesting names himself. As he is suggesting names, he also adds context to his rollercoaster.

> Tom: How about Spookey design. People should climb up there and the go down. If there's something that you use to climb up here? It could be like stairs. Or elevator? Or somewhere like right here, and then you could end, and then you go all the way down. [looking at the researcher] Are we allowed to add a thing right here, and then have a spooky thing inside?
>
> Researcher: You can tell them. We're video recording this, so you can tell them!
>
> Tom: I can cut out pieces of paper, and put them along there, right? (***Solution Development -Idea generation***)
>
> Dad: Yeah. But you don't have those papers here. They could be [Crosstalk]
>
> Tom: All right, so then I guess we'll just call it something else until we get the actual. Or we do something else. That’d be cool though, dad.

He continues to come up with names and discuss why the name is good or not. This takes about 5 minutes to find a name and asks everyone’s votes! Finally, he names the rollercoaster: Dragon's Tail. He asks the researcher to let the company know about the name. He then describes how they have to design it to match the name:

> Tom: Let them know. So, the flame of the dragon's tail goes. Oh, and also you should design this like a flame. I need to describe what it's going to look like on the actual rollercoaster. So if you can make it like a flame, like a flame, that like ... The dragon's flame and it gets all ... You know how dragons have fires on their tail? We could do that, right? (***Solution Development -Idea Generation***)

He tests his rollercoaster and it works. Everyone cheers again. He retests it few times and is excited that his rollercoaster works. He asks is he has to check off everything he did (***Optimization-Evaluation***) He grabs a marker to write something on the table, but Dad suggests that they read the letter.

Letter Two. Dad reads the letter aloud, "Dear engineers, thank you for learning to design a rollercoaster for my park. Do not forget, children have asked for a very exciting rollercoaster ... Very exciting rollercoaster, it's a whole ... To make them happy, the rollercoaster needs to start very high, and ends very low." (**Providing Guidance- Explanation**) As he is reading, Tom takes notes on the table and says aloud, "To have a loop, and to pass at least one tunnel. So, it needs a tunnel." (***Problem Scoping-Problem Definition***) Then he starts exploring more information.

Tom: How do I make a tunnel, though? (***Problem Scoping-Information Gathering***)

Dad: You talked about a tunnel before.

Tom: Do I just put this over something? (***Problem Scoping-Information Gathering***)

Dad: Well, it's ... What looks like a tunnel? (**Soliciting Information-Prompting**)

Tom: That says a tunnel (He looks at the guide and sees the tunnel] (***Problem Scoping-Information Gathering***)

Dad: That's ... Yeah, that's a tunnel (**Affirmation-Confirmation**)

Tom: So, what do I do with it now? What's ... Oh, like this? You mean like this, and then this is the end or something? What's it for? How do I work where the tunnel's going to end? (***Problem Scoping-Information Gathering***)

Dad: So, the tunnel, how do you think you would work the tunnel? (**Soliciting Information-Prompting**)

Tom: So, I put the orange [the start track] first as the .. (***Solution Development - Idea Generation*** & ***Problem Scoping- Information Gathering***)

Dad: Where do you think this would fit on the base? (**Soliciting Information-Prompting**)

Tom: Hm. Wait, wait, wait. I got this. One second. Like this? [He takes a tunnel and put it on top of the start track.] (***Problem Scoping- Information Gathering***)

Dad: Where's the base?

Tom: Right here. Oh, like this? [moved the tunnel to another place.]

Dad: Yeah. That's the base, right? So where do you think that would fit? Where do you think that [the tunnel] would fit, inside there? (**Soliciting Information-Prompting**)

> Tom: Right there. And then this would go right here. So that's ... So this would be the end of the tunnel. And then you go down.. (***Solution Development -Idea Generation***)
>
> Dad: Okay. So to start …[continues reading the letter] (***Providing Guidance-Explanation***)

After Dad reads the letter, he disengages from the activity by not saying anything (**<u>Disengagement</u>**), since Tom is very engaged building. Tom tries the tunnel at different places on the base, and finally he realizes where it should go. "So now I just need this right here. Yeah. All right, there you go. So there's the tunnel." (***Problem Scoping-Information Gathering & Solution Development -Idea Generatio***n) They then engage in the process of designing the solution together.

