NORTHWESTERN UNIVERSITY

FUSE Studios:

Bringing Interest-driven, Integrated-STEAM Learning into Schools via Makerspaces

A DISSERTATION

SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

for the degree

DOCTOR OF PHILOSOPHY

Field of Learning Sciences

By

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EVANSTON, ILLINOIS

September 2017

ABSTRACT

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Bringing Interest-driven, Integrated-STEAM Learning into Schools via Makerspaces

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Makerspaces have become explosively popular in recent years. Many believe they hold promise as contexts for integrated STEAM (science, technology, engineering, arts, and math) learning, meta-disciplinary skill learning, and promoting interest and equity in STEAM. However, we still know relatively about what is actually learned in these spaces, how interest and learning develop, and how to evaluate learning in ways that don't interfere with the informal structure of making activities. As makerspaces gain in popularity and move increasingly from informal contexts into schools, it is essential that we answer these questions.

The goal of this dissertation is to provide empirical analyses to answer these questions, by examining one set of in-school makerspaces, FUSE studios. Within this investigation, I focus on furthering our understanding of interest development and learning in makerspaces in four specific ways. First, I examine what is learned in FUSE and how it is learned, focusing on meta-disciplinary skills such as twenty-first century skills and spatial skills. Second, I propose a framework for evaluating learning endogenously in FUSE and other makerspaces. Third, I examine the relation between interest and learning in FUSE, as a choice-based, makerspace context. Finally, I examine the connections learners made between FUSE and outside interests and practices, both in and out of school. Throughout all of these analyses, I examine the role that the structure of the FUSE activity system plays in facilitating interest development and learning, both within and across contexts. I also attend to ways in which FUSE studios are similar or different from both other makerspaces and other in-school learning contexts and discuss design

implications that we can take away from understanding interest development and learning in this particular context.

To conduct this investigation, I observed 90 (41 male, 48 female) fifth and sixth grade (58 fifth, 32 sixth) students in five FUSE studios, in a large, diverse, suburban school district, over the course of the 2014-15 and 2015-16 school years. I collected data on these students both in FUSE and in related STEAM learning contexts, including ethnographic observations, video recordings, field notes, surveys, web data, interviews, and photos of artifacts. I analyzed this data using a combination of qualitative coding and interaction analysis.

From my analysis of the data, I propose four key findings. First, interest and choice in FUSE led to deeper learning by increasing engagement, helping students work through frustration to achieve goals, shaping career interests and identity, and motivating learners to find ways to pursue interests and learning across contextual boundaries. Second, I identified four types of interest pathways through FUSE and found that despite engaging in different challenges and engaging with challenges differently, students on these different interest pathways learned similar twenty-first century skills, but the ways in which that learning was demonstrated differed by pathway. Third, in contrast, spatial thinking and learning differed between FUSE challenges. I show how the different sociomaterial contexts (Orkilowski, 2007) and task constraints of the different FUSE challenges facilitated different types of spatial thinking, spatial learning, and related STEAM problem-solving and learning. Finally, fourth, by comparing and contrasting students' participation in FUSE with their participation in other STEAM learning contexts, I identify design components of FUSE that make it open to the import and export of interests and practices, in ways that other STEAM learning contexts are not and more general features of activity systems which help or hinder the movement of interests and practices across contextual boundaries.

These findings further our understanding of both what and how learning occurs in makerspaces and provide insight into both strengths and best practices but also potential pitfalls in bringing makerspaces or other integrated STEAM learning activities and environments into schools. They also deepen our understanding of learning more generally, particularly in regards to the relation between interest and learning, the learning of meta-disciplinary skills, such as twenty-first century skills and spatial skills, and factors contributing to cross-context learning.

Acknowledgements

I would like to thank the National Science Foundation (NSF) grants DRL-1348800 and DRL-1433724, for their financial support of this research. However, any opinions, findings, conclusions, and/or recommendations are my own and do not reflect the views of NSF.

I would also like to acknowledge my dissertation committee, David Uttal, Reed Stevens, and Kemi Jona for their guidance, insight, and support throughout this process. I thank the FUSE research team, including Lauren Penney, Jaakko Hilppö, Dionne Champion, Ruben Echevarria, Peter Meyerhoff, Sean Walsh, and David Bar-el for their help collecting and analyzing data and for their insights and feedback on my work. I also thank the teachers and students who shared their FUSE experiences with me and the FUSE design team for all their hard work, designing, creating, and maintaining the content for this program. I would like to thank the graduate students and faculty from the Learning Sciences program at Northwestern University for providing a vibrant academic community in which to cultivate big ideas. In particular, I thank the members of my Ph.D. cohort – Stina Krist, Laurel Schrementi, and Arthur Hjorth – the members of Peer Re:View, and my Ph.D. student mentor, Danielle Keifert, for their thoughtful feedback, guidance, and support. I would also like to thank the members of David Uttal's lab, both from psychology and from the learning sciences, for providing me with valuable feedback and pushback on my work, especially Erin Jant, Kinnari Atit, and Emily Hollenbeck.

I owe special thanks to my husband, Devin Ramey, for being so supportive of me through this process, and my unborn daughter, Charlotte Ramey, for motivating me to finish this dissertation in a timely fashion. Finally, I thank my parents, Keith and Carol Striggow, for instilling in me a love of learning, the drive to help people, and the passion and confidence to pursue my dreams. Thank you. I couldn't have done it without you.

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Chapter 1. Introduction

Two of the most pressing questions in education today are how to equitably teach and engage learners from diverse backgrounds and how to prepare learners for success in a rapidly changing labor economy. These issues are particularly salient in STEM (science, technology, engineering, and math) disciplines. STEM jobs make up an increasing proportion of the labor market (U.S. Department of Commerce, 2011), but our students seem to be consistently lagging behind in STEM skills and preparation (e.g., Gonzales et al., 2008; NAE & NRC, 2009; U.S. Department of Commerce, 2011). For example, many of our students are not adequately prepared for careers in integrative, creative disciplines like engineering (Augustine, 2007; Duderstadt, 2008; NAE & NRC, 2009). On average, citizens neither deeply understand complex scientific problems like climate change (Augustine, 2007) nor have the skills to engineer solutions to those problems (Augustine, 2007; Duderstadt, 2008; NAE & NRC, 2009). Students profess anxiety or disinterest toward math (Ashcraft, 2002; Betz, 1978; Meece, Wigfield, & Eccles, 1990), and either never enter or drop out of the pipeline leading toward STEM (science, technology, engineering and math) careers (Huang, Taddeuse, Walter, & Samuel, 2000; National Science Board, 2007).

Women and minorities, in particular, are less likely to end up in STEM fields, either because of lack of exposure, lack of interest, or lack of appropriate preparation or skills (e.g., Chang, 2002; Duderstadt, 2008; Gonzalez et al., 2008; Griffith, 2010; Huang, et al., 2000; NAE & NRC, 2009; NAE & NRC, 2014; National Science Board, 2007; Price, 2011). This is unfair to learners, because some children who might excel at and enjoy careers in STEM never get the exposure or tools to do so. It is also problematic for society, because we fail to benefit from the diverse perspectives and innovations these individuals from underrepresented groups might bring to STEM fields (e.g., Chubin & Malcolm, 2008; Margolis & Fisher, 2002).

In large part, our failure to prepare students equitably and adequately for success in STEM is the result of design flaws in our education system. Traditional learning in schools is siloed, teacher driven, and disconnected from the contexts in which knowledge will actually be used (e.g., Dewey, 1897; Becker, 1972). In math class, learners are required to solve textbook problems on geometry; in science, they memorize facts about renewable energy, and in art class, they draw pictures of their houses. It is rare for a teacher to pose a design problem, like "How could renewable energy be used to power your home?" and ask learners to integrate knowledge from all three disciplines to research, design, and model an integrative solution. It is even rarer for teachers to allow learners to explore problems of interest to them, and to help them design integrative solutions to those problems. This has two potential negative consequences. First, it may make it harder for students to understand why they are learning the STEM concepts they are learning or how to apply them to solve real-world problems they care about. Second, it may deter them from careers in STEM disciplines and potentially from effectively engaging in STEM thinking and problem-solving in everyday life.

Fortunately, in recent years, researchers and policymakers have begun to imagine a new future for schools, one that draws on research regarding learning practices in out-of-school contexts (e.g., Brown, Collins, & Duguid, 1989; Cole, 2009; Lave & Wenger, 1991; Stevens, Wineburg, Herrenkohl, & Bell, 2005; Stevens, Satwicz, & McCarthy, 2008). This form of education breaks down disciplinary barriers and engages learners in interdisciplinary problem-solving (e.g., NAE & NRC, 2014; Stevens et al., 2005). It is learner-driven, collaborative, and project-based, rather than teacher-driven, individual, and focused on texts or lectures as the objects of learning. In current school contexts, a version of this approach has manifested in the Next Generation Sciences Standards, which emphasize disciplinary and meta-disciplinary practices, rather than rote memorization of facts (NRC, 2012a). It is also reflected in the push toward integrating engineering and integrated-STEM learning activities into K-12 classrooms (e.g., NAE & NRC, 2009; NAE & NRC, 2014). However, it still exists in its purest form in out-of-school contexts like makerspaces and tinkering studios, found in libraries, museums, and after-school programs.

Many argue that making and tinkering activities, particularly those taking place in out-of-school contexts, such as makerspaces and tinkering studios, may provide solutions to the problem of equitably and adequately preparing learners to be successful in STEM fields and in STEM reasoning in their everyday lives (Vossoughi & Bevan, 2014). This claim is based on the fact that out-of-school spaces are less constrained by standards and standardized tests and thus allow for more open-ended, interest-driven inquiry and design (Resnick & Rosenbaum, 2013; Vossoughi & Bevan, 2014). Consequently, the argument is that these activities allow for the active construction of personally meaningful ideas and artifacts (e.g., Brahms, 2014; Dewey, 1897; Martin, 2014; Martinez & Stager, 2013; Papert, 1980; Resnick et al., 2009; Sheridan et al., 2014). In other words, they have the potential to be engaging and to help learners understand both why they're learning what they're learning and how they can apply it to problems they care about. To the extent that they allow learners to bring in outside interests or *funds of knowledge* (e.g., Hogg, 2011; Moll, Amanti, Neff, & Gonzales, 1992; Vélez-Ibáñez & Greenberg, 1992), they also have the potential promote equitable learning (Vossoughi & Bevan, 2014). Making and tinkering activities also tend to be more truly integrative, bringing together not just STEM disciplines but, in many cases, also the arts, creativity, and design (turning STEM in STEAM; e.g., Land, 2013; Maeda, 2013; Peppler, 2013). As a result, they have the potential to foster meta-disciplinary skills such as creativity, collaboration, critical thinking, and adaptive problem-solving, all critical for the twenty-first century labor force (e.g., Hilton, 2010). Finally, because of their interdisciplinary and hands-on nature, making and tinkering activities have the potential to foster alternative approaches to thinking and problem-solving, such as spatial thinking, which have been shown to predict STEM success (e.g., Hsi, Linn, & Bell, 1997; Humphreys, Lubinski, & Yao, 1993; Lubinski, 2010; Sorby, Casey, Veurink, & Dulaney, 2013; Shea et al., 2001; Wai et al., 2009), but which have traditionally been marginalized in K-12 schools (e.g., NRC, 2006; Schultz, Huebner, Main & Porhownik, 2003; Newcombe, Uttal, & Sauter, 2013).

However, despite the promise of these activities and spaces, relatively little empirical research has been done showing that they deliver on their promised benefits. Additionally, because there is such wide variation between different making and tinkering activities and spaces, it is difficult to draw conclusions about specific features of these activities and spaces that may or may not lead to specific outcomes of interest. This problem is further complicated by recent pushes to move making and tinkering activities and spaces into schools (Martinez & Stager, 2013), as doing so adds pressure to structure and assess learning in ways that may disrupt the very aspects of these activities that are most important for facilitating student interest and learning.

Research Objectives

The goal of this dissertation is to fill in these gaps in prior research on interest development and learning in making activities, by examining one set of in-school makerspaces, FUSE studios (www.fusestudio.net). In framing this investigation, it is important to clarify the ways in which FUSE both does and does not resemble other makerspaces, as such distinctions will move the field closer to understanding not just what types of interests and learning makerspaces cultivate, in general, but the affordances of specific features of making activity systems for cultivating student interest and learning. First, although FUSE started as an after school program, and was designed based on prior research on informal learning practices and environments (e.g., Cole, 2009; Ito, et al., 2007; Stevens et al., 2005; Stevens, et al., 2008), the majority of FUSE studios are now found in schools, and students participate in FUSE as either a required or elective course, as part of the regular school day. Second, choice is fundamental to FUSE, but is constrained somewhat, in order to spark student interests and provide onramps into different types of making activities. In other words, students in FUSE choose STEAM challenges from a gallery hosted on the FUSE website, and these challenges level up like video games, increasing in difficulty (e.g., Salen & Zimmerman, 2005). Students also choose who to work with, whether to work alone or with a group, at what pace they wish to work, and when to start and leave challenges. In regards to choice, FUSE is different both from the activity in many informal makerspaces, where no structured activities, only materials are provided (e.g., Brahms, 2014; Sheridan et al., 2014) and from more structured making and tinkering activities, where everyone does the same activity — or at least uses the same tools to design individual projects — (e.g., Fields & King, 2014; Peppler, 2013; Resnick et al., 2009).

FUSE is also distinct from traditional learning in schools in a number of ways. First, is the emphasis on choice described above. Second is the fact that it integrates STEAM disciplines into one activity system. Third is the emphasis on iteration and low penalty for failure. There is formal adult assessment; students decide when they are done with challenges, and self-document level completion in order to move on to the next challenge level. Fourth is that rather than focusing on the a textbook or teachers' lectures as the object of learning, FUSE provides heterogeneous resources for students to learn with and from (e.g., other participants, facilitators, physical and digital materials, and online help resources, such as help videos). Finally, fifth is that rather than being designed based on particular standards or topics, FUSE challenges are designed (and redesigned) based on students' interests and based around tools and activities of STEAM professionals, typically in partnership with those STEAM professionals.

In examining FUSE as making activity system for STEAM learning and interest development, I focus on four important questions:

1. What is the relation between choice, interest, and learning in FUSE?
2. What is learned in FUSE and how is it learned?
3. How permeable is the membrane between FUSE and other in-school and out-of-school STEAM learning contexts? In other words, what interests and practices do students from FUSE carry across contextual boundaries into other contexts?
4. What features of the FUSE activity system facilitate learning and interest development (both within and across contexts)?

Each of the three analysis chapters in this dissertation focuses on one of the first three questions, with the fourth serving as an overarching theme across analysis chapters. The first analysis chapter (Chapter 3) focuses on the relation between choice, interest, and learning in FUSE. In this analysis, I describe four student cases, and examine how, in the choice-based activity system of FUSE, student interests both shape and are shaped by students' pathways through FUSE. I conclude that understanding and evaluating learning in a choice-based activity system like FUSE requires an understanding of student interests, and evaluating learning requires an individualized and endogenous (Hall & Stevens, 2015; Stevens, 2010) approach, rather than one-size-fits-all assessments. I propose a framework for doing this sort of qualitative evaluation, which arranges learning along a continuum from proximal to distal learning outcomes. Using this framework, I identify different approaches to or pathways students took through FUSE and the types of meta-disciplinary learning that occurred along those pathways.