> Dad: Okay. So, it needs to start very high (**<u>Providing Guidance-Explanation</u>**) Is that very high? (**<u>Soliciting Information-Prompting</u>**)
>
> Tom: Yeah, it's very high (***Solution Development -Decision Making***)
>
> Dad: Could it be higher? (**Soliciting Information-Prompting**) Because guess what else you have to ... This is the only loop you have, right? (**<u>Soliciting Information-Prompting & Confirmation</u>**)
>
> Tom: Mm-hmm (affirmative).
>
> Dad: Let's see how many loops do we have? One loop. [hands the loop to Tom.] (**<u>Soliciting Information-Prompting</u>**)
>
> Tom: I thought this was a loop. [Pointing to the orange slide that has a loop on it.]
>
> Dad: [pointing to the guide] No. That's your loop, see? Loop. And what does our boss ... What does the boss want? He wants to have a loop (**<u>Providing Guidance-Explanation</u>**]
>
> Tom: I don't know where to put it, though! It's impossible to put anywhere. I don't have enough room! (***Solution Development - Idea Generation* & *Decision Making***)
>
> Dad: You're going to have to re-engineer your design, like an engineer (**<u>Providing Guidance-Explanation</u>** & **<u>Affirmation-Encouragement</u>**).
>
> Tom: Oh. All right, all right. Let's do this, I guess.
>
> Dad: Be patient about it/
>
> Researcher: And don't worry. We will send the picture of your design to him.

> Dad: Yeah. We have a picture of what you designed already. We know that you did a good job on it (**<u>Affirmation-Encouragement</u>**). [The assurance of having one design helps him refocus on the activity)
>
> Tom: All right, well that ... Well, it's called the dragon's tail. Don't forget.
>
> Researcher: Yeah. Dragon's tail.

Dad re-engages Tom by reading the letter. "Hey. It says, 'Imagine the fastest, loopiest, and steeper rollercoaster you can, and try to build it.' So, the kids want it to be fast. The steeper it is, the faster it's going to be. So, we want to make it big." (**<u>Providing Guidance-Explanation</u>**)

> Tom: This is big, see? (Solution Development -Decision Making)
>
> Dad: Yeah. Let's do the rest (<u>Providing Guidance-Direction</u>).

Since Tom had already worked for 50 minutes, Tom asks if he can come the next and work on it. Dad tells him this is a one-day activity that they have to do it all then. Thus, Dad suggests that he can help him to quickly wrap up the activity (**<u>Assisting-Verbally</u>**) Tom agrees as he learns that he cannot work on this tomorrow. He asks the researcher if they can send a picture of his design to the CEO and if they like it. When Researcher reassures him that she has a picture of his design and will send it to the CEO and she will like it, he calms down and starts adding pieces to his design.

Dad gets hands-on to attach the loop to the design, but Tom does not let him. He tries to attach the loop to his design himself. He puts the loop next to the rollercoaster. Based on the size of the loop, he removes the few last parts that are the same size as the loop (***Solution Development -Decision Making, Idea Generation & Prototyping***). He tries to attach the loop to the part but it does not fit there as the loop is longer. He says aloud, "Yeah, that's not going to fit. That's the only thing." (***Optimization-Troubleshooting***)

Dad gets the loop from him to fix it (**<u>Assisting-Building</u>**), but he gets it back to do it himself. Tom tries to attach the loop to his design again, however, he gets so frustrated that he cannot it. While trying, he constantly says, "I don't know how to do this." & "This is hard." Dad encourages him by reminding him that he is an engineer (**<u>Affirmation-Encouragement</u>**) Dad then suggests that he changes the beginning parts (**<u>Providing Guidance-Suggestion</u>**) He disagrees strongly, "I can't ruin my rollercoaster just for this!" (***Solution Development -Decision Making***) Dad then suggests, "What if we started it up at the very top [pointing to the start track]? Then we fit the loop at beginning here and then we change the height of tower only." (**Providing Guidance-Suggestion**) He agrees by saying, "Let me see this, let me see this, wait. Dad. What is ... Does this fit like that?" (***Solution Development -Decision Making***) However, the loop does not get attached to the second tower. He gets upset, "But I will not give it up. And a few more of these. [He collects some black posts and put them on top of each other. He connects the two towers with a very small slide.] (***Solution Development -Modeling/Prototyping & Idea Generation***) He tries hard to attach the loop to the tower. He gets frustrated. He pushes the loop hard to the tower, until the loop breaks. That attempts to help him.

> Tom: This is a problem. This... It won't fit. (***Solution Development -Troubleshooting***)
>
> Dad: The only problem is, is that-
>
> Tom: It's the problem. The problem is that it won't fit.
>
> Dad: Okay. Even if it fit, look where the bottom is. So .. (**Providing Guidance-Suggestion**)
>
> Tom: I got this, I got the idea. See, look, check this out, Dad. Now it can totally fit (***Solution Development -Troubleshooting & Improving)*** [He attempts to attach the loop by adding some pieces to the start tower. However, the loop breaks apart because he pushed it very hard.] And dang it. Now it's broken. Ah!
>
> Dad: What is broken?
>
> Tom: The thing, the loop. It's broken!
>
> Dad: Oh. Yeah, it was broken before.
>
> Tom: Yeah, well how do I do it now?

Dad: We'll fix it, okay? [looking at the loop and putting the pieces together] (**Assisting-Verbally & Building**)

Tom: Yeah. There's no way you can fix it.

Dad: It's fixed.

Tom: All right. Finally. This part still won't cooperate! Great. I give up.

Tom gets very upset and leaves the room. Researcher and Dad have a conversation and decide that Dad fixes the rollercoaster and have him test it. Dad fixes the rollercoaster by attaching a loop and asks him to come in after few minutes (**Assisting-Building**).

Tom: Well, I came back here because my mom forced me to.

Dad: All right. Here, Tom, try it out! (**Providing Guidance-Direction**)

Tom: Ah, let me see this. Thank you. [He then tests his rollercoaster (***Optimization-Testing***)]

Tom: It's this. Wait, stop. Wait, wait, wait. We got to fix this, though. [points to the end track and last tower, suggesting that that's the problem (***Optimization-Troubleshooting***)]

Dad: All right, fix that, and then make a tunnel, too (**Providing Guidance-Direction**)

Tom: I know what I'm doing (***Optimization-Improving***)

He improves the solution by adding few things. He tested the rollercoaster (***Optimization-Testing***). They see that the rollercoaster does not work. He gets upset and says, "This still won't work! Nothing ever will." He then attempts to change the parts at the beginning. Dad engages in a conversation to help him find the solution.

Dad: No, I wouldn't change anything right there (**Providing Guidance-Suggestion**) Where's the problem at? (**Soliciting Information-Prompting**)

Tom: I get this. I mean, I know what I'm doing. Ah! That is why I gave up! How retarded this is. It stops, until it's complete (***Optimization-Troubleshooting***) Ah! That's always when it stops!

Dad: Where? (<u>**Soliciting Information-Prompting**</u>)

Tom: Right there! I don't get it! (***Optimization-Troubleshooting***)

Dad: Stops right there? Let me see [Dad tests that part.]

Tom: Ah! Now we just ruined it. I ruin everything! Well, there's no way I can do this.

He leaves the room again. Researcher and the family decide that they have to stop now.

Note: He received his compensation while Researcher explained to him that engineers always fail until they succeed. She acknowledged the good work he had done and was doing engineering. Tom felt very proud of himself as he told his dad that he knew he is going to be an engineer.

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VITA

Hoda Ehsan
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School of Engineering Education, Purdue University
516 Northwestern Avenue, WANG 3500, West Lafayette, IN 47906

EDUCATION

Purdue University, West Lafayette, IN June 2020

Degree: Ph.D. Engineering Education

Advisor: Dr. Monica Cardella

Fifth year PhD student with interests in supporting and promoting engineering design and computational thinking in ALL individuals, including those with special needs. Also interested in linking in-school and out-of-school learning settings and designing learning resources to support engineering opportunities in both settings.

City College of New Year, New York, NY February 2015

Degree: Childhood Education

Advisor: Dr. David Crismond

Research Project: "Learning Science through Engineering Design Projects: Impacts on Different Learning Styles"

Shahid Bahonar University, Kerman, Iran August 2010

Degree: Mechanical Engineering

Advisor: Dr. Reza Baradarn

Thesis: *"Simulation and analyzing Buckling on Carbon Nanotubes Research Area: Molecular Dynamics"*

RESEARCH EXPERIENCE

Bilsland Doctoral Fellow

Fall 2019-Summer 2020

- Explored engineering design thinking of elementary-aged children with mild autism
- Explored effective parental strategies to engage their children with mild autism in engineering design practices
- Explored effective characteristics of engineering activities/toys to provide engineering learning opportunities for children with mild autism

Graduate Research Assistant, Purdue University, West Lafayette, IN

STEM+C: Integrated STEM and Computing Learning in Formal and Informal Settings for Kindergarten to Grade 2 ***(NSF Award # 1543175; Amount awarded: $2,044,930.00)***

Spring 2016-Summer 2019

Supervisor: Dr. Monica Cardella

- Led research on the informal settings portion of the project and mentored three graduate students & one undergraduate
- Contributed to synthesis of INSPIRE Computational Thinking Definitions

- Contributed to the development of *Coding for the Critters* exhibit for Imagination Station, Lafayette's family science center
- Organized a field trip and designed multiple research-based STEM+C activities for the field trip
- Contributed to INSPIRE Teacher Professional Development
- Contributed to the development of the NSF Showcase video
- Organized and executed the 2019 INSPIRE Open House and Colloquium
- Analyzed existing data that was collected as part of the "GRADIENT"(Gender Research on Adult-child Discussions in Informal ENgineering environmentTs) project (*NSF Award # 113625)* to investigate and describe children's troubleshooting practices

Autism and STEM
Summer 2016- Summer 2018
Supervisor: Dr. Mandy Rispoli

- Conducted a systematic literature review to summarize and synthesize research-based interventions and instructions that support STEM learning of individuals with autism
- Was trained to conduct Single Case Research Designs methods for clinical and applied settings often used for autism studies
    - Behavioral assessment
    - ABAB designs
    - Multiple-baseline designs
    - Multiple-treatment designs

Strengthening the STEM Pipeline for Elementary School African Americans, Hispanics, and Girls by Scaling Up Summer Engineering Experiences ***(NSF Award # 1614739; Amount awarded: $272,804.00)*** Summer 2018
Supervisor: Dr. Monica Cardella

- Contributed to the analysis of data collected in multiple sites to examine 3-5th grade students' understanding of engineering design processes.