The second analysis chapter (Chapter 4) examines learning in FUSE, specifically focusing spatial thinking and learning. I chose spatial thinking as a particular focus, because it: (1) has traditionally been undervalued and underemphasized in K-12 schools (e.g., NRC, 2006; Schultz, et al., 2003; Newcombe et al., 2013); (2) predicts success in STEAM disciplines (e.g., Hsi et al., 1997; Humphreys et al., 1993; Lubinski, 2010; Sorby, et al., 2013; Shea et al., 2001; Wai et al., 2009); (3) is likely to be both used and learned in hands-on making activities (e.g., Levine, Ratliff, Huttenlocher, & Cannon, 2011; Ping, Ratliff, Hickey, & Levine, 2011; Ramey & Uttal 2017); but (4) is conspicuously absent from research on learning in makerspaces or making activities. Here, my unit of analysis is specific FUSE challenges, and I conclude that the specific sociomaterial contexts and constraints of different challenges facilitated different types of spatial thinking and learning.

Finally, in the third analysis chapter (Chapter 5) I examine the permeability of the membrane between FUSE and learning in other parts of students' lives, both in-school and out-of-school, with a particular focus on ways in which the FUSE activity systems and other STEAM learning activity systems might facilitate or inhibit boundary-crossing. I chose this as a final focus of analysis both because of research demonstrating the difficulties inherent in getting students to "transfer" knowledge and practices across contexts (e.g., Carraher, 1986; Carraher, Carraher, & Schliemann, 1985; Lave, 1988), and because of research demonstrating the importance of looking across contexts in order to truly understand interest development and learning (e.g., Barron, 2006;

Bell, Tzou, Bricker, & Baines, 2013). I conclude that because the choice-based nature of FUSE allows learners to bring in and pursue outside interests and practices, this activity system also makes it easier for students to extend interests and practices out into other parts of their lives.

Theoretical Framework

In framing my investigation of thinking and learning in FUSE, I draw on research and theory from the learning sciences. This framing involves certain assumptions about the nature of thinking and learning. First among these are that knowledge is actively constructed by learners (Piaget, 1964) and that this construction occurs particularly felicitously when learners are engaged in the construction of a personally meaningful idea or physical artifact (Papert, 1980). These theoretical assumptions shape my interest in makerspaces and making activities as contexts for learning and my emphasis on interest as an important aspect of learning.

Next is that learning and knowledge are both situated (Brown, et al., 1989) in particular activities and contexts and distributed between individuals, representations, and physical artifacts in those activities and contexts (Hutchins, 1995a; 1995b). From situated perspectives on learning, I draw the notion that learning should be studied endogenously — through observations and analysis of activity in context — rather than exogenously — through standardized tests or other assessments (Hall & Stevens, 2015; Stevens, 2010). In other words, it is preferable to examine thinking and learning in the context of real-world problem-solving activities, looking at the complete picture of learning, rather than isolating individual variables or studying thinking and learning in contexts or tasks that are divorced from the contexts and tasks in which knowledge and practices are learned (Brown, et al., 1989).

From distributed perspectives on learning, I draw the notion that thinking and learning do not occur purely inside the individual mind but are distributed process involving not just the learner's own mind and body but also other people, representations, and physical objects (e.g., Hutchins, 1995a; 1995b). Thus, understanding interactions with sociomaterial context or analyzing the ways in which representations travel across representational media in a distributed cognitive system is or more important for understanding thinking and learning as an analysis of individual knowledge and experience. I also draw on distributed cognitive theory for a definition of learning, employing Hutchins' (1995a) definition of learning as the *adaptive reorganization* of ideas, tools, and people.

Finally, from cultural historical activity theory (CHAT), I draw the idea that thinking and learning are simultaneously influenced by multiple layers of cultural experience and context, and thus, part of learning is learning to engage in cultural practices and to engage with cultural tools (Vygotsky, 1978; Cole, 1996; Rogoff, 2003). In particular, I draw on CHAT perspectives to shape my understanding of how interest and learning develop within and across contexts and are shaped by those contexts (e.g., Azevedo, 2011; 2013; Barron, 2006; Bell, et al., 2013; Hollet, 2016, Ingold, 2011). From CHAT perspectives, I also draw the related notion that obtaining a complete picture of thinking and learning requires an examination of how the specific social and material conditions of the activity system influence interest development and learning (e.g. Cole, 1996; Engeström, 1987), both within the original learning context, and in any context to which we might expect transfer of skills or practices. In other words, drawing on CHAT perspectives, I argue that we must not assume transfer between problems and contexts, but rather examine individual and contextual features that facilitate transfer (e.g., Stevens & Hall, 1998; Lobato, 2012; Tuomi-Gröhn & Engeström, 2003). In examining these individual and contextual factors, I also draw on research from the CHAT tradition, which highlights specific, important aspects of activity systems that might distinguish learning contexts and help or hinder cross-context learning, such as openness (Gresalfi, Martin, Hand, & Greeno, 2009), agency (e.g., Engeström, 2006; Holland, Lachiocotte, Skinner, & Cain, 1998; Rajala et al., 2013; Wertsch, Tulviste, & Hagstrom, 1993), and differences in the object of learning (e.g., Engeström, 1994; Greeno & Engeström, 2014; Leander, 2002; Leont'ev, 1978; 1981).

In the chapters that follow, I expand upon this basic theoretical framework, explaining in greater detail how specific research from each of these traditions shaped the specific theoretical framing and analytic methods presented in each of the three analysis chapters. The reader should also note that this dissertation is written more in the style of a multiple manuscripts dissertation. So, although I have provided basic framing ideas here and provide an overview of my research methods in the next chapter, each analysis chapter includes further analysis of relevant literature, theoretical framing, and a more in-depth description of data analysis, unique to the questions asked and data analyzed in that chapter.

Chapter 2. Method

Research Context

As explained in Chapter 1, the research presented in this dissertation was conducted in one set of in-school makerspaces, FUSE studios. FUSE provides students with a set of integrated STEAM making and design challenge. These challenges are designed to be interest-driven, learner-centered, and inclusive of many different types of learners. There are over twenty challenge sequences, in which students complete challenge levels of increasing difficulty, according to their interests (for a full list of challenges, see Table 2.1). Instruction for FUSE challenges is housed on the FUSE website, at www.fusestudio.net. However, the actual challenges are done using a combination of open-source software programs, such as Sketchup or Inkscape, housed on learners' local computers, and physical tools and materials, such as 3D printers, circuit boards, or building materials, stored in individual FUSE studios.

These challenges were designed for use by fifth- to twelfth-grade students, who are encouraged to, independently or collaboratively, explore challenges of interest to them, with minimal instruction from an adult. The FUSE challenges were originally designed for use in out-of-school contexts, such as libraries, youth centers, or after-school programs. Although FUSE challenges continue to be used in a number of such contexts, they are now also used in certain fifth- and sixth-grade classrooms as a standalone class, meeting twice a week for a total of 90 minutes.

Table 2.1

List of FUSE Challenges by Category, with Number of Levels and Descriptions for Each

Challenge Type	**Challenge**	**Number of Levels**	**Description**
CAD Challenges	Dream Home	3	Learners design CAD model homes in Sketchup.
	Dream Home 2: Gut Rehab	4	Learners modify existing CAD model homes, given “clients” design constraints.
CAD 3D Printing Challenges	Jewelry Designer	3	Learners design earrings, a bracelet, or a pendant in Sketchup and print them using a 3D printer.
	Print My Ride	3	Learners use images of cars to design model cars in Sketchup and print them using a 3D printer.
	Eye Candy	3	Learners use images to design glasses/sunglasses in Sketchup and print them using a 3D printer.
	Keychain Customizer	3	Learners design keychains in Tinkercad and print them using a 3D printer.
	3D You	3	Learners use Meshmixer to make CAD model animals, then use both Meshmixer and a Kinnect or model and print their own busts.
Computer Programming and Robotics Challenges	Game Designer	4	Learners use Stencyl and basic programming skills to customize video games.
	How to Train Your Robot	4	Learners program a Sparki robot to walk, bark, draw, and fetch treats.
Graphic Design and Animation Challenges	Selfie Sticker	3	Learners use Inkscape graphic design software to design Vinyl stickers and print them using a special printer.
	Minime Animation	4	Learners use 3D animation software to bring a CGI character to life, as they customize its colors and expressions and make it dance.
Electronics Challenges	Electric Apparel	4	Learners create circuits out of conductive materials to create light-up clothing.
	LED Color Lights	5	Learners create circuits to power colored LED lights.
	Party Lights	4	Learners use an Arduino to program moving light displays.
	Crystal Ball	3	Learners use an Arduino to program colored light displays inside a crystal ball.
	Music Amplifier	3	Learners use electronic circuit components to create a music amplifier for use with an MP3 player and speaker.
	Get in the Game	3	Learners use a Makey Makey kit to make and use a custom video game controller.
Light Challenges	Laser Defender	5	Learners use mirrors and lasers to create and test a laser “security system.”
Renewable Energy Challenges	Wind Commander	4	Learners experiment with using wind energy to power a turbine and complete various tasks.
	Solar Roller	3	Learners experiment with using solar energy to power a model car.
Sound Challenges	Ringtones	3	Learners use Soundation to mix tracks into custom ringtones.
Chemistry Challenges	Just Bead It	5	Learners explore principles of chemistry and biology by making bead “cells.”
Building Challenges	Spaghetti Structures	2	Learners use spaghetti and marshmallows to build towers, given specific constraints.

Coaster Boss	3	Learners attempt to build the fastest roller coaster using foam and marbles.

The research presented here was primarily conducted in a subset of these fifth and sixth grade classrooms, in order to see how these informal activities were adopted into a more formal school context. These classrooms were all from one large, suburban, Midwestern school district, with a relatively racially and socioeconomically diverse student population.[1] In this particular district, elementary school includes kindergarten to sixth grade, and middle school includes grades seven and eight. So all of the fifth and sixth grade classrooms I observed were in elementary schools. Only the five STEM-focused elementary schools in the district run FUSE as an in-school and after-school program, whereas, at the time of data collection, the rest of the 22 elementary and middle schools in the district only had FUSE as an after-school club.

The data presented in this dissertation come from observations of five classrooms, from four of these five STEM-focused elementary schools, over the course of the 2014-15 and 2015-16 school years. Focal classrooms were chosen based on an interest in achieving variability and representativeness on specific instructor and student characteristics. First, to insure a representative picture of how students at different grade-levels participated in FUSE activities, my sample of focal classrooms was comprised of three fifth-grade classes, one sixth-grade class, and one mixed, fifth-sixth-grade class. Second, to insure a representative picture of how teachers with different amounts of FUSE experience and expertise facilitated FUSE activities, my sample of focal classrooms included two classrooms with teachers who were new to FUSE (one fifth and

[1] The student population in this district is 31 percent low income, and 22 percent of students are English language learners. The racial composition of the student body is 42 percent white, 24.7 percent Hispanic, 22.8 percent Asian, 6.3 percent black, 3.5 percent multiracial, 0.4 percent American Indian, and 0.2 percent Pacific Islander.

one sixth), and three classrooms with teachers who had facilitated FUSE before (two fifth and one mixed fifth and sixth, for more detail, see Table 2.2). In addition to identifying facilitators with different levels of prior experience facilitating FUSE, I also worked with the district STEM coordinator to identify teachers who had demonstrated more or less comfort with FUSE facilitation or epistemic alignment with the design goals of FUSE (for more detail, see Table 2.2).

Table 2.2

List of Focal FUSE Studios by School, Grade Level, and Level of Facilitator Experience and Alignment

School	**Class**	**Facilitator**	**Grade Level**	**Facilitator Experience**	**Facilitator Alignment**
School 1	Class 1	Ms. Ross	5	Experienced FUSE facilitator	High
School 2	Class 2	Mr. Lewis	5	Experienced FUSE facilitator	High
School 3	Class 3	Mr. Williams	5 and 6 mixed	Experienced FUSE facilitator	Moderate
School 4	Class 4	Ms. Vonn	5	New FUSE facilitator	Initially unknown
	Class 5	Ms. Tinsel	6	New FUSE facilitator	Initially unknown

Finally, in order to examine the questions in my last analysis chapter, regarding the permeability of the membrane between FUSE and other STEAM learning contexts, I also observed selected focal participants, as they engaged in: (1) after-school FUSE club; (2) a tetrahedron kite-making activity in their math class; (3) a wind turbine engineering activity in their Project Lead the Way (Project Lead the Way, 2015) class; (4) a school science fair; and (5) a school-sponsored family STEM night. Figure 2.1 provides a timetable of observations in each focal FUSE studio and related STEAM learning context. Each class is coded with a different color, and non-FUSE activities are given colors based on which classes of focal students participated in them. The reader will note that STEM night at School 4 is colored neither blue like Class 4 nor purple like Class 5 at school 4, but rather indigo. This is to indicate that students from both Classes 4 and 5 participated in it.

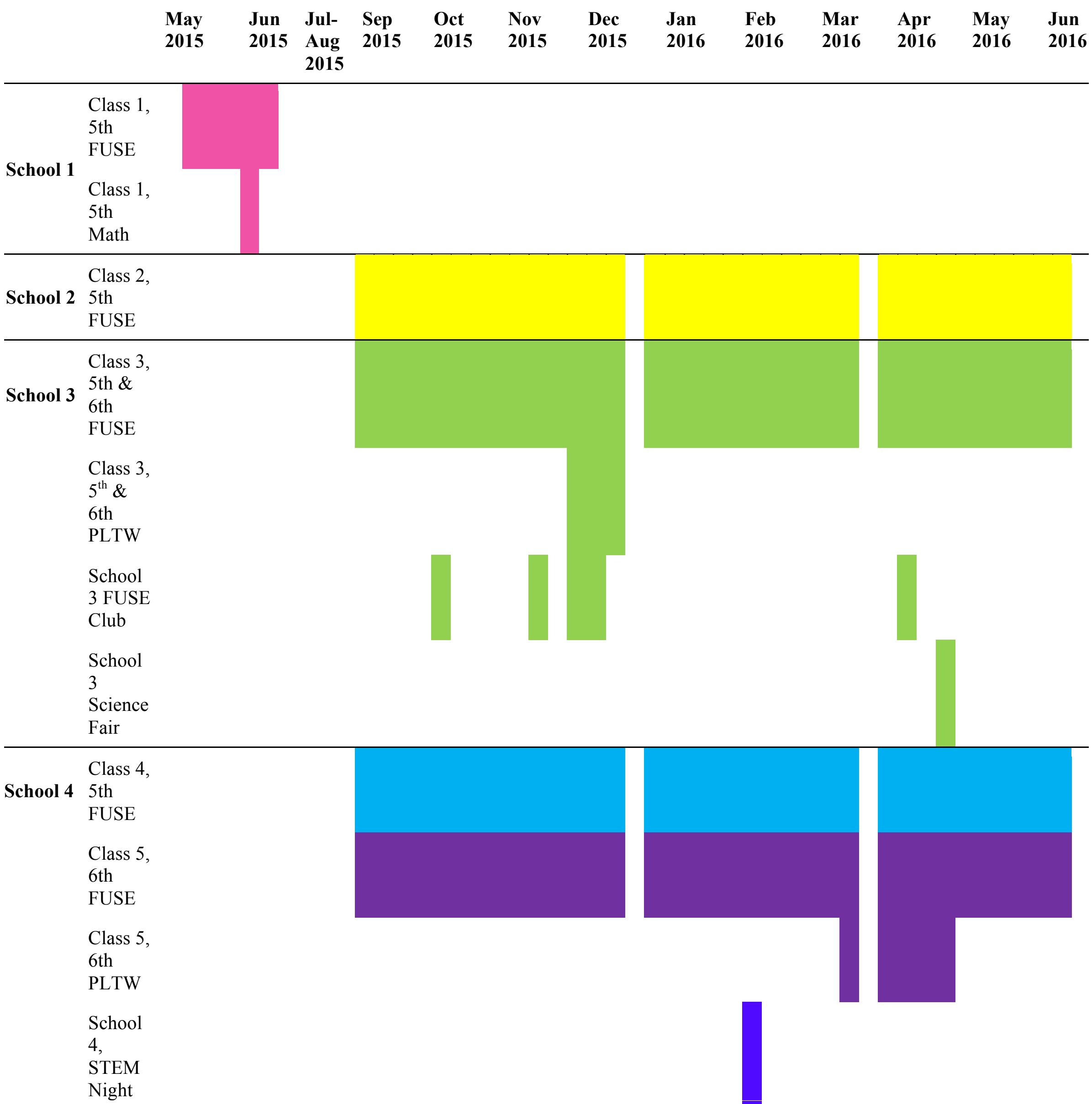


Figure 2.1. Timetable of observations in each focal FUSE studio and related STEAM learning context.

Participants

Of the 127 students in the five focal classrooms, 90 agreed to participate in this research. Of these, 58 were fifth graders, and 32 were sixth graders. 42 were male, and 48 were female. I wasn't able to collect racial demographic information for all students, but an estimate derived from those students I do have this information for suggests that the racial composition of my group of participants closely resembles that of the district as a whole. In referring to these participants throughout this text I use pseudonyms which preserve gender.

Data Collection

Drawing on cognitive ethnographic methods (Hutchins, 1995a; Hollan, Hutchins, & Kirsh, 2000), I investigated and analyzed students' moment to moment thinking and learning during FUSE activities, but I situated that analysis within a broader understanding of both the culture of FUSE studios and the relation between FUSE and other learning activities in students' lives. In order to understand both the cognitive and contextual factors involved in thinking and problem-solving during FUSE activities, I collected a number of different types of data, including: (1) ethnographic observations and field notes; (2) video recordings; (3) pictures of artifacts; (4) surveys; (5) and interviews.

Ethnographic Observations and Field Notes. First, I conducted ethnographic observations of classroom activity in five FUSE studios, one during the Spring of the 2014-15 academic year, and the other seven during the entire 2015-16 academic year. For these observations, I, or another member of the research team, attended every FUSE session (two per week for a total of 90 minutes). I also observed focal participants as they engaged in a number of activities outside of the FUSE classroom, including: (1) after-school FUSE club; (2) a tetrahedron kite-making activity in their math class; (3) a wind turbine engineering activity in their Project Lead the Way (Project Lead the Way, 2015) class; (4) a school science fair; and (5) a school-sponsored family STEM night (for more details, see Figure 2.1). The specific non-FUSE activities observed were chosen based on conversations with students, teachers, and administrators, in which they named activities they deemed related to FUSE in some way. When students mentioned pursuing activities related to FUSE at home, I also reached out to parents and requested permission to come and observe those activities. However, I was unsuccessful gaining access to observe those home activities. During all of these observations, I acted as a participant ethnographer, observing and taking field notes on students' and teachers' behavior, but also interacting with them, asking informal questions, guiding them toward relevant resources, and relaying information from them back to our design team, regarding bugs in the FUSE website or missing or broken materials in the studios.

Video Recordings. In addition to ethnographic observations, during every FUSE studio visit, our research team also collected whole-room and point-of-view video. Whole-room video was capture using a tripod-mounted camera. This camera was usually located in one stationary location at the back of the classroom and positioned to capture as much of the classroom activity as possible. Point-of-view video was captured by up to six focal participants per class, wearing small Go-Pro®, Drift®, or Mobius® cameras mounted on tennis visors. Figure 2.2 depicts a student wearing one of these cameras, attached to a visor. It is hand-rendered, rather than photographed to protect the identity of the student.

Figure 2.2. Student wearing camera attached to a visor.

These cameras allowed me to capture first-person perspectives on students' work, clear audio of their conservations with other students, and the ability to follow their activity as they moved about the classroom space (a frequent occurrence in FUSE Studios). On any given day of studio observations, focal participants were chosen to wear visor cameras based on the following criteria: (1) formally consented to participate in research and specifically to wear visor cameras; and (2) informally gave consent to wear the visor on that day (i.e., asked for a camera or said yes when we asked them to wear one that day). Occasionally, I, or other members of the research team, would also wear a camera, to capture our conservations with students and teachers. For observations in the after-school FUSE club, tetrahedron kite-making activity, and Project Lead the Way wind turbine activity, I used the same video-recording protocol. The only observed activities that were not video-recorded (at the request of the school) were the school science fair and the school-sponsored family STEM night.

Pictures of Artifacts. In addition to video recordings, I, and other members of the research team, also took pictures of artifacts in the FUSE studios. These included digital or physical artifacts created by students, as part of FUSE challenges, and artifacts created or used by teachers to facilitate FUSE activities. These pictures allowed me both to document artifacts not captured on video and also to obtain more detailed records of things already captured in the video recordings.

Surveys. As part of an external, systematic evaluation of the FUSE program, students in my focal classrooms completed online surveys administered at three time points throughout the school year (beginning, middle, end). In order to understand the relation between interest development and learning and between learning in FUSE and learning in other areas of students' lives, I analyzed responses to selected items on these surveys, related to connected learning (Ito et al., 2013; Maul et al., 2016), STEAM interests, and career aspirations (for a complete list of survey questions, see Appendix A).

Interviews. At the end of the 2015-16 school year, our research team conducted semi-structured interviews (Bernard, 1988) with the students and facilitators in our focal classrooms to understand what they thought about FUSE, what they had learned or remembered from the past year, and what impact, if any, FUSE might have had on students' future learning, interests, or career aspirations (for a full list of student interview questions, see Appendix B; for facilitator interview questions, see Appendix C). I analyzed responses to a subset of these questions, related to interest development and learning and learning across contexts, and used them to triangulate findings from ethnographic observations and analysis of video recordings.

Data Analysis

To analyze the data from these various data sources, I first collated the data from different sources in order to triangulate the story of particular students, activities, or FUSE studios using all available information about that student, activity, or studio. I next drew on two methods of analysis: qualitative coding and interaction analysis. Each analysis chapter in this dissertation differs in ways in which I used these different methods to answer my research questions. Thus, in each chapter, I provide further detail on how analytic methods were used and coordinated with one another to answer the specific questions therein. Here, however, I provide a general overview of each method and how I've used it.

Qualitative Coding. My first method was iterative qualitative coding. Throughout the coding process I placed the data I'd collected in conversation with relevant literature, and allowed both to collaboratively inform my coding schemes and analyses. The primary unit of analysis, to which I applied qualitative codes, differed between analysis chapters, ranging from idea units (Chafe, 1979; 1980), to episodes, to students, to activity systems (Engeström, 1987). Each analysis chapter differs in the units being analyzed and the types of codes that are applied to those units of analysis.

Interaction Analysis. In addition to qualitative coding, I analyzed episodes of interaction in accordance with the tradition of interaction analysis (e.g., Goodwin, 2000; Hall & Stevens, 2015; Jordan & Henderson, 1995; McDermott, Gospodinoff, & Aron, 1978; Mehan, 1982; Schegloff, 1992). This is a method for "the empirical investigation of the interaction of human beings with each other and with objects in their environment…[investigating] human activities, such as talk, nonverbal interaction, and the use of artifacts and technologies, [and] identifying routine practices and problems and the resources for their solution" (Jordan & Henderson, 2002, p. 39). I used this method of analysis to make sense of the moment to moment thinking and learning occurring during each episode. I employed interaction analysis, rather than conversation analysis, because, it better accounts for the multiple modalities of communication (e.g., talk, gesture, gaze, expression, body position, tone and inflection, and engagement with material objects) the students and facilitators used to communicate with one another and solve

STEAM problems. In other words, interaction analysis is the methodological consequence of seeing cognition as socially and ecologically distributed (Jordan & Henderson, 2002). As Jordan and Henderson (1995), wrote,

> Interaction analysis finds its basic data for theorizing about knowledge and practice not in traces of cranial activity (e.g., protocol or survey interview data), but in the details of social interactions in time and space and, particularly, in the naturally occurring, everyday interactions among members of communities of practice (p. 41).

As a consequence, interaction analysis not only aligns with a situated and distributed theoretical lens on learning but has unique affordances for understanding how thinking and learning unfold in moment-to-moment, multimodal interactions between people, objects, and representations. This makes it ideal for understanding how processes like interest development and learning unfold in context. Interaction analysis also has a history of use in cross-context examinations of learning. One way in which it affords comparison across contexts is through the examination of *participation frameworks* — "fluid structures of mutual engagement and disengagement characterized by bodily alignment (usually face-to-face), patterned eye-contact, situation-appropriate tone of voice, and other resources the situation may afford." (Jordan & Henderson, 1995, p. 68). Jordan and Henderson (1995) argue that,

> The analysis of participation structures is also essential to understanding interaction in formal school settings. To what extent do teacher and students sustain different kinds of participation structures in group work or in lecture format? How do computers, workbooks, table arrangements, and other kinds of artifacts support or destroy such structures? (p. 69).

The fact that interaction analysis allows for such an analysis, makes it an apt method for comparing contexts in terms of their differing sociomaterial conditions and the specific types of practices and interactions that these contexts afford.

To analyze episodes using interaction analysis, I first engaged in *recursive transcription*, a systematic, sequential analysis and transcription of verbal and nonverbal interactional phenomena made relevant to the interaction by participants (Ramey et al., 2016). In creating these transcripts, I employed a modified version of Jefferson's transcription notation (Sacks, Schegloff & Jefferson, 1974).[2] In keeping with the traditions of interaction analysis (e.g., Goodwin, 2000; Hall & Stevens, 2015; Jordan & Henderson, 1995; McDermott, et al., 1978; Mehan, 1982; Schegloff, 1992), within my analyses, I present excerpts of transcripts to display my interpretations of video data. When relevant and necessary, I also augment written transcripts with *visual transcripts* of episodes, as these better capture important nonverbal interactional phenomena (Ramey et al., 2016). Finally, in keeping with both the methods of interaction analysis and the theoretical frame of distributed cognition, after creating detailed transcripts, I performed a turn-by-turn analysis of all human and non-human participants in the interaction (e.g., Hutchins, 1995a; 1995b; Pomerantz & Fehr, 1997).

[2] Jefferson's transcription notation does not include actions, which I include, as a separate column in all transcripts where relevant actions appeared. I do not include Jefferson's symbols for stress and intonation in my transcripts, as these aspects of talk are not relevant to my analyses, and they make the transcripts difficult to read.

Chapter 3. Interest-driven Learning in a Choice-based, In-school Makerspace

Making activities and makerspaces have become increasingly popular in recent years, particularly in informal settings (Honey & Kanter, 2013), and have shown promise for engaging youth in integrated STEAM (science, technology, engineering, arts, and math) learning (e.g., Vossoughi & Bevan, 2014). Given this potential, school districts are increasingly incorporating these activities into the school day (Martinez & Stager, 2013). As making activities and makerspaces move into schools, however, there is increased pressure to understand what students are learning in these spaces and activities. In doing so, there are at least two questions that need to be answered.

The first is *what* learning we care about. K-12 educators, who are constrained by the current school culture of standards and accountability, are often preoccupied with concerns about how making activities relate to existing curricula or help develop domain content knowledge. They also tend to be concerned with whether and how making can support student engagement in the science and engineering practices outlined in the Next Generation Science Standards (NRC, 2012a). In contrast, researchers examining learning in informal making and tinkering activities have tended to focus on meta-disciplinary skills, such as twenty-first century skills (for a recent review, see Vossoughi & Bevan, 2014; see also Hilton, 2010), and have argued for these skills being the most important things learned in makerspaces.

The second question is *how* to assess learning in these spaces. There are at least two factors that make assessing learning in making activities or spaces challenging. The first is deciding how and when to assess learning in ways that don't interfere with the learning process. The second is that choice is a fundamental component of many making activities, the choice to pursue projects of interest to the learner, rather than a one-size-fits-all curriculum (Papert, 1980).

Thus, not all learners are doing (or learning) the same things. This makes assessing learning using standardized assessments difficult, if not impossible. It also makes understanding student interests a critical part of understanding learning, because interests may determine what activities students engage in, how they engage in those activities, and whether engagement in those activities leads to a longer-term interest in making or STEM learning. In fact, Maltese & Tai (2010) argued that early interest is as or more important than academic performance in determining later pursuit of and success in disciplines such as science.

Research Objectives

With these challenges in mind, the goal of this chapter is to enhance our understanding of the full range of knowledge and practices learned in makerspaces and the relation between student interests and learning in these types of activity systems (Engeström, 1987) for learning. I examine these issues specifically within FUSE Studios, a set of in-school, choice-based makerspaces. Within this research context, I examine the following specific research questions: (1) what is learned in FUSE? (2) how do student interests shape learning? and, (3) how do we assess that learning?

In the sections that follow, I draw on prior literature on learning in makerspaces and the relation between student interests and learning. I then propose a framework for understanding and assessing interest development and learning in makerspaces. I present four student cases that represent different interest pathways through FUSE. For each case, I discuss how these pathways are both shaped by, and in turn, shape student interests, and I demonstrate how the proposed framework can be applied to analyze what is learned along each pathway. Through these cases, I argue that one problem with traditional learning in school is that it too often does not allow learners to shape their own learning and therefore does not allow for the reciprocal interaction between interest, learning, and identity development. In contrast, in FUSE, there is space to choose one's own interest pathway and thereby produce one's own learning and identity.

What Counts as a Makerspace?

Before examining prior literature on interest development and learning in makerspaces, it is important to clarify what counts as a makerspace and how FUSE Studios, as examples of in-school makerspaces are similar or different from other makerspaces. Sheridan et al. (2014) define "makerspaces" as "sites for creative production in art, science and engineering where people blend digital and physical technologies to explore ideas, learn technical skills and create new products" (p. 505). They argue that "making" involves "developing an idea and constructing it into some physical or digital form" (p. 507).

FUSE remains true to these definitions of makerspaces and making. However, there are also important ways in which FUSE is different from other makerspaces. The most obvious of these is that the data I've drawn on for this analysis is from in-school FUSE studios. So the activities that took place occurred during the regular school day and were part of a required course. This has the advantage of giving more students access to making activities and giving all students a prolonged period of time (1.5 hours per week for the entire school year) to engage with making activities. However, it also has the potential disadvantage of making students feel required or coerced to engage in making, rather than doing it because it is of interest to them.

Because of this, choice within the activity system becomes particularly important, and choice is a fundamental design principle of FUSE. While FUSE provides more structure and support than some out-of-school makerspaces, it also provides more choice and freedom than the types of making activities that typically make their way into schools. For example, in FUSE, students begin by choosing from a gallery of challenges hosted on the FUSE website. This contrasts with both open-ended makerspaces, where learners can choose to do any project they desire using any tools available (e.g., Brahms, 2014; Sheridan et al., 2014), and more structured making activities, where all learners do the same project or use the same tools (e.g., Fields & King, 2014; Peppler, 2013; Resnick et al., 2009). Further, for each challenge, there are specific guidelines and help resources available on the FUSE website. This means that, in addition to the help resources available to learners in a typical makerspace (facilitators, other learners, physical tools and materials), learners in FUSE have an additional set of curated support resources at their disposal, throughout the making process.

As a consequence, whereas making activities have often been divided into two different types of activities: the relatively planful, goal-oriented, and constrained *engineering design activities* (e.g., Brophy, Klein, Portsmore, & Rogers, 2008; Museum of Science, 2015; Project Lead the Way, 2015), and the relatively open-ended, playful *tinkering activities* (e.g., Martinez & Stager, 2013; Resnick & Rosenbaum, 2013; Vossoughi et al., 2013), FUSE allows multiple different approaches to making within one activity system. For example, while some students may choose to engage in challenges sequentially, carefully following instructions and attending to prescribed goals, others may choose to explore the affordances of available tools and materials and adhere only loosely to suggested challenge goals.