Engineering Education Explorer's Fellow
Fall 2015
Supervisor: Dr. Stephen Hoffmann

- Conducted research on the experiences of underrepresented students in the First-Year-Engineering Programs.
- Developed a survey to quantify student experiences in teams based on group dynamics frameworks.

GRANT EXPERIENCE

Early Engineering: Parent Child Conversations During Design Activities
Submitted to the National Science Foundation Advancing Informal STEM Learning (AISL) program 2018, $804,165. Unfunded.
PI: Dr. Monica Cardella
Leadership Team: Dr. Gina Navoa Svarovsky, Dr. Scott Pattison, Hoda Ehsan

TEACHING EXPERINCE

Graduate Level

CO-Instructor, School of Engineering Education, Purdue University

- *Inquiry and Research Methodology*. Graduate level, Fall 2017
  - Participated in syllabus design and aligned content, pedagogy and assessment of class material
  - Prepared and facilitated classroom activities and in-class discussion—Half of every class
  - Taught one entire session
  - Held office hours: assist students with class assignments and provided detailed feedback on their systematized literature reviews
  - Assessed half of students' assignments throughout the semester

Undergraduate level

Co-Instructor, Interdisciplinary Engineering Studies, School of Engineering Education, Purdue University

- *Design Methodologies for Diverse Stakeholders*. Undergraduate level, Fall 2019,
  - Taught multiple sessions
  - Provided feedback on team projects
  - Provided assessment of team projects

Guest Lecturer, EPICS Professional Development**,** Purdue University

- Designed and taught a skill session on designing learning resources and environments. Spring 2019
- Project reviewer and consultant. Fall 2018-Fall 2019

Guest Lecturer, Interdisciplinary Engineering Studies, School of Engineering Education, Purdue University

- *Design Methodologies for Diverse Stakeholders*. Undergraduate level, Fall 2018,
  - Taught one session on design
  - Modified class material

K-12 Education Level

Instructor, Gifted Education Research and Resource Institute, Purdue University

- STEAM lab™ : 3-weeks STEAM integrated class with the focus on engineering design and systems thinking. Middle school & High school, Summer 2016
  - Modified the existing course
  - Taught two courses (total of 6 weeks)
  - Conducted an engineering panel consisting
  - Evaluated students' design

Elementary School Teacher, Central Park East II, New York City, NY

- Student Teacher, Third Garde, Fall 2014

  - Taught 120 hours
  - Developed, implemented and assessed multiple STEM integrated curriculum
- Volunteer Teacher, Second Grade, Fall 2013, Spring 2014
  - Assist students with special needs
  - Taught literacy and science lessons

Teacher Trainings

Instructor, INSPIRE, School of Engineering Education, Purdue University, West Lafayette, IN

- K-2 STEM-C Teacher Professional Development, Summer 2016, 2017, 2018
  - Taught lessons of PictureSTEM 2nd grade curriculum
  - Developed and facilitated computational thinking hands-on sessions
- Cumberland Elementary School Professional Development, Spring 2018
  - Taught engineering lessons of PictureSTEM Kindergarten curriculum

WORK EXPERIENCE

Pioneers of Computer in Iran schools, Kerman, Iran

- Educational Executive Director, 2010-2012
- Part Time English Teacher , 2011-2012
- Founder and Editor of PCI Seasonal Journal (Four Editions), 2010-2012

Arvand Wheel Company (AWMC), Rafsanjan, Iran

- Junior Product Designer, 2009-2010
- Internship, Design Mechanical Engineer, 2008-2009

AWARDS AND HONORS

Scholarly Awards/Honors

Outstanding Research Award, College of Engineering, Purdue University, 2020
Best Diversity Paper Award, ASEE Pre-College Engineering Education Division, 2019
Best Diversity Paper Award Finalist, selected by ASEE Committee on Inclusion and Diversity, 2019
Bilsland Dissertation Fellowship, Purdue University, 2019-2020
Outstanding Graduate Student Scholarship. City College of New York ($500), 2014

Service Awards/Grants

Purdue Graduate Student Government Travel Grant, Purdue University ($500), 2020
Service Learning Grant, Purdue University ($1450), 2019
Service Learning Grant, Purdue University. ($1500), 2018
College of Engineering Conference Travel Fund, Purdue University ($500), 2018
Service Learning Grant, Purdue University ($750), 2017
Superior Student Association Leader Award. Shahid Bahonar University, 2009

PUBLICATIONS- PEER-REVIEWED CHAPTERS

1. Ehsan, H., & Cardella, M. (submitted) First Graders' Design Processes During a Field Trip Activity in a Science Center: Expanding Problem and Solution Spaces.

PUBLICATIONS- PEER-REVIEWED JOURNAL

1. Ohland, C., **Ehsan, H**., & Cardella, M. (in review). Child Interactions during a Computational Thinking Activity in an Informal Learning Environment. *International Journal of Computer Child Interactions (IJCCI)*
2. Rehmat, A., **Ehsan, H**., & Cardella, M. (in review). Computational Thinking in Grades K-2: Exploring Teachers' and Students' Perceptions of Computational Thinking. *Journal of Computer Science Education*
3. **Ehsan, H.**, & Cardella, M. (2020). Capturing Children with Autism's Engagement in Engineering Practices: A focus on Problem Scoping. *Journal of Pre-College Engineering Education Research (JPEER).*
4. **Ehsan, H.**, Rehmat, A., & Cardella, M. (2020) Computational Thinking embedded in Engineering Design: Capturing Computational Thinking of Children in an Informal Engineering Design Activity. *International Journal of Design and Technology Education.* doi.org/10.1007/s10798-020-09562-5
5. Rehmat, A., **Ehsan, H.**, & Cardella, M. (2020). Instructional Strategies to Promote Computational Thinking for Young Learners. *Journal of Digital Learning in Teaching Education, 36*(1), 46-62.
6. **Ehsan, H.**, Rehmat, A., & Cardella, M. (2019). Computer Science Unplugged: Design a Puppy Playground Using Computational Thinking. *NSTA Science and Children. 57*(3), 32-38. (Paper Featured in the Special Issue: Early Childhood Engineering Experiences)
7. **Ehsan, H.**, Gajdzik, E, & Cardella, M. (2019). Design an Amusement Park: Engineering for Children with Autism. *NSTA Journal of Connected Science Learning.* (May 2019 Special Issue: Serving Youth with Special Needs)
8. **Ehsan, H.**, Rispoli, M., Lory, C., & Gregori, E. (2018). A Systematic Review of STEM Instruction with Students with Autism Spectrum Disorders. *Review Journal of Autism and Developmental Disorders, 5*(4), 328-348.
9. EbrahimiNejad, H., **Ehsan, H**., & Mirkiani, S. (2018). Engineering Education Reform: Thinking Globally, Acting Locally. *Iranian Journal of Social Sciences and Humanities Research. 6*(4), 28-32.

PUBLICATIONS- PEER-REVIEWED JOURNAL (in preparation)

1. **Ehsan, H**., Rehmat, A., Osman, H., Yeter, I., Ohland, C., & Cardella, M. Examining a Homeschooled Child' Computational Thinking and the Role of Parents. To be submitted to *Journal of Pre-College Engineering Education Research (JPEER)*
2. **Ehsan, H**., Ohland, C., Osman, H., Dandridge, T., & Cardella, M. Computational Thinking in Children: Examining Unplugged and Plugged Experiences. To be submitted to *International Journal of Child-Computer Interaction (IJCCI)*
3. **Ehsan, H**., Quintana, J., Purzer, S., & Cardella, M. A Systematic Literature Review of Children and Engineering Engagement. To be Submitted to Review of Educational Research