In short, similarities between FUSE and other makerspaces suggest that we might expect the types of learning occurring in FUSE to be similar to those occurring in other makerspaces. Therefore, it is important to consider prior literature on learning in makerspaces to determine what types of learning to look for in FUSE. However, because there are also important ways in which FUSE is different from other makerspaces, and these differences may lead to differences in both *how* and *what* learning occurs in FUSE, further investigation is needed in order to understand how specific features of the FUSE activity system might lead to interest development and learning.

Makerspaces as Contexts for Learning

Many researchers have advocated for the potential of makerspaces for engaging youth in personally meaningful, interest-driven, and creative investigations of the material and social world (e.g., Blikstein, 2013; Martin & Dixon, 2013; Martinez & Stager, 2013; Vossoughi & Bevan, 2014). In a recent review of research on learning in making and tinkering activities, Vossoughi & Bevan (2014) cite two reasons for this excitement around learning through making. The first is that makerspaces have the potential to democratize learning, by making tools, and associated tasks and skills, previously available only to experts, available to a wider audience of students and entrepreneurs (Blikstein, 2013). The second is that makerspaces have the potential to expand participation in STEM fields by leveraging the strengths of interest-driven, integrated-STEM (or STEAM) learning environments (Brahms, 2014; Martin, 2014; Sheridan et al., 2014).

Vossoughi and Bevan (2014) outline a number of theoretical reasons why making should promote STEM learning and interest development. Specifically, they argue that making activities are aligned with constructivist (Piaget, 1964), constructionist (Papert, 1980), and socio-cultural (Vygotsky, 1978) learning principles (e.g., Martinez & Stager, 2013; Resnick & Rosenbaum, 2013; Vossoughi & Bevan, 2014). For example, making activities are aligned with constructivist learning principles, because they allow understandings to be constructed by the individual learners through experience, rather than developed through transmission of facts from teacher to student. They are aligned with constructionist learning principles, because they provide learners with opportunities to develop and represent understanding through the process of building personally meaningful physical or digital objects. Finally, they are aligned with socio-cultural theories of learning, because they allow novices and experts to work side-by-side and assist one another through processes of investigation and invention. Finally, Vossoughi and Bevan (2014) argue that the use of new technologies (such as Arduinos or 3D printers) and the aesthetic and playful qualities of many making activities may operate to create a lower barrier for participation and higher potential for engagement than in traditional text-based, test-driven, and teacher-centered, STEM instructional activities. This is consistent with arguments from Papert (1980) and Resnick (2011) emphasizing the importance of developing activities and technologies with a low floor (easy to get started), a high ceiling (opportunities to create sophisticated projects) and wide walls (supporting many different types of projects).

Vossoughi & Bevan (2014) further outline a number of different benefits that previous theoretical and empirical work suggests making might facilitate. Here, I divide these into three general categories: (1) social and emotional skills, (2) interest development and identity formation, and (3) STEAM concepts, skills, and practices (both disciplinary and meta-disciplinary).

Social and Emotional Skills. Making activity systems have the potential to facilitate the learning of social and emotional skills in a number of important ways. First, to the extent that making activities provide learners with opportunities to work together, share tools and ideas, provide assistance to others, and embrace intellectual diversity, they have the potential to facilitate collaboration and collaborative relationships (Blikstein, 2013; Chavez & Soep, 2005;

Vossoughi et al., 2013). They also have the potential to expand experiences and skills in communication, leadership, the negotiation of differences, flexibility, initiative, and metacognition (NRC, 2012b). Second, to the extent that makerspaces create a supportive community of learners (Sheridan et al., 2014; Vossoughi et. al., 2013), they have the potential to cultivate a sense of belonging and mattering (NRC & IOM, 2002). Third, if making activities provide opportunities for and encourage learners to leverage each other's interests and skills towards shared goals (NRC & IOM, 2002), students may be able to take on new leadership and teaching roles (Sheridan et al., 2014) and to develop skills and practices involved in sharing projects (e.g., confidence, communication, drawing connections between artifacts, and giving and receiving feedback; Martin, 2014; Vossoughi et al., 2013).

Interest Development and Identity Formation. Making activity systems also have the potential to support learners in developing both interests and identities (NRC, 2009). For example, researchers have argued that they support learners in developing new dispositions and ways of thinking (Sheridan et al., 2014), including providing them with new ways of viewing themselves and their STEM capacities (Bowler, 2014; Dixon & Martin, 2014; Fields & King, 2014). This includes developing new roles and trajectories of participation (Brahms & Crowley, 2014; Gutiérrez et al., 2014), such as working with ideas, materials, tools, and processes in increasingly complex and iterative ways (Sheridan et al., 2014), experiencing new levels of frustration and excitement (Blikstein, 2013), and embracing the process of iteration (Vossoughi et al., 2013). Mechanisms through which STEM interest and identity may develop through participation in making include: (1) the pursuit of future making-related activities and skills (Fields & King, 2014; Dixon & Martin, 2014); (2) becoming activated towards particular STEM topics or disciplines, where “activation” includes dispositions, skills, and knowledge (Dorph & Cannady, 2013); (3) the development of dispositions, skills, and knowledge that aren’t tied to STEM, such as confidence, persistence, authorship, and resourcefulness (Brahms & Crowley, 2014; Petrich et al., 2013); (4) making connections to outside community and school experiences (NRC & IOM, 2002) or integrating knowledge and practices across settings (Blikstein, 2013; Dixon & Martin, 2014; Fields & King, 2014; Vossoughi et al., 2013); and (5) developing critical literacies, such as distinguishing between making and consuming (Martin & Dixon, 2013) and rewriting narratives about oneself and one’s community (Chavez & Soep, 2005).

STEAM Content, Skills, and Practices. Finally, makerspaces have the potential to support the learning of STEAM content, skills, and practices by: (1) contextualizing STEAM concepts and practices in meaningful activity; (2) cultivating inter-disciplinary practices; and (3) encouraging intellectual risk-taking, experimentation, and iteration (Vossoughi & Bevan, 2014). Through these mechanisms, makerspaces have the potential to promote deepening understandings of STEAM concepts (Blikstein, 2013; NRC, 2009; Peppler, 2013), and to engage learners in STEM practices (Blikstein, 2013; Gutiérrez et al., 2014), including problem-finding, solving, testing, and iteration (Petrich et al., 2013; Vossoughi et al., 2013), as well as scientific reasoning (NRC, 2009). Because of their integrative nature, makerspaces also have the potential to cultivate the development of innovative combinations, juxtapositions, and uses of disciplinary content and skill from multiple STEAM disciplines (Brahms & Crowley, 2014; Peppler, 2013; Sheridan et al., 2014), as well as related critical thinking and innovation skills (NRC, 2012b). Finally, technical STEAM skills learned in makerspaces include fabrication skills (e.g., programming, interface design, animation, graphics, 3D design) and dexterity with a range of tools (e.g., programming software, design software, electronics, and 3D printers; Ito et al., 2013; Kafai & Peppler, 2010; Sheridan et al., 2014).

However, *how* and *whether a* particular making activity system supports some or all of these different forms of interest and identity development or learning remains an open question, in need of further empirical investigation. For example, if the culture within a makerspace becomes too focused on competition, rather than collaboration, or particular groups of learners are systematically ostracized or marginalized, participants may not learn certain social and emotional skills. Similarly, if students are not given the choice to pursue projects of interest to them, they may not develop STEM or STEAM interests or identities or be motivated to engage in the learning of STEAM content, skills, and practices. Thus, it is important to attend carefully to culture of a particular makerspace, in order to understand its benefits for interest development and learning. Further, as much of the prior literature on interest development and learning in makerspaces relies more heavily on theoretical argumentation and advocacy than on empirical research, further empirical support is needed for many of the claims of interest development and learning made about these spaces and activities.

Interest-driven Learning, Equity, and Inclusion

In addition to open questions regarding whether and which types of makerspaces actually facilitate these different types of interest development and learning, an additional gap in the literature on making is in understanding *who* sees these gains. For example, in a study of design thinking in an urban classroom serving young women of color, Norris (2014) found that "although some students were able to make meaning as they designed individual projects that helped them to develop more positive identities, other young women did not make tangible projects...social constructions and the need for privacy overshadowed their willingness to design and their need to share their designs" (p. 73). Martin (2014) also wrote:

> …the ways that young people identify with a domain such as engineering can have substantial influence on the kinds of choices they make for future educational experiences, including courses and majors, and can partly predict the likelihood that they will pursue a career in that field (Tai et al., 2006). When young people are interested in the things they are working with, when they feel like their activities align with their sense of themselves and their possible futures, and when they feel connected to the community they are working within, tremendous amounts of learning can occur (p. 10).

Martin's words here highlight the importance of considering interest and identity development as factors in learning in makerspaces, particularly if we are concerned about equity and inclusion.

One important reason to attend to issues of equity and inclusion — both in makerspaces and in the STEM fields more generally — is that female and minority students are underrepresented in STEM fields either because of lack of exposure, lack of interest, or lack of appropriate preparation or skills (e.g., Chang, 2002; Duderstadt, 2008; Gonzalez et al., 2008; Griffith, 2010; Huang, et al., 2000; NAE & NRC, 2009; NAE & NRC, 2014; National Science Board, 2007; Price, 2011). Making activities have the potential to bring these students into STEM by: (1) leveraging the strengths of interest-driven, multi-disciplinary STEM or STEAM learning environments (Brahms, 2014; Martin, 2014; Sheridan et al., 2014); and (2) allowing learners to pursue questions of interest to them and to integrate existing knowledge, skills, and interests from other contexts (Blikstein, 2013; Fields & King, 2014; Gutiérrez et al., 2014; McDermott, 2010; Vossoughi & Bevan, 2014; Vossoughi et al., 2013). For example, researchers have found that females prefer to learn new technology-based skills by incorporating them into more traditional craft skills, such as e-textiles (Barniskis, 2014; Kafai, Fields & Searle, 2014). Many studies also suggest that if designers can get female students in the door and get them engaged in making, then they are particularly likely to express increased feelings of confidence and empowerment related to the tools and skills involved (e.g., Barniskis, 2014; Bowler, 2014; Fields & King, 2014). Additionally, because makerspaces support novices and experts to working side-by-side, assisting one another, and continually shifting roles through processes of investigation and invention, these activities have the potential to challenge deficit views and support more inclusive learning and development.

However, if not designed carefully, makerspaces also have the potential to reproduce, rather than challenge, existing inequities (Vossoughi & Bevan, 2014). For example, many out-of-school makerspaces present well-documented barriers to entry, particularly for female students, such as “there's no easy way to get in,” or “It's not clear what spaces offer,” or “There's often no goal” (Lewis, 2015). In one sense, these barriers may be mitigated by moving making activities into schools, where they are either required or more easily available to all students. However, there is significant cause for concern that should the design of traditional makerspaces and associated activities be imported wholesale into schools without attention to issues of inclusivity and equity, then cultural barriers such as lack of interest, issues of identity, and intimidation (Lewis, 2015), may perpetuate rather than mitigate the disenfranchisement of female students and other underrepresented groups.

Further, to date, the maker movement has not engaged with issues of remediation, segregation, and tracking, which shape the schooling experiences of underrepresented minority students and students from lower socioeconomic status backgrounds (Vossoughi & Bevan, 2014). These policies are deeply tied to cultural assumptions about ability and intelligence, such as the notion that students who are constructed as “underachieving” should be given a more basic set of tasks, rather than intellectually rich tasks with ample support (Cole & Griffin, 1983;

Gutierrez, 2008). Therefore, it is particularly important to document the interest and learning pathways of students from non-dominant groups and to examine how FUSE, as an in-school makerspace, either invites or prevents their engagement with STEAM.

Interest Pathways and Learning

So how might interests shape learning in a makerspace like FUSE? And why focus on interests as a central aspect of learning in this sort of activity system? To answer these questions, I draw primarily on accounts of interest and interest development from sociocultural activity theory. For example, I draw on Ingold's (2011) notions of *lines* and *trails of becoming* (p. 14), as well as Bell, et al.'s (2013) concept of "*cultural learning pathways* – connected chains of personally consequential activity and sense-making – that are temporally extended, spatially variable, and culturally diverse with respect to value systems and social practices" (p. 270). Ingold emphasizes the need for tracing learners' "multiple trails of becoming, wherever they lead" (Ingold, 2011, p. 14) and also invokes Marx's notion of *production,* that "[humans] produce themselves and one another…by reciprocally laying down, through their life activities, the conditions for their own growth and development" (Ingold, 2011, p. 7). In a similar vein, Bell, et al. (2013) write that "we need to account for how individuals and groups arrange or transform the conditions of their own learning in relation to their expectations, interests, concerns, and available resources, as well as how such acts of agency and activity within situations are impeded, resisted, or even co-opted" (p. 271). In other words, the choice-based nature of makerspaces means that interests and identity are intertwined with learning so that learning stories are interest and identity development stories and vice versa.

The problem with traditional learning in school is that it too often does not allow learners to shape their own learning in this way, and therefore does not allow for the reciprocal interaction between interest, learning, and identity development. In contrast, in FUSE, there is space to choose one's own interest pathway and thereby produce one's own learning and identity. Consequently, unlike traditional school, FUSE allows for true interest-based engagement, consistent with a definition offered by diSessa (2000), that interest-based engagement refers to self-motivated, often self-guided, short- and long-term participation in the activities that make up a practice.

Importantly, in contrast to more cognitive-psychological accounts of interest development, such as Hidi and Renniger's (2006) four phase model, I do not frame interest as a psychological state triggered in and later possessed by an individual, nor do I see the individual as largely passive in the early stages of interest development. Rather, I draw on Hollet's (2016), notion of "interests in motion", which frames interests as dynamic and mutually constituted by individuals' interactions with multiple socio-material environments over time. Drawing also on Barron (2006), I argue that the strongest evidence for interest development is learners doing the work of pursuing those interests across contextual boundaries and arranging the material constraints of new activity systems to accommodate the pursuit of those interests.

Similarly, while Hidi and Renninger (2006) frame interest as tied exclusively to content and interest development as a linear pathway, I adopt a more flexible and fluid understanding of interest and interest development, drawn from Azevedo (2013). He describes interests in terms of *lines of practice,* where a line of practice is "a specific subset of a person's *preferences*…[which] can thus be seen in the specific patterns of activities that spring from any single, enduring cluster of *preferences* and *conditions of practice"* (p. 488). Azevedo also emphasizes that the topic or domain of learning is not necessarily the driving force around which students' work and interests develop. In contrast, "*lines of practice* theory suggests that, given certain *conditions of practice,* people will weave all sorts of *preferences* into ongoing and long-term activities of interest, thus sometimes deviating from the intended curriculum and its topical core, often in dramatic ways" (p. 501). For example, commenting on Joseph and Edelson's (2002) example of a Video Crew — students learning video production skills in an after-school program — he wrote:

> …although some students were passionate about video, some were motivated by very different projects. Perhaps worse, still others appeared to be motivated solely by the *social* aspects of the given activities, such as cultivating friendships or mediating the execution of group tasks, to the detriment of other substantive components of the program…*Lines of practice* theory suggests that interest-based participation in a practice cannot be dissociated from its *multitopical* and *social preferences*—and, thus, students pursuing an interest might end up extending the boundaries of the proposed activities beyond the immediate substantive core of the activity, just as Edelson and Joseph observed. (p. 501).