PEER-REVIEWED CONFERENCE PUBLICATIONS & PRESENTATIONS

1. Fagundes, B., **Ehsan, H**., Moore, T. J., Cardella, M. E., & Tank, K. M.. (2020). First-Graders' Computational Thinking in Informal Learning Settings (Work-in-Progress). *Proceedings of the 2020 American Society for Engineering Education Annual Conference & Exposition. Virtual Confenerence.*
2. **Ehsan, H**. & Cardella, M. (2020). Examining Computational Thinking Engagement of Children with Mild Autism: A Qualitative Approach. *Purdue Autism Research Center 2020 Conference*. (Conference canceled)
3. **Ehsan, H**., Cardella, M., & Sanger, M. T. (2020). First Graders' Engineering Design Processes During a Field Trip Activity: Expanding Problem and Solution Spaces. The National Association of Research on Science Teaching (*NARST) Annual Conference. Portland, OR.* (Conference canceled)
4. **Ehsan, H**., Cardella, M., & Hynes, M. M. (2020). Exploring Computational Thinking Engagement: An Exploratory Study on Children with Mild Autism. The *American Educational Research Association (AERA) Annual Meeting.* San Francisco, CA. (Conference canceled)
5. Rehmat, A., **Ehsan, H.,** & Cardella, M. (2019). Instructional strategies to engage children in computational thinking. *Big10+ Maker and CS Education Research Conference*. Indiana University, Bloomington, IN.
6. **Ehsan, H.**, & Cardella, M. (2019). Advancing Homeschooling Education through Museums: Parents Promote Computational Thinking and Engineering in Children. *Associations of Science and Technology Centers (ASTC),* Toronto, CAN.
7. **Ehsan, H.,** & Cardella, M. (2019). Advancing the Field: Designing and Implementing Computational Thinking Activities for Five-to-Seven Year Old Children. *Associations of Science and Technology Centers (ASTC),* Toronto, CAN.
8. **Ehsan, H.**, Cardella, M., & Cardella, P. (2019). Unplugged and Plugged Computational Thinking for Children: Research and Practice. *Visitor Studies Association (VSA) Annual Conference,* Detroit, MI.
9. **Ehsan, H**., Sanchez-Pena, M., Al-Yaghub, H., EbrahimiNejad, H. (2019). Capturing the Experiences of ESL Graduate Students in Engineering Education. *Proceedings of the 2019 American Society for Engineering Education Annual Conference & Exposition,* Tampa, FL.
10. **Ehsan, H.**, & Cardella, M. (2019). Investigating Children with Autism's Engagement in Engineering Practices: Problem Scoping (Fundamental). *Proceedings of the 2019 American Society for Engineering Education Annual Conference & Exposition,* Tampa, FL.
11. **Ehsan, H**., Rehmat, A., Osman, H., Yeter, I., Ohland, C., & Cardella, M. (2019). Examining the Role of Parents in Promoting Computational Thinking in Children: A Case Study on one Homeschool Family (Fundamental). *Proceedings of the 2019 American Society for Engineering Education Annual Conference & Exposition,* Tampa, FL.
12. Ohland, C., **Ehsan, H**., & Cardella, M. (2019). Parental Influence on Children's Computational Thinking in an Informal Setting. *Proceedings of the 2019 American Society for Engineering Education Annual Conference & Exposition,* Tampa, FL.
13. Yeter, I., Rynearson, A., **Ehsan, H**., Rehmat, A., Cardella, M., Meneske, M. (2019). Design and Implementation of Data Collection in a Large-Scale, Multi-Year Pre-College Engineering Study: A Retrospective (Other). *Proceedings of the 2019 American Society for Engineering Education Annual Conference & Exposition,* Tampa, FL.

14. Hynes, M. M., & Moore, T. J., & Cardella, M. E., & Tank, K. M., & Purzer, S., & Menekse, M., Brophy, S., Yeter, I. & **Ehsan, H**. (2019). Inspiring Young Children to Engage in Computational Thinking In and Out of School (Research to Practice). *Proceedings of the 2019 American Society for Engineering Education Annual Conference& Exposition*, Tampa, FL.
15. Rehamt, A., **Ehsan, H**., Yeter, I., Moore, T., & Cardella, M. (2019). Exploring Elementary Teachers and Students Perceptions of Computational Thinking. Paper presented at the National Association of Reserch on Science Teaching (*NARST) Annual Conference.* Baltimore, MD.
16. Dandridge, T., **Ehsan, H**., Ohland, C., Lowe, T. Yeter, I., Gajdzik, E., Brophy, S., Cardella, M. (2019). Integrated STEM+C for children in formal and informal settings as a precursor to K-2 computer science education practices. Paper presented at *ACM SIGCSE Technical Symposium.* Minneapolis, MN.
17. **Ehsan, H**., Ohland, C., Dandridge, T., & Cardella, M. (2018). Computing for the Critters: Exploring Computational Thinking of Children in an Informal Learning Setting. *Proceedings of the 2018 IEEE Frontiers in Education Conference,* San José, CA.
18. **Ehsan, H**., Dandridge, T., & Cardella. M. (2018) Parental Influences in Computational Thinking of Children during an Engineering Design Task. Paper presented at *Visitor Studies Associations (VSA) Annual Conference.* Chicago, IL.
19. **Ehsan, H**., Dandridge, T., Yeter, I., & Cardella, M. (2018). K-2 Students' Computational Thinking Engagement in Formal and Informal Learning Settings: A Case Study (Fundamental). *Proceedings of the 2018 American Society for Engineering Education Annual Conference & Exposition,* Salt Lake City, UT.
20. **Ehsan, H**., Leeker, J., & Cardella, M. (2018). Examining Children's Engineering Practices During an Engineering Activity in a Designed Learning Setting: A Focus on Troubleshooting (Fundamental), *Proceedings of the 2018 American Society for Engineering Education Annual Conference & Exposition,* Salt Lake City , UT.
21. **Ehsan, H**., Cardella, M., & Svarovsky, G. (2018). Engineering and Computational Thinking among Families Engaging with an Exhibit. Paper presented at *American Educational Research Association (AERA) Annual Conference,* New York City. NY.
22. EbrahimiNejad, H., **Ehsan, H**., Mirkiani, S. (2017). Engineering Education Reform: Thinking Globally, Acting Locally. Paper presented at *Iranian Society of Engineering Education*. Tehran, IR.
23. **Ehsan, H**., Beebe, C., & Cardella, M. (2017). Promoting Computational Thinking in Children Using Apps. *Proceedings of the 2017 American Society for Engineering Education Annual Conference & Exposition*, Columbus, Oh.
24. **Ehsan, H**., & Cardella, M. (2017). Capturing the Computational Thinking of Families with Young Children in Out-of-School Environments. *Proceedings of the 2017 American Society for Engineering Education Annual Conference & Exposition*, Columbus, OH.
25. Dasgupta, A., Rynearson, A., Purzer, S., **Ehsan, H**., & Cardella, M. (2017). Computational Thinking in Kindergarten: Evidence from Student Artifacts (Fundamental). *Proceedings of the 2017 American Society for Engineering Education Annual Conference & Exposition*, Columbus, OH.
26. **Ehsan, H**., Beebe, C., & Cardella, M. (2016) *Promoting Computational Thinking Using Apps*. Paper presented at *P-12 Engineering & Design Education Research Summit,* Chicago, IL.