Finally, like Anderhag et al. (2016), I rely primarily on observations and video recordings of classroom interactions to analyze how interest develops. However, I also augment this classroom interaction data with student reflections from end-of-year interviews. In other words, I operationalize the concept of *interest* in terms of either explicit statements from learners or (more often) in terms of their choices to pursue (and continue pursuing) particular challenges. So a learner could express interest in an activity or idea by explicitly stating that interest or by choosing to engage with the activity or idea. This analysis of interest development over time in a makerspace environment, using both classroom interaction data and students' self-reflections, provides a relatively unique and important contribution to the literature on interest generally, as well as to the specific literature on interest development in makerspaces.

To summarize how I have applied these prior theories on interest to understanding the relation between interest development and learning in FUSE, I define *interests* as learners choices to engage in particular challenges or activities. *Interest development* is seen when the nature of engagement with that interest deepens or changes. *Identity development* is seen to have occurred when learners make explicit statements related to personal qualities or future career aspirations that they connect to their work in FUSE. Finally, I describe learners as following unique *interest pathways* — dynamic, meandering lines of practice co-constructed by both individual interests and socio-material context — during their time in FUSE. It is these interest pathways, and the specific interests and practices learners engage with along these pathways, that produce learning.

Assessing Learning in Makerspaces

In a review of literature on making, Vossoughi & Bevan (2014) wrote that the emerging research literature has taken a largely qualitative (e.g., ethnographic, case study, interview, descriptive) approach to studying teaching and learning in makerspaces, with a smaller number of studies incorporating quantitative measures (e.g., surveys, pre-post assessments). I continue in this vein, drawing primarily on qualitative techniques in my analysis. In order to address the problem of how educators might assess learning in makerspaces, I propose a framework for qualitative analysis that could be applied not just by researchers, but also by teachers, as an evaluation rubric for student learning. In doing so, I draw on similar work from Wickman's

(2004) analysis of practical epistemologies in science classrooms, which also sought to provide a framework that educators could use to analyze learning by examining classroom interactions, either between individuals or between individuals and objects. Like Wickman, I propose that educators could use this analysis to understand what students are learning in makerspaces and make changes to the social or material conditions of these activity systems to improve future learning.

In this analysis, rather than focusing on content learning, I focus on meta-disciplinary skills, such as twenty-first century skills (for more detail and definition of each skill analyzed, see Data Analysis section of this chapter). FUSE should cultivate these meta-disciplinary skills, because it meets many of the criteria outlined for twenty-first century learning environments (Partnership for 21st Century Learning, 2015). For example, it enables "students to learn in relevant, real world 21st century contexts (e.g., through project-based or other applied work)," and allows "equitable access to quality learning tools, technologies and resources" (Partnership for 21st Century Learning, 2015, np). In the analyses presented in this chapter, I investigate whether this is the case. I also investigate how specific features of the FUSE, such as choice and students' resulting freedom to pursue activities of interest, might help cultivate this learning.

Data Analysis

Different Interest Pathways through FUSE. In examining the relation between choice, interest, and learning in FUSE, I began my investigation with a look at the different interest pathways students took through FUSE. I identified, through iterative coding, four distinct interest pathways that students took through their year in FUSE. In conceptualizing these pathways, I drew on Ito et al.'s (2010) description of levels of engagement in media-rich learning environments: “hanging out”, “messing around,” and “geeking out.” However, in order to better capture the range of pathways I observed in FUSE studios, I further teased these categories apart, particularly the “messing around” and “geeking out” categories. The four resulting categories I describe in my analysis are:

1. *sampling* - similar to messing around, involves dabbling in different challenges, and occasionally, but not necessarily completing levels or maintaining prolonged interest in any one
2. *completing* - taking a more completion oriented approach to challenges, trying more than one, but going through each in a more systematic fashion, completing many or all levels before moving on to the next challenge
3. *diving* - deeply engaging in one or more challenges or challenge sequences, completing levels but also going beyond what’s required for the level completion
4. *off-roading* - going beyond the provided challenges by either integrating tools, skills, or concepts from multiple challenges or integrating outside tools, skills, or concepts with those from one or more FUSE challenges.

These forms of engagement are not mutually exclusive. Students may engage in more than one of these pathways throughout the course of their participation in FUSE. However, within the current data corpus, one form of engagement seemed to predominate each individual’s pathway through FUSE.

Assessing Learning in FUSE: Learning at Different Levels. To assess “learning” along these different interest pathways, I used a framework, derived from Enyedy & Stevens’ (2015) framework for analyzing collaborative learning, which arranged evidence for different forms of learning along a spectrum of proximal to distal learning outcomes. Arranged from spatially and temporally proximal to distal, the levels of learning I identified included:

1. Learning through iteration within challenge levels, in order to achieve a goal,
2. Using knowledge, skills, or practices from one level of a challenge on the next level,
3. Using knowledge, skills, or practices from one challenge on another subsequent challenge,
4. Teaching another student something with which the learner had previously struggled,
5. Integrating skills from multiple challenges with each other or with outside knowledge, skills, and practices,
6. Using knowledge, skills, and practices learned in FUSE in other contexts.

Assessing Learning in FUSE: Different Types of Learning. To assess what was learned at these different levels and using these different resources, I engaged in iterative cycles coding, drawing both on prior research on learning in maker spaces and on analysis of field notes and video from studio observations. The primary set of skills that I focused on in my analysis were meta-disciplinary or 21st century skills. In defining "21st century skills," I focused on six, around which there seems to be the most convergence across multiple frameworks of 21st century skills (e.g., Jerald, 2009; NRC, 2012b; Partnership for 21st Century Learning, 2015). These include: 1) critical thinking; 2) adaptive problem-solving; 3) communication and collaboration;

4) creativity and innovation; 5) information, media, and technology literacy; and 6) initiative & self-direction. In the following section, I provide the definitions of each, drawn from the literature, that I used in my analysis.

Critical Thinking. I define critical thinking as the use of various types of reasoning as appropriate to the situation, including 1) effectively analyzing and evaluating evidence, arguments, claims and beliefs; 2) Synthesizing and making connections between information and arguments; 3) interpreting information and drawing conclusions based on the best analysis; and 4) reflecting critically on learning experiences and processes (Partnership for 21st Century Learning, 2015).

Adaptive Problem-Solving. I define adaptive problem-solving as the ability to "solve different kinds of non-familiar problems in both conventional and innovative ways" (Partnership for 21st Century Learning, 2015; p. 4).

Communication and Collaboration. I define communication as the ability to "articulate thoughts and ideas effectively using oral, written and nonverbal communication skills in a variety of forms and contexts," and to "listen effectively to decipher meaning, including knowledge, values, attitudes and intentions" (Partnership for 21st Century Learning, 2015, p. 4). I define collaboration as the "ability to work effectively and respectfully with diverse teams," and to "exercise flexibility and willingness to be helpful" and make "necessary compromises to accomplish a common goal" (Partnership for 21st Century Learning, 2015; p. 4).

Creativity and Innovation. In defining creativity and innovation, I use a definition from Medin, Ross, and Markman (2005), which integrates notions of creativity as incremental problem-solving (e.g., Ward 1995; Weber & Dixon, 1989; Weisberg, 1986) and notions of creativity as novel problem representation (e.g., Getzels & Csikzentmihalyi, 1976; Holyoak &

Thagard, 1995; Perkins, 1988; Weisberg, 1993). Medin, et al. (2005) define creativity as "arising from a great deal of refining, elaborating, and reformulating of the problem and its possible solutions. Much problem solving involves reformulating the problem by using information gained from failed solution attempts" (p. 445). In other words, creativity is not a personal characteristic, but a process of iterative change, resulting in new ideas or solutions to problems.

Information, Media, and Technology Literacy. I define information skills as the ability to access information efficiently and effectively and evaluate information critically and competently (Partnership for 21st Century Learning, 2015). I define media skills as the ability to both effectively analyze and create media (Partnership for 21st Century Learning, 2015), and I define technology literacy as the ability to "use technology as a tool to research, organize, evaluate, and communicate information" and to use technology "to access, manage, integrate, evaluate and create information to successfully" (Partnership for 21st Century Learning, 2015, p. 5-6).

Initiative & Self-direction. Finally, I define initiative and self-direction as the ability to 1) set both short-term (tactical) and long-term (strategic) goals and success criteria; 2) utilize time and manage workload efficiently; 3) work independently, monitoring, defining, prioritizing, and completing tasks without direct oversight; and 4) engage in self-directed learning, explore and expand one's own learning and opportunities to gain expertise and reflecting critically on past experiences in order to inform future progress (Partnership for 21st Century Learning, 2015).

Other Disciplinary and Meta-disciplinary Skills. In places, in my analysis, I also identified aspects of disciplinary thinking in science, mathematics, engineering, and the arts. However, as these are both more familiar and are not the central focus of this analysis, I will not go into detail here on how I've defined each. In a number of places I also identified students engaging in the learning of another category of meta-disciplinary skills, spatial skills. However, as these skills are the focus of my activity-centered analysis in Chapter 4, I again, will refrain from providing lengthy definitions of those skills here.

Student Cases

In the pages that follow, I present four student cases detailing students' interests and their consequent learning trajectories. Drawing on social (e.g., CHAT) and distributed (e.g., distributed cognition) accounts of learning, I define a "case" as either one student or a group of students following a particular interest pathway and include, in my description and analysis of each case, not just the focal student or students but the people and objects in their social and material context that facilitated their learning.

The cases presented here were selected from the broader data corpus of focal participants, because they are both representative of that corpus and nicely illustrate the different categories of interest pathways and types of learning I identified within that corpus. I will present a brief summary of each case and then present my data and analyses on learning and interest development for that case. Following the presentation of these student cases, I will address, in more detail, issues of representativeness, demonstrating how these cases fit into the larger picture of the data corpus. I will also summarize what we can learn from these cases, regarding the relation between interest development and learning in FUSE, and how lessons learned in FUSE may be applicable to designing for, understanding, and assessing learning in other makerspaces.

These cases will demonstrate four key functions that interest served for students in FUSE. First is that interest distinguished FUSE activities as more engaging than regular school. Second is that interest prompted students to work through frustration to achieve goals. Third is that interest and engagement in FUSE activities helped shape career interests and identity development, and fourth is that interest motivated learners to find ways to pursue interests and learning across contextual boundaries.

Case 1: Sampling. The first case is one of a fifth grade girl, who I'll refer to as Amadia. Amadia's case is primarily one of sampling, trying different challenges but only occasionally completing a level and rarely completing more than one level. Throughout the course of the year, Amadia sampled a number of challenges, including *Laser Defender*, *3D You*, *Dream Home*, *Ringtones*, *Jewelry Designer*, *Keychain Customizer*, *Selfie Sticker*, and *MiniMe Animation*. Of all the challenges she sampled, she only completed one level of *Laser Defender*, one level of *Keychain Customizer*, one level of *Dream Home* and two levels of *3D You*. Of these, three were formally completed, only because she worked on them with her friend Reagan, who took a more completion-oriented approach to FUSE. However, despite not formally completing many challenge levels, Amadia appeared to learn a great deal during FUSE, as the analyses in the pages that follow will show.

Although Amadia occasionally collaborated with other students on challenges, particularly with her friend Reagan, she also frequently worked independently, making hers an individual, rather than a stable, collaborative case. Finally, although Amadia did not express particularly strong interest in any one FUSE challenge, early in the year, while browsing through the gallery of challenges on the FUSE website, she expressed excitement about a number of FUSE challenges, all of which she eventually sampled. For example, she shared her enthusiasm for *Laser Defender*, saying "I want to do something awesome. Ooh! *Laser Defender*! That would be awesome. Hey maybe I'll do the *Laser Defender*." Then, looking at the *Dream Home* challenge and playing the video trailer for it, she said, "Ooh the *Dream Home* looks awesome!...It's like Minecraft. I'm going to make this house awesome." Then, at the end of the year, she expressed general interest in FUSE, and particularly in the choice-based structure of FUSE, saying "They give us a lot of different challenges and things to do…" and then went on to give yet another example of a specific challenge she found interesting, saying "…like that's Minime. It's fun, because you can put the little character in different = in different poses to make him look weird." This general interest in FUSE was particularly notable when contrasted with her lack of interest in other aspects of school, as reported by both her and her teacher. Because of her particular pattern of engagement in FUSE, Amadia primarily demonstrated learning through iteration within challenge levels and by applying learning from one challenge sequence to another.

Demonstrating Learning at Different Levels: Iteration within Challenge Levels. One place where Amadia learned important meta-disciplinary skills through iteration within challenge levels was in her work on the *Laser Defender* challenge. For example, one day, toward the beginning of the school year (early October), she went to get the kit of materials for *Laser Defender*. At this point, she had already worked on *Laser Defender* alone at least twice. However, because there was more than one *Laser Defender* kit in Amadia's FUSE studio, the kit she got on this day was different than the kit she had gotten in previous classes. Amadia quickly realized that the laser in this kit was different from the laser in the other kit. While the old laser would stay on by itself, once the "on" button was clicked, the new laser had a faulty button, which had to be held in continuously, in order for the laser to stay on. This meant that the strategy Amadia had been using previously for laser defender — placing the laser on a table and then leaving it to go put up a mirror where the beam landed — wouldn't work.

To solve this problem, she recruited her friend Reagan to help her, asking her to hold the laser while she put up the mirrors. In making this move, Amadia used adaptive problem-solving skills, by coming up with a novel solution to a problem presented by the challenge, and collaboration skills, by recruiting another student for help.   In fact, Amadia discovered that the team approach to the Laser Defender challenge worked so well enough that in every subsequent class when she worked on *Laser Defender*, she again recruited Reagan to do it with her. This shift suggests that Amadia learned the benefits of collaboration.

In her work on the *Dream Home* challenge, Amadia used and learned practices related to creativity and spatial thinking. Rather than closely following the directions for the *Dream Home* challenge, when Amadia began the challenge, she began by exploring the different tools in Sketchup (the CAD program used for *Dream Home*). She drew lines and extruded shapes, seemingly haphazardly, in Sketchup, to create a structure. The haphazardness of her structure was compounded by the fact that she was often looking at her structure from one two-dimensional perspective and not realizing that some of the lines she was drawing were actually going backward or forward diagonally in three-dimensional space. However, rather than get frustrated that the structure wasn't turning out the way she wanted, she noticed, and commented, that the emergent structure looked like a spaceship. So then, having, at this point, gained a bit of familiarity with the tools in Sketchup, she started adding to it, making planful decisions about what to add to make it look more like a spaceship.

One such decision was to add round windows. However, when Amadia tried to add these windows, she ran into another spatial reasoning problem. Looking at the spaceship from one view, it appeared that she was drawing windows directly on the ship. However, when she later rotated her model, she realized that the windows were not on the ship, but were floating in midair in front of it. Determined, at this point, to get the windows on or at least connected to the spaceship, Amadia had the idea to turn them into cylinders that extruded from the spaceship like tubes. Using the, now familiar, "push/pull" tool in Sketchup, she extruded the circles into cylinders and connected the to her spaceship (see Figure 3.1). This move showed both her creativity and her growing understanding of the three-dimensional nature of Sketchup.

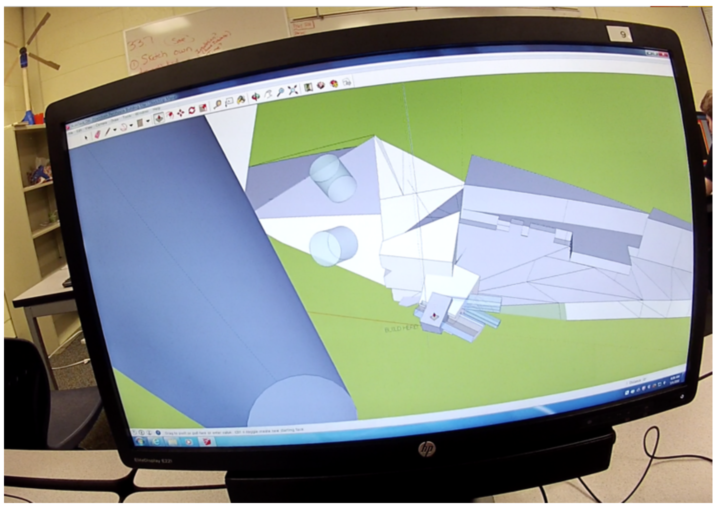


Figure 3.1. Amadia's dream home spaceship with the added cylindrical windows.