27. **Ehsan, H**., Xinrui, X., & Cardella, M. (2016) "Representation of Underrepresented Characters in Engineering Children Books". *Proceedings of the 2016 IEEE Frontiers in Education Conference*, Erie, PA.
28. **Ehsan, H**. (2016). A Systematized Review of Engineering Design in Science Classrooms and its Impacts on Student Learning. Paper presented at *American Society of Engineering Education 2016 Illinois-Indiana Section Conference*, Moline, IL.
29. Ibrahimi-Nezhad, S., Shokuhfar, A., Ebrahiminejad, H., **Ehsan, H**, (2010) "Mechanical Behavior of Shape Memory Nanowires". *5th International Conference of Diffusion in Solids and Liquids*. Rome, Italy.

INVITED TALKS & SEMINARS

1. "Design-Based Research: An Approach to Include Neurodiverse Individuals in Engineering Education." ENE seminar, School of Engineering Education, Purdue University, December 2019.
2. "Children with Autism Engagement in Engineering Design Practices", Lassonde School of Engineering, York University, September 2019.
3. "Capturing Engineering Design Thinking of Children with Autism: A Focus on Design Evaluation", Department of Engineering Education, Virginia Tech University, December 2018.
4. **"**Designing Effective Engineering Exhibits." ENE seminar, School of Engineering Education, Purdue University, August 2016.

OTHER PRESENTATIONS: PANELS, SYMPOSIUMS, RECEPTIONS

1. **Ehsan, H.** (2019, June). *STEM+C in Informal Learning Environments for Young Children*. Chinese Society for Engineering Education's visit at Purdue University.
2. **Ehsan, H.** (2019, May). *Engineering Design and Autism: Let's Engage in Problem Scoping*. Presented at Purdue Autism Research Center Symposium. Purdue University
3. **Ehsan, H**. (2019, April*). Examining the Role of Parents in Promoting Computational Thinking in Children*. INSPIRE Open House and Colloquium. Purdue University
4. **Ehsan, H**. (2019, April). *Plugged VS Unplugged: Capturing Computational Thinking of Children across Different Informal Learning Activities.* INSPIRE Open House and Colloquium. Purdue University
5. **Ehsan, H**. (2019, April). *Integrated STEM and Computing Learning in Informal Settings for Kindergarten to Grade 2.* INSPIRE Open House and Colloquium. Purdue University
6. Roundtable Organizer and Facilitator: *Challenges of Engineering Education ESL students* (April, 2019). School of Engineering Education. Purdue University.
7. **Ehsan, H.** (2018). *Capturing Engineering Design Thinking of Children with High Functioning Autism*. PhD Student Symposium. Frontiers in Education Conference (FIE).
8. **Ehsan, H**. & Rispoli, M. (2017, May) *Autism & STEM*. Interdisciplinary Graduate Program Reception, Purdue University.
9. Invited Panelist: *Inquiry and Research Methodology* (2016, September). School of Engineering Education, Purdue University

10. **Ehsan, H**., Beebe, C. & Xinrui, X. (2015, December) *Investigating International Students' Experiences in Engineering Teams.* ENE seminar, School of Engineering Education, Purdue University