Demonstrating Learning at Different Levels: Applying Learning from One Challenge Sequence to Another. Another way in which Amadia demonstrated learning was by applying things learned from one challenge sequence to another. For example, in the spring, we saw Amadia use other students as resources in the same way across two different challenges. First, in doing Level One of Keychain Customizer, Amadia recruited help from her friend Reagan. Reagan explained to her that the goal of Level One was to make a letter keychain. Reagan then showed her how to make a letter shape in Tinkercad, scale it, and add a key ring. In this initial teaching phase, Reagan did the work for Amadia, while Amadia watched and gave input only into what letter she wanted (A for Amadia) and what color she wanted it to be. However, the following week, Amadia started over from scratch and replicated the steps Reagan had shown her in order to make the keychain. She then went to Reagan for help with the next step in the process, saving the file on an SD card and printing it on the 3D printer. In other words, she used Reagan as a just-in-time help resource (Stevens, Satwicz, & McCarthy, 2008), similar to how the directions and videos on the FUSE website are designed to be used.

Later, Amadia used other students as resources in a similar way, as she worked of Level One of the *MiniMe Animation* challenge. Here, she recruited help from Evan (and later Johnny), because they had been working on *MiniMe Animation*, whereas Reagan had not. The transcript in Table 3.1 shows how Amadia used Evan and Johnny as just-in-time help resources, as she completed Level One of *MiniMe Animation,* in the same way she'd use Reagan during Keychain Customizer.

Table 3.1
Amadia Uses Evan as a Just-in-time Help Resource During the MiniMe Animation Challenge

Line	**Person**	**Talk**	**Actions**
1	Amadia:	Wait, Evan, what's the name of that software that that's on?	
2	Evan:	Oh[1]	[1]*Evan comes over.*
3	Amadia:	Cuz I didn't save it.	
4	Evan:	[1]Boom! Let's go to challenges. Oh they're going. Just click this.[2]	[1]*Evan takes Amadia's mouse.* [2]*Evan clicks link to open file and application for MiniMe from FUSE challenge page, already open.*
5	Amadia:	Oh seriously? That's it?	
6	Evan:	Play, then open.	
7	Amadia:	Seriously? That's it? That's it?	
8	Evan:	Wait, and then hold on.[1] Click. Do you want to pose him now?	[1]Evan puts hand on Amadia's mouse again and clicks on character.
9	Amadia:	Yeah, pose him. Wait first I want to change his color.	
10	Evan:	Ok.	

11	Amadia:	Then when I'm done, come back and help me	

In this interaction, we saw Amadia ask Evan what the name of the software for *MiniMe* was (line 1). Instead of telling her, he showed her how to open it from the FUSE page (line 4). However, when Evan offered to show her something else (how to pose the character, line 8), Amadia stopped him, saying that she wanted to change the character's color first (line 9). She then told him to come back when she was done to help her (line 11), indicating that she was using him as a just-in-time help resource.

After Amadia sent Evan away, she changed the character's shirt and skin color. Then she turned to Evan to share what she had done and ask for additional help. Evan tried to help her put the character in "pose mode" so that she could move it, but it didn't work. Instead, he accidentally turned the character into a wireframe. Evan then told Amadia that he'd forgotten how to do it and that she should ask Johnny for help instead. In the meantime, however, neither he nor Amadia could figure out how to get the character out of wire frame mode. So, after Evan left, Amadia opened a new file and started over. She replicated the process Evan had just shown her, of opening the file from the FUSE website and changing the character's color, demonstrating that she had learned how to do this from watching him. When she finished changing the character's colors, she recruited Johnny's help (See Table 3.2).

Table 3.2
Amadia Uses Johnny as a Just-in-time Help Resource During the MiniMe Animation Challenge

Line	**Person**	**Talk**	**Actions**
1	Amadia:	Could somebody help me?	
2	Amadia:	Johnny! Johnny! Johnny! Help!	
3	Johnny:		*Johnny comes over.*
4	Amadia:	Help, it's not working.[1]	[1]*Amadia points to screen.*

5	Johnny:	You want to move him?	
6	Amadia:	Duh.	
7	Johnny:	[1]For next time, all you have to do is that. You have to go and click here so that everything becomes green. Then make sure you're on the world one. Then over here where it says object, you click that, and then up on top it'll say pose mode. You select your joint you want to move. Um G is to move it.[2]	[1]*Johnny grabs Amadia's mouse and adjusts settings to put character into "pose mode."* [2]Johnny grabs character with mouse, pressing G and moves character.
8	Amadia:	Ok, ok, ok. Don't do that!	
9	Johnny:	Then R is to	
10	Amadia:	Ok, don't do that! Don't do that! Last time that happened, it got all twisted and I couldn't fix it!	
11	Johnny:		*Johnny smiles and laughs.*
12	Amadia:	Put it back!	
13	Johnny:	You can just do control Z.[1]	[1]*Johnny hits control Z, returning character to normal pose.*
14	Amadia:	Control Z	
15	Johnny:	Control Z is redo.	
16	Amadia:	Oh sweet.	
17	Johnny:		*Johnny leaves.*

In this interaction, we again saw Amadia recruiting another student (Johnny) for help (lines 1 and 2), but only asking him to help her with one specific thing (putting the character in pose mode, lines 4-6). Once Johnny had shown her how to do that, she stopped him as she had stopped Evan (lines 8, 10, and 12).

After Johnny left, Amadia started moving her character. She moved it into a position, but then, in an attempt to undo the movement, tried hitting control Z, like Johnny had shown her. However, it didn't work, because she was hitting the keys serially rather than simultaneously. After trying multiple times, she gave up and continued moving the character. Then she clicked something on the keyboard by accident and the character became a wireframe outline again. The following excerpt shows Amadia's response and her solution to the problem.

Table 3.3
Amadia Uses What She Learned from Johnny and Evan to Troubleshoot a Problem in the MiniMe Animation Challenge

Line	Person	Talk	Actions
1	Amadia:	What happened?	
2	Amadia:	[1]Go back! Go back! Go back! Go back![2]	*[1]Amadia tries hitting control Z (serially) again multiple times. [2]Nothing happens. So Amadia tries clicking some other things on the screen. Still, nothing happens.*
3	Amadia:	Ugh! Um, Travis, look.[1]	*[1]Amadia turns to Travis, who is sitting next to her.*
4	Travis:	Oh my god!	
5	Amadia:	[1]Ugh! I need someone to fix it![2]	*[1]Amadia turns and looks around. [2]No one responds. Johnny is at the front of the room helping Evan with MiniMe.*
6	Amadia:	I'll start over.[1]	*[1]Amadia opens a new file, and changes character's color like before.*
7	Amadia:	[1]I can't find pose mode.[2]	*[1]Amadia opens a dropdown menu and scrolls through it with her mouse. [2]Amadia clicks on a menu option. Now her character is in a green wireframe again, but she still cannot move it.*
8	Mr. Williams:	Ladies and gentlemen, it is time, if you are working with supplies to please put them away.	
9	Amadia:	Seriously?!	
10	Mr. Williams:	If you are working on a computer start signing off. Sign out of FUSE.	

After Mr. B's instruction to clean up, Amadia continued trying to get her character to move, until she finally got it to work. Then she called Evan over to look at her character as she moved it. By now most of class was cleaning up or lined up, but Amadia continued working. Reagan came over, and Amadia asked her how to save her file, but Reagan didn't answer. So Amadia found "save" in the drop down menu by herself and clicked it.

In this final excerpt, we saw Amadia run into a problem (her character turning into a wireframe outline), and then we saw her try multiple solutions to that problem. First, she tried the solution Johnny had shown her earlier (control Z, line 19). When that didn't work, she returned to a strategy that had proven useful in the past, asking another student for help (lines 20 and 22). However, no one responded. So then, she tried another strategy, which had worked in the past, starting over with a new file (line 23). This final strategy was effective, but only because, once again, Amadia demonstrated having learned from what her classmates had shown her. Although it took her a couple of tries this time, she was eventually able to replicate all the steps shown to her by her classmates to get her character to do what she wanted.

By organizing other students as resources in similar ways across these two different challenges, Amadia demonstrated at least four meta-disciplinary skills. First, she demonstrated initiative and self-direction, showing an ability to direct and organize resources for her own learning. Second, she demonstrated collaboration skills, by learning to successfully elicit help from her classmates and then using this strategy across multiple challenges. Third, by drawing on other students as help resources, Amadia learned technology literacy skills related to each of the challenges — learning which she demonstrated by being able to replicate and build upon steps shown to her by the other students. Finally, Amadia demonstrated learning adaptive problem-solving skills by trying different approaches to solving problems she encountered in the challenges (asking another student, tinkering with different tools in the software, and when all else failed, going back to the beginning and starting from scratch with a model that she knew would work).

Interest and Identity Development. The transcripts and analysis presented on Amadia demonstrate her interest and engagement in FUSE. Not only was she actively engaged in trying to do challenges and solve problems within the challenges, but in line 9 of the last excerpt, she actually expressed disappointment that it was time to clean up (i.e., "Seriously?!"). As described in the overview of her case, Amadia also expressed explicit interest in particular challenges (e.g., "I want to do something awesome. Ooh! *Laser Defender*! That would be awesome. Hey maybe I'll do the *Laser Defender*.") and about the choice-based nature of FUSE ("They give us a lot of different challenges and things to do"). The transcript shown in Table 3.4, from Amadia's end-of-year interview demonstrates how this interest in FUSE contrasted with her lack of interest in other parts of school.

Table 3.4
Amadia Talks About Differences between FUSE and Math and Science Class in Her End-of-year Interview

Line	Person	Talk	Actions
1	Researcher:	How is FUSE different from math and science class?	
2	Amadia:	Actually, it kind of isn't. But, most of us get bored in those classes, but they made this. = It's kind of like it, so they just made FUSE so that we can be interested in math and science and us not knowing we're interested in it.	
3	Researcher:	Why are Math and Science boring?	
4	Amadia:	Because the way that they're teaching it to us. Everybody's always bored. Not to lie, but I actually think that I once did	

		see someone sleeping.	
5	Researcher:	How is FUSE not boring?	
6	Amadia:	They give us a lot of different challenges and things to do, like that's Minime.[1] It's fun, because you can put the little character in different = in different poses to make him look weird.	[1]*Amadia points to computer screen.*

In this excerpt, Amadia explicitly contrasted her feelings about math and science class (line 2, “most of us get bored in those classes”) with her feelings about FUSE (line 2, “It's kind of like it, so they just made FUSE so that we can be interested in math and science and us not knowing we're interested in it.”) When asked (line 5) how FUSE is not boring, she responded (line 6) by citing the number of challenges (“They give us a lot of different challenges and things to do”), before going on to talk about a specific challenge, she had recently started and enjoyed (*MiniMe Animation*).

In addition to this explicit statement about interest from Amadia, I also received confirmation from Amadia’s teacher that she was neither interested in nor performing as expected during her other school classes. For example, in early March, Amadia’s teacher approached me and explained that he was planning to pull Amadia aside during FUSE time in the coming weeks to have her make up homework that she was missing. His explanation of his plan to pull her out of FUSE is shown in Table 3.5.

Table 3.5
Mr. Williams Explains that He’s Pulling Amadia out of FUSE to Motivate Her to Do Makeup Work for Other Classes

Line	**Person**	**Talk**
1	Mr. Williams:	The data that you have from Amadia?
2	Researcher:	Yeah?
3	Mr. Williams:	Um, I have to um maybe not have her do FUSE for several weeks.

4	Researcher:	Okay.
5	Mr. Williams:	Is that an issue?
6	Researcher:	Oh, oh, um, no?
7	Mr. Williams:	She has not done a stitch of homework all second trimester.
8	Researcher:	Oh I see. Okay.
9	Mr. Williams:	She's failed everything.
10	Researcher:	Okay.
11	Mr. Williams:	So some of the other teachers what they do, which I was trying not to do
12	Researcher:	Sure
13	Mr. Williams:	is that she sits there.
14	Researcher:	Sure
15	Mr. Williams:	and does her work.
16	Researcher:	Sure, yeah.
17	Mr. Williams:	I send her to, we have, at lunch time, we have this thing called ZAP,
18	Researcher:	Mmmhmm
19	Mr. Williams:	"Zeros Are prevented."
20	Researcher:	Mmmhmm
21	Mr. Williams:	It's like a homework club.
22	Researcher:	Sure. Sure.
23	Mr. Williams:	She goes every day
24	Researcher:	Yeah, oh.
25	Mr. Williams:	and she never turns anything in.
26	Researcher:	Yeah.
27	Mr. Williams:	And her parents
28	Researcher:	Sure, sure
29	Mr. Williams:	don't seem to care either. So I told her, I said I am not going to let her fail this third trimester.
30	Researcher:	Mmmhmm, mmmhmm
31	Mr. Williams:	She doesn't seem to care, so she does kind of enjoys this. So I'm like, well I guess I could add to that now.
32	Researcher:	Well, I mean, that's obviously your call and that situation is more important than our, you know.
33	Mr. Williams:	I was trying hard not to, because I don't want to disrupt anything or anything, but she's not doing anything! She hasn't turned in a stitch of homework in like three months. So um, I might do that.
34	Researcher:	Okay
35	Mr. Williams:	So hopefully she'll kind of get the clue.
36	Researcher:	Mmmhmm.
37	Mr. Williams:	I'm gonna kinda, I'm gonna warn her and just say, if you don't
38	Researcher:	Sure.
39	Mr. Williams:	Because she doesn't do any homework either
40	Researcher:	Yeah.

41	Mr. Williams:	And it's stuff that even in class she doesn't finish. So I send it home and never see it again. So, um, I'm going to tell her that if she doesn't do that, she's going to sit out of FUSE.
42	Researcher:	Okay.
43	Mr. Williams:	Until she catches up.
44	Researcher:	Okay.
45	Mr. Williams:	Because we just started the third trimester, and there's things she hasn't turned in. So I'm like, and she's a fifth grader so I'd have her again next year. So I'm like no, I'm going to break this one.

In the weeks that followed, Amadia was pulled aside for two class periods to do makeup work during FUSE time. As I watched her sitting at a side table, completing worksheets for other subjects, the contrast between her engagement with FUSE and her engagement with other school subjects became very apparent, through changes to her posture and facial expressions. It also appeared to me that she wasn't getting much work done. Finally, Amadia's teacher decided that pulling Amadia aside during FUSE to provide time and motivation to make up her missing work for other subjects wasn't working. So he abandoned this strategy and allowed Amadia to rejoin her classmates in doing FUSE activities. The transcript in Table 3.6 shows what he said when I asked him why.

Table 3.6
Mr. Williams Explains Why Amadia Is Back Doing FUSE Again

Line	**Person**	**Talk**	**Actions**
1	Researcher:	Um, so I was actually = I was going to ask you, so I saw that she's back you know doing yeah FUSE time. How's that, how's that going?	
2	Mr. Williams:	Well, I've given up.[1]	[1]*Mr. Williams laughs.*
3	Researcher:	Ok, oh ok.	
4	Mr. Williams:	Yeah like right now I've said uncle. I can't keep track.	
5	Researcher:	Yeah ok.	
6	Mr. Williams:	She's got so many missing assignments.	
7	Researcher:	Yeah.	
8	Mr. Williams:	She's failing.	

9	Researcher:	Yeah, and	
10	Mr. Williams:	Her parents know.	
11	Researcher:	And it didn't help to have her like doing it in here?	
12	Mr. Williams:	[1]I tell her every time. She decides not to. So I'm like, I can't make her. And when she sits there, she doesn't do much anyway.	[1]*Mr. Williams shakes his head.*
13	Researcher:	Oh, ok. ok, alright.	

What we see in the contrast between Amadia's apparent lack of school achievement and engagement and her success and engagement in FUSE, highlights a problem in our education system in regards to STEM education. Amadia showed, in her engagement in FUSE and her comments during the end-of-year interview, that she had the potential to be interested in STEM or STEAM activities and learning. However, the way in which these subjects were presented in other parts of school (e.g., math and science class) was not interesting to her. Amadia's interest pathway through FUSE helps us to understand why there may have been such a stark contrast between her interest and engagement in school and her interest and engagement in FUSE. For example, her initial enthusiasm for multiple challenges in the challenge gallery and her later statement of her interest in FUSE being connected to the many choices available there, indicates that choice or agency were important catalysts for interest and engagement for Amadia. We saw further evidence for this in the way she engaged with challenges, tinkering with tools and setting her own informal goals, rather than strictly adhering to challenge guidelines. Finally, in addition to sparking interest, we saw evidence that the choice-based nature of FUSE facilitated Amadia's STEAM learning by allowing her to organize her learning in a way that worked for her, drawing on other students as just-in-time help resources. As a result, it seems that in FUSE, not only did Amadia more often have opportunities than in regular school to engage with STEAM content in ways that were interesting to her, but consequently, she was also more likely to see STEAM learning as a positive experience and see the topics and activities as interesting and worthy of future pursuit.

Case 2: Completing. The next case is a group of fifth grade girls, Johanna, Victoria, and Andrea, who spent the whole year working together on a series of challenges. They began by doing the *Dream Home* challenge, each creating their own model home using the CAD program, Sketchup, but sitting together, helping each other, and showing each other things they'd made or discovered. After finishing all three levels of *Dream Home*, they worked through all the levels of a second, related challenge, *Dream Home 2: Gut Rehab*. Then, finally, they worked through a graphic design and vinyl cutting challenge called *Selfie Sticker*.

I've grouped these girls together as a case, because they worked on all of the same challenges simultaneously, sat next to each other, and helped and consulted with each other about each challenge as they were doing them. However, this is not to say that there weren't differences between the three girls in interests, orientation towards the challenges, and things learned during the challenges, and I will discuss those differences as I describe their case below. It is also not to say that they didn't also collaborate with other students in the class. In fact, when they were working on *Dream Home*, they frequently asked questions of and offered help to two fifth-grade boys, Travis and Evan, who were also working on *Dream Home*. However, whereas the girls eventually completed the first *Dream Home* challenge sequence and went on to do *Dream Home 2: Gut Rehab*, and *Selfie Sticker*, Thomas continued working only on Dream Home for the duration of the school year, while Evan went on to do Print my Ride with another student named Juan. Then later, when the girls began doing *Selfie Sticker*, they did so with the assistance and collaboration of a group of sixth grade girls, Karen, Beatrice, and Marjorie. However, like the boys, although Karen, Beatrice, and Marjorie's interest pathways intersected temporarily with Johanna, Victoria, and Andrea's, these sixth-grade girls worked on both *Selfie Sticker* and other challenges without the fifth-grade girls, both before and after they did *Selfie Sticker* together.

These girls' engagement in FUSE is primarily an example of completing — trying more than one challenge, but going through each in a more systematic fashion, completing many or all levels before moving on to the next challenge. Because of the nature of the girls' challenge engagement, I saw them engaging in learning on multiple levels, ranging from the proximal to the more distal. These included: (1) iteration within challenge levels in order to achieve a goal; (2) using knowledge, skills, or practices from one level of a challenge on the next level; (3) using knowledge, skills, or practices from one challenge on another subsequent challenge; and (4) teaching another student something with which the learner had previously struggled.

Demonstrating Learning at Different Levels: Iteration within Challenge Levels. The girls demonstrated a great deal of learning simply through iteration within individual challenge levels. For example, one day, Johanna was trying to add a wing onto her Dream Home, but because of the direction she was looking at the house from in the 3D software, she made the square base on a diagonal, rather than flat on the ground (See Figure 3.2).

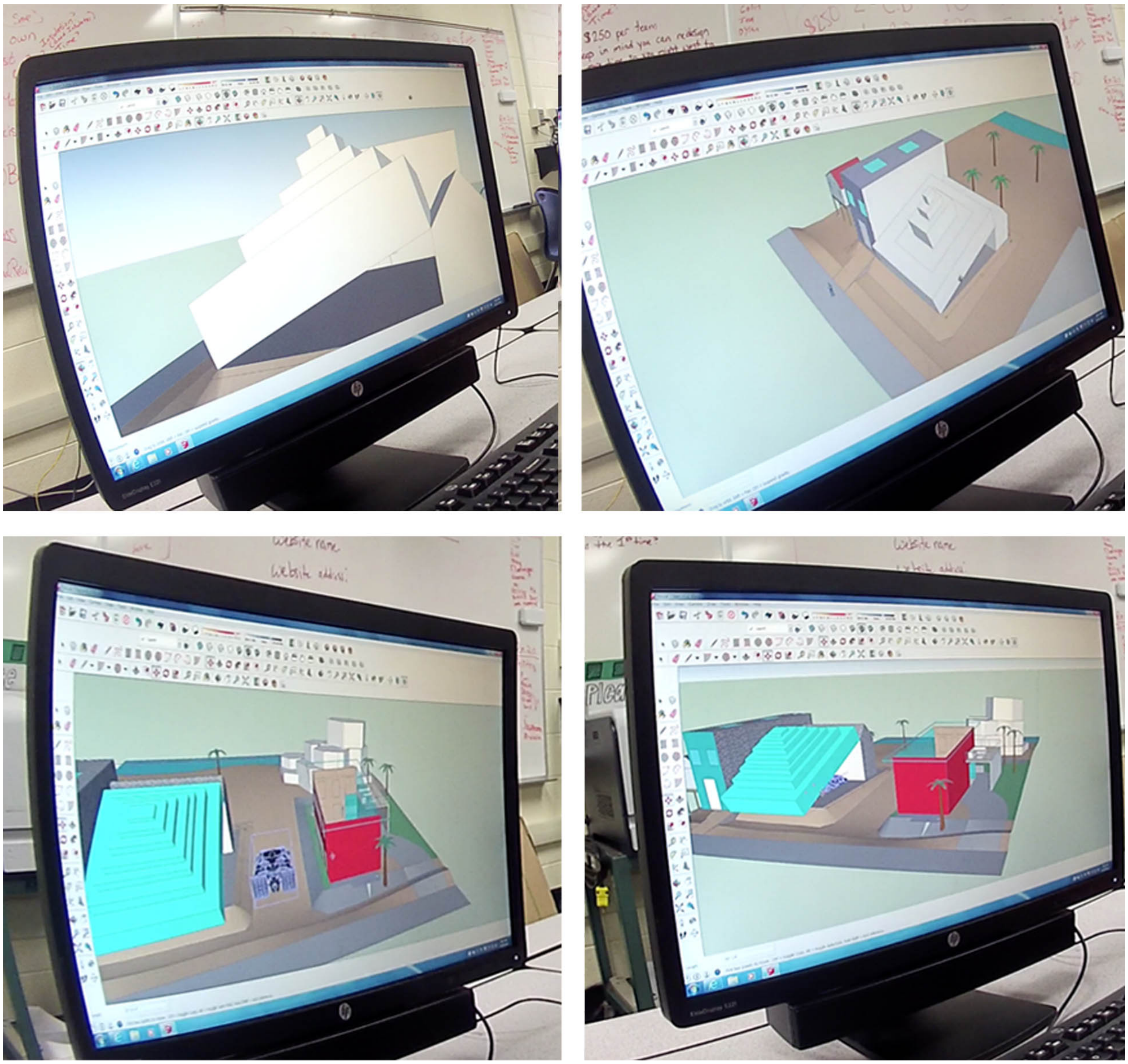


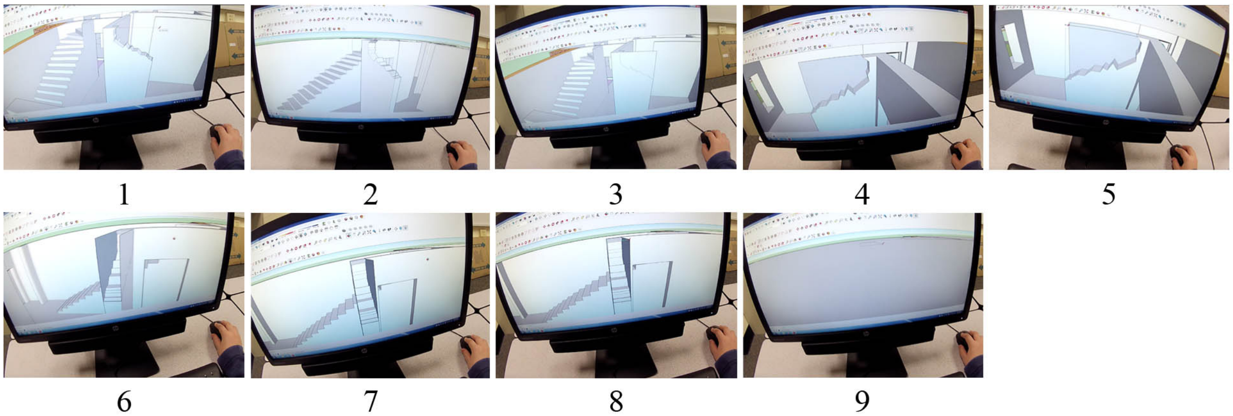
Figure 3.2. Johanna's dream home garage evolved from an accident (top left and right) to a planned design element (bottom left and right).

At first, she expressed confusion and frustration, but then she turned it into a unique stacked pyramid structure. She liked this structure enough that later, after realizing that she had forgotten to save her model before closing Sketchup, she decided to recreate it. To do so, she had to figure out how she had created it to begin with, a task that required technical skills and spatial thinking. While rebuilding the structure, she also made improvements, making the intervals between steps on the pyramid more regular and painting the structure light blue, demonstrating creativity and innovation. Finally, when she was finished, she had the idea to turn it into a garage, showing both creativity and a principle from the arts, best captured by Bob Ross as, "There are no mistakes, only happy accidents."

This example also alludes to another skill demonstrated by these girls, initiative and self-direction. At multiple points, they encountered problems, ranging from spatial problems like Johanna's accidental diagonal base, to technical problems with hardware or software, to problems figuring out how to use tools to achieve desired goals. When faced with such challenges, rather than give up or get overwhelmed with frustration, they persevered, as Johanna did in the example just described, trying different approaches, seeking help from each other or resources from the FUSE website.

A second example, which demonstrates both this initiative and self-direction and also adaptive problem-solving, comes from an interaction between Johanna and Victoria, soon after they'd begun working on *Dream Home 2: Gut Rehab*. Unlike the original *Dream Home* challenge, where the goal is to build a CAD model of a home from scratch, the goal in *Dream Home 2: Gut Rehab* is to repair and furnish an existing model home. For example, one of the specific tasks required in *Dream Home 2* is to repair broken walls (walls with jagged holes in them). In theory, there appear to be two ways to do this in Sketchup: (1) drawing the missing edges of each surface of the wall; or (2) extruding a two-dimensional surface from the existing three-dimensional wall to fill in the hole (See Figure 3.3).

Strategy 1:
Johanna's process of drawing the missing edges of each surface of the wall



Strategy 2:
Victoria's process of extruding a two-dimensional surface from the existing three-dimensional wall to fill in the hole

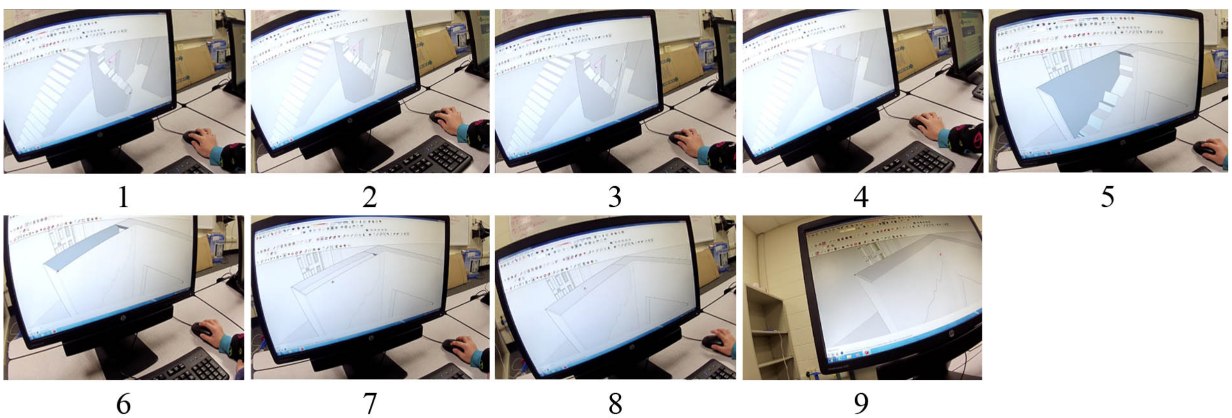


Figure 3.3. Johanna and Victoria's differing strategies for repairing damaged walls in their dream homes for the *Dream Home 2: Gut Rehab* challenge.

Johanna took one approach to this problem, drawing the missing edges of each surface of the wall (e.g., front, back, right end, left end, top, bottom) involved in the break, so that each surface was a complete rectangle again and then erasing the crack lines on each surface (See Figure 3.3). One problem with this approach is that it is difficult to make sure that the surfaces connect at the corners, particularly if one is (as Johanna was) drawing just the edges of the surface using the line tool, rather than redrawing the whole surface using the rectangle tool.

Another problem is that even if one does manage to draw lines that connect in the form of perfect rectangles and then later connect to other surfaces to form a perfect rectangular prism, Sketchup does not seem to recognize the resulting object as a three-dimensional rectangular prism, and therefore, doesn't fill in the wall the way it's supposed to. Johanna ran into both of these problems while trying to fill in the cracks in her walls. The transcript in Table 3.7 shows how the second problem led to her whole house being filled in as one solid object, rather than just the wall filling in (line 4).

Table 3.7
Johanna Encounters Problems While Trying to Repair the Walls of Her House for the Dream Home 2: Gut Rehab Challenge

Line	Person	Talk	Actions
1	Researcher:	How's it going?	
2	Johanna:	Hard	
3	Researcher:	Oh.[1]	[1]*Researcher chuckles.*
4	Johanna:	I can't finish this wall.[1] Oh wait! I think I got it. Because when I try to like fill in the wall, the whole house gets filled in like it just, the whole house is just a block.	[1]*Johanna rotates the view of her house and sees that the inside of the wall looks different now that she has deleted lines outside.*
5	Researcher:	Ohh	
6	Johanna:	[1]Let's try, wait, little line. Ok now there's lines in there. Let me try to erase those and see what happens, then fill it in.[2] See the whole house gets filled in![3]	[1]*Johanna erases lines from other wall face.* [2]*Johanna erases lines. Then she tries to connect wall faces with a line again, and the roof fills in again.* [3]*Johanna throws up her hands and leans back in her chair.*

The transcript in Table 3.7 also shows Johanna's frustration (line 6), when she says "See the whole house gets filled in!" and then throws up her hands and leans back in her chair. As this was happening, Victoria also noticed Johanna's frustration and came over to help (See Table 3.8 and Figure 3.3).