OTHER PUBLICATIONS: RESEARCH TO PRACTICE

1. **Ehsan, H.** (2019). *Pedagogical Techniques & Tips: How to Engage Children with Mild Autism in Engineering and Computational Activities.* Engineering Gift Guide. Purdue University.
2. **Ehsan, H.**, Ohland, C., Cardella. M. (2019). Parental Influences: Roles for supporting Computational Thinking Engagement. Engineering Gift Guide. Purdue University.
3. **Ehsan, H.** (2018). *Teaching Troubleshooting: Helping Children Overcome Challenges, One Step at a Time*. Engineering Gift Guide. Purdue University.
4. **Ehsan, H.**, Cardella, M. (2019). 5 Computational Thinking Competencies that can help your Child Become a Better Problem Solver. Engineering Gift Guide. Purdue University.
5. **Ehsan, H.** (2012). "*I love science - Kindergarten Science Workbook"* (Farsi), Pioneers of Computer in Iran (PCI) Schools. Iran.
6. **Ehsan, H**. (2012). "*World of Math - Kindergarten Math Workbook*."(Farsi), Pioneers of Computer in Iran (PCI) Schools. Iran.

WORKSHOPS

1. **Ehsan, H**. (2019, September) *Planning for a Productive Semester.* Graduate Education. College of Engineering. Purdue University. West Lafayette, IN.
2. **Ehsan, H**., Rehmat, A. & Cardella. M. (2019, June) *Design a Puppy Playground: Computational Thinking for Children*. 126th ASEE Annual Conference & Exposition. Tampa, Fl.
3. **Ehsan, H**. (2019, January) *Planning for a Productive Semester.* Graduate Education. College of Engineering. Purdue University. West Lafayette, IN.
4. **Ehsan, H**., Rehmat, A. & Cardella. M. (2019, January) *Computational Thinking: Unplugged and Plugged*. Indiana STEM Education Conference (I-STEM). West Lafayette, IN.
5. **Ehsan, H.** (2015, July) *Teach in Inclusive Classrooms.* Department of Education, Kerman, Iran.
6. **Ehsan, H.** (2014a, June) *Let's Make Science and Math Yummy!.* Department of Education, Kerman, Iran.
7. **Ehsan, H.** (2014b, June) *How to Make Literacy More Fun in Classrooms!.* Department of Education, Kerman, Iran.
8. **Ehsan, H.** (2012, June) *The Power of Technology in Elementary Classrooms: Creating Online Games.* Pioneers of Computer of Iran School, Kerman, Iran.
9. **Ehsan, H.** (2012, March) *The Power of Technology in Elementary Classrooms: Using Microsoft Office.* Pioneers of Computer of Iran School, Kerman, Iran.
10. **Ehsan, H.** (2012, March) *The Power of Technology in Elementary Classrooms: Designing worksheets.* Pioneers of Computer of Iran School, Kerman, Iran.

PROFESSIONAL ENGAGMENT & SERVICE

Leadership

Imagination Station, Lafayette Science Center for Children

- Co-Chair: Education & Exhibits Committee, 2018 - present

Engineering Education Graduate Student Association, Purdue University

- Founder and Chair: Academic Mentoring Program, 2019-2020
- Executive Board: English as a Second Language Founder and Chair, 2018-2019

American Society of Engineering Education, Student Division

- Executive Board: Student Chapter Chair, 2018-2019

American Society of Engineering Education**,** 2018 IL-IN Section Conference

- Student Co-Chair
- Conference Planning Committee

American Society of Engineering Education, Student Chapter, Purdue University

- Executive Board: Instruction and Classroom Practices Chair, 2017-2018

Engineering Education Graduate Student Association, Purdue University

- Executive Board: Professional Development Chair, 2017-2018

Mechanical Engineering Student Association, Shahid Bahonar University

- Executive board, 2009-2010

ASME conference, Kerman, Iran

- Student Committee, 2010

Service & Membership

Member: Care Team, School of Engineering Education, Purdue, 2018-present
Member: Toastmasters International at Purdue, 2018-present
Member & Reviewer: American Educational Research Association- Informal Learning SIG (AERA), 2018-present
Member: Iranian Society of Engineering Education (ISEE), 2017-present
Member & Reviewer: American Society of Engineering Education (ASEE), 2015-present
Reviewer: Purdue University Engineering Projects in Community Service (EPICS), 2018-present
Reviewer: Frontiers in Education (FIE-IEEE), 2016, 2017
Reviewer: International Journal of Child-Computer Interaction (IJCCI), 2018
Reviewer: ACM Interaction Design and Children (IDC), 2018
Reviewer: Journal of Engineering Education (JEE), 2017, 2018
Reviewer: Brunei International Conference on Engineering and Technology (BICET), 2016

CERTIFICATES

State of New York Teaching Certificate (K-6th grade), 2016-2021
Museum Educator Certificate (Offered by Coursera. Org), 2014
Basic Programming of PLCs Airtech, Kerman, Iran, 2008
Advanced Programming of PLCs Airtech, Kerman, Iran, 2008
Introduction to Pneumatics PIII Festo, Kerman, Iran, 2008