Table 3.8

Victoria Helps Johanna Repair the Walls of Her House by Showing Her a Different Strategy

Line	Person	Talk	Actions
1	Johanna:	I just did that!	
2	Victoria:	You're not supposed to. Here,[1] first, wait, let me get rid of that thing.	[1]*Victoria takes Johanna's mouse.*
3	Johanna:	You just ruined my whole wall again.	
4	Victoria:	Well, it was because it wouldn't work out in the end if you did that.	
5	Johanna:	Then how'd you do it?	
6	Victoria:	You start with this one[1]	[1]*Victoria extrudes one segment of the jagged edge of the wall upward until it is the same height as the rest of the wall. One side of the wall, in addition to the end, immediately fills in.*
7	Johanna:	Is it straight?	
8	Victoria:	Make sure it's in line.	
9	Johanna:	I don't think it's in line.	
10	Victoria:	So then bring it down to where it's in line.[1]	[1]*Victoria adjusts wall segment.*
11	Johanna:	Oh, ok, can I try?[1]	[1]*Johanna reaches for the mouse.*
12	Victoria:	[1]Here to here.[2]	[1]*Victoria, hand still on mouse, rotates view so the girls see wall from other side.* [2]*Victoria draws a line connecting other side of wall. Other side of wall fills in, but top middle is still open.*
13	Johanna:	Ok, now give me it!	
14	Victoria:		*Victoria extrudes one side of wall over to meet the other side using the "push/pull" tool. The whole wall is now filled in.*
15	Johanna:	O::h	

As is shown in the transcript in Table 3.8, Victoria took over Johanna's mouse and undid what Johanna had just done with the wall, using the back button (line 2). At first, Johanna did not seem pleased with this (see line 3, "You just ruined my whole wall again."), but then after

Victoria explained why she did it (line 4), Johanna invited further assistance from Victoria, by asking “Then how'd you do it?” (line 5). Victoria then showed Johanna a different approach that she had been using to fill in the wall (line 6). Victoria’s approach involved using the extrude or “push/pull” tool in Sketchup. So instead of filling in individual surfaces and connecting them, she found one portion of the wall that she could recreate as an intact rectangular prism (line 6). Then, after connecting that segment to the rest of the wall on both sides (lines 6 and 12) she extruded one side of the wall over to meet the other. When Victoria concludes her demonstration, Johanna says, “O::h”, seeming to acknowledge that she now understands Victoria’s solution.

The last step in the wall repair process was to delete any other lines or surfaces that were in the way or that remained after the wall had been filled in. Victoria left this part for Johanna. The transcript in Table 3.9 shows how Johanna went about doing this (lines 8-12), and also how she explained Victoria’s solution to me (lines 13-15).

Table 3.9

Johanna Fixes the Wall and Explains to Me How Victoria Had Shown Her to Fix It

Line	**Person**	**Talk**	**Actions**
1	Researcher:	Did you get it?	
2	Johanna:	Yeah.	
3	Researcher:	Alright!	
4	Johanna:	Well she got it.	
5	Researcher:	Yeah? So how'd you do it? How'd you fill it in?	
6	Johanna:	Wait, Victoria?	
7	Victoria:	What?	
8	Johanna:	Now do I erase the lines?	
9	Victoria:	Yeah. Wait, I don't know if you erase the top line.	
10	Johanna:	Well let's just see.	
11	Victoria:	Ok.	

12	Johanna:	Yeah.[1] Yeah that's ok.	[1]*Johanna tries erasing the top line.*
13	Researcher:	So Victoria, what's the, what was the secret?	
14	Victoria:	U::m, so	
15	Johanna:	Use the pushup tool!	

In the transcript shown in Table 3.9, when I asked Johanna whether she'd figured out how to fix her wall (line 1, "Did you get it?"), she credited Victoria as being the one who had actually fixed her wall (line 4, "Well she got it.") However, later in the episode, when I asked Victoria how she had done it (line 13), Johanna answered for her (line 15), and explicitly referenced the "push/pull" tool (or "pushup" tool, as she called it). This indicated that she had identified the difference between her initial approach and Victoria's approach. Taken together, the transcripts in Tables 3.7, 3.8, and 3.9 demonstrate the girls' ability to consider and test different problem-solving approaches until finding one that worked, demonstrating both initiative and self-direction and adaptive problem-solving.

Finally, during their work on *Dream Home 2: Gut Rehab*, the girls learned ideas related to empathy and design thinking. For example, while working on *Dream Home 2: Gut Rehab*, Andrea gave me a narrated tour of her dream home. When she got to one of the rooms, she said, "See and this is grandpa's room. He needed this room, because it's close to the bathroom." In doing so, she demonstrated empathy for the needs and desires of users, a fundamental building block of design thinking. It was not uncommon for students to demonstrate this type of user-centered design thinking, while working on FUSE challenges. For example, while working on *Dream Home*, another pair of sixth grade girls in this same class decided to design rooms for their classmates, giving each student their own room and then asking that student what types of things they would like in their room.

Demonstrating Learning at Different Levels: Applying Learning from One Challenge Level to Another. Moving beyond individual challenge levels, Johanna, Victoria, and Andrea also demonstrated learning by applying things learned in one level to another level of the same challenge. For example, in Sketchup, a large portion of the learning, particularly early on, involved finding and figuring out how to use different tools. While completing Level 1 of *Dream Home*, the girls spent a good amount of time tinkering with different tools, before, after, and in the midst of doing what was actually required to complete the level. These same tools were then used in later levels to complete related tasks.

There was also an initial learning curve surrounding saving files from Sketchup and then accessing them in the next class to continue working. In this particular school, student profiles and files are saved to a remote server, rather than on local computers. This had the advantage of allowing students to access their files from any computer in the classroom. However, it also had the disadvantage that students had to be intentional about where they were saving files (to their individual folder, not the local desktop or the downloads folder) in order to be able to access them again later. Like all of their classmates, Johanna, Victoria, and Andrea had to learn how to do this. They did so through a combination of trial and error (i.e., accidentally saving a file to the wrong place or not saving it at all and realizing they'd lost their work) and helping each other (i.e. showing each other what they'd learned about how and where to save files). Once they had learned these skills, they were able to apply them to later challenge levels. In doing so, they demonstrated learning technical or technology literacy skills.

Demonstrating Learning at Different Levels: Applying Learning from One Challenge Sequence to Another. Some of these technical skills (such as saving files properly) were also applied in subsequent challenges. For example, after learning how to save files from Sketchup to their folders on the computer, while doing *Dream Home*, the girls were also able to save files from Inkscape to their folders, while working on *Selfie Sticker*.

Another set of skills, or really practices, that the girls learned while doing *Dream Home* and *Dream Home 2: Gut Rehab* and then later applied while doing *Selfie Sticker*, involved communication and collaboration. There were three ways in which the girls used communication and collaboration practices learned while doing *Dream Home* and *Dream Home 2: Gut Rehab* later on during *Selfie Sticker.* The first was maintaining their core collaborative unit, working together as a threesome, across these three challenges. Second, they drew on other students as resources in similar ways across the different challenges. For example, during Dream Home they occasionally requested or offered help to the two fifth grade boys, Travis and Evan who were also working on Dream Home. Then later during Selfie Sticker, they requested help from the sixth grade girls, Karen, Beatrice, and Marjorie. Finally, both the structure of their core collaboration and the ways in which the drew on each other and other students as resources was consistent across challenges. For example, during both Dream Home and later Selfie Sticker, although the girls sat next to each other and went through the challenge levels together, each girl sat at her own computer and made her own project. They would frequently ask each other for help and request input on design decisions. However, unlike some of the other students who worked collaboratively on FUSE challenges, each girl produced her own dream home, and her own selfie stickers (rather than all working together to create one artifact).

In structuring their own collaboration in this way across challenges, Johanna, Victoria, and Andrea also demonstrated initiative and self-direction. A second way in which initiative and self-direction were visible in the girls' work across challenge sequences was in the methodical way in which they completed level after level of each challenge sequence, until the challenge was completed. Now, it should be noted that, in a regular school classroom, this methodical completion of tasks would not seem extraordinary, because it is what would be required of students (i.e., do this assignment when the teacher assigns it, then when that is complete, do the next assignment the teacher assigns). However, in FUSE, there is no teacher standing over students' shoulders enforcing this process. Therefore, Johanna, Victoria, and Andrea's consistent, methodical completion of challenge levels in *Dream Home, Dream Home 2*, and *Selfie Sticker* is a testament to their discipline and their ability to self-direct their own learning.

This is particularly noteworthy when viewed in light of the many frustrations the girls encountered along the way. Johanna, in particular, was quite vocal about her frustration on a number of occasions when working on Dream Home and often came to me to vent that frustration and request help. However, gradually, she began to do less of this, learning to try different solutions or going to her classmates for help instead. Finally, in an end-of-year interview, Johanna said of FUSE, "This is almost a practice round, because you can't ... if you mess up, you just break it down, it's a lot of money wasted, but for this you can just click a button." Johanna's reflection on her learning process here demonstrates critical thinking and suggests that she had learned that the stakes for failure are lower in FUSE than they would be in other contexts. We might also infer that these low stakes for failure helped motivate Johanna to work through her frustration. Certainly, the fact that the girls continued working and completed all challenge levels indicates an ability to overcome frustration, learn from it, and continue on.

Demonstrating Learning at Different Levels: Teaching Others Things with Which Learners Had Previously Struggled. Finally, given that Johanna, Victoria, and Andrea engaged in ongoing collaboration throughout their year in FUSE, there were many examples of them demonstrating learning by teaching each other things with which they had previously struggled.

We saw one example of this in Victoria showing Johanna how to repair the walls of her dream home for *Dream Home 2: Gut Rehab*. A second example comes from when the girls first began working on *Dream Home* and Victoria discovered how to see the inside of a her dream home. Seeing her make this discovery, Andrea asked Victoria, “How are you doing that? How'd you get it to that view?” Victoria showed her. Then, a few moments later, when Johanna also asked Victoria how to do it, Andrea jumped in and offered to show her instead. The transcript in Table 3.10 shows this interaction.

Table 3.10
Andrea Shows Johanna How to Get inside Her House After Just Learning How to Do It, Herself

Line	**Person**	**Talk**	**Actions**
1	Johanna:	Victoria, how do you get inside?	
2	Andrea:	Got it! I got it, I got it, I got it!	
3	Johanna:	How do you? How do you do it? Can you tell me.	
4	Andrea:	Ok, so you're going to go to like the feet.	
5	Johanna:	I am at the feet.	
6	Andrea:	Uh huh.	
7	Johanna:	Mmm hmm	
8	Andrea:	And then[1]	[1]*Andrea takes Johanna’s mouse and scrolls forward.*
9	Johanna:	And just zoom in or?	
10	Andrea:		*Andrea continues scrolling forward with mouse until girls can see inside of Johanna’s house.*
11	Johanna:	Thanks.	

From the transcript in Table 3.10, we can that Johanna initially asked Victoria for help (line 1). However, when Andrea immediately replies with “Got it! I got it, I got it, I got it!” (line 2), Johanna requests help from her instead (line 3). Andrea then explains to Johanna how to see (or “get”) inside her dream home, the same problem Andrea had been struggling with just moments before. She does so by directing Johanna to “the feet” (line 4), a specific tool with an icon that looks like footprints, then taking Johanna's mouse (line 8) and scrolling forward until the girls can see the inside of Johanna's dream home (lines 8 and 10). This example shows how the girls passed knowledge from one to another to another, as needed while working through challenges. It demonstrates one way in which the girls learned technical skills related to the challenges (e.g., discovering tools, then sharing those discoveries with each other). Further, the girls' ability to use each other as learning resources in this way, and their willingness to share information with each other shows communication and collaboration skills.

Interest and Identity Development. In both their choice of challenges and their actions while completing challenges, Johanna, Victoria, and Andrea demonstrated interests in arts, design, and working together. At multiple points during the year, the girls discussed how their interests both shaped and were shaped by participation in these FUSE challenges. For example, as the transcript in Table 3.11 shows, midway through the year, Johanna explained to me that her mother wanted her to be an architect (line 4), but she wasn't sure she was interested in or capable of that (lines 2, 4, and 6).

Table 3.11
Johanna Talks about Her Mom Wanting Her to Be an Architect but Expresses Doubts about Her Abilities

Line	Person	Talk	Actions
1	Researcher:	So, Johanna, what do you want to be when you grow up?	
2	Johanna:	I don't know.	
3	Researcher:	You don't know? Oh ok[1]	[1]*Researcher laughs.*
4	Johanna:	Well my mom wants me to be an architect, but I don't want to.	
5	Researcher:	But you like *Dream Home*, right?	
6	Johanna:	Well if I can't do this, then I can't	

		be an architect.	

It should be noted that this interaction occurred while Johanna was struggling to delete and redraw walls for a room she was trying to add onto her *Dream Home*. Thus, the statement "Well if I can't do this then I can't be an architect" (line 6) may likely be specifically connected to that task, rather than to *Dream Home* as a whole.

In contrast, in Johanna's end-of-year interview, conducted after she had successfully completed all levels of both *Dream Home*, and *Dream Home 2: Gut Rehab*, Johanna told a significantly different story. In the context of explaining why she hoped she would be able to do FUSE again next year, Johanna said, "…*this kind of helped me decide that I wanted to be an architect*, after my mom said it, because it's fun to make your own things." Here, she again cited her mother's interest in her becoming an architect, but at this point, she also expressed her own interest in this career and attributed this interest to FUSE ("this kind of helped me decide that I wanted to be an architect").

Connecting her interest in challenge activity to her family and their goals for her was a common practice for Johanna. For example, as the transcript in Table 3.12 shows, when I asked the girls why they chose Selfie Sticker (line 1), Johanna brought up the fact that her parents are sign makers (lines 4 and 7).

Table 3.12
Johanna and Andrea Talk about Their Motivations for Choosing the Selfie Sticker Challenge

Line	Person	Talk	Actions
1	Researcher:	So what made you girls choose *Selfie Sticker*, as the next challenge to work on?	
2	Andrea:	'Cause my case is boring for band.	
3	Researcher:	Ohh, ok so.	
4	Johanna:	Even though my parents can do this, I	

		still did it, because they don't have time.	
5	Andrea:	This is her parents job.	
6	Johanna:	Oh really? Are your parents graphic designers?	
7	Johanna:	They're sign makers, but they do.	
8	Researcher:	They're sign makers, ok cool cool. Huh.	
9	Johanna:	They have like a giant printer like that.[1]	[1]*Johanna points to vinyl cutter used for Selfie Sticker.*
10	Researcher:	Oh really?	
11	Johanna:	I'd stick my hand in it, but I'm scared to.	

Johanna also expressed an interest in the printer her parents used at work for sign making and drew a connection between this professional grade device and the smaller version used in the FUSE classroom (line 9). However, she also implied a contrast between the professional grade printer and the one in FUSE (line 11), saying of the professional grade one "I'd stick my hand in it, but I'm scared to" but later demonstrating, through her work on the *Selfie Sticker* challenge, that she did not have the same reservations about the smaller one used in FUSE. This suggests that the FUSE experience may have provided a safe, low-stakes context for her to explore this type of technology — one that has the potential to pave a pathway to her later using the professional-grade version of this tool.

In contrast to Johanna's interest in *Selfie Sticker,* which centers around career and family, just as her interest in *Dream Home* did, Andrea expressed a more immediate, utilitarian reason for choosing to do the *Selfie Sticker* challenge (line 2, "'Cause my case is boring for band.") Here, Andrea was referencing her flute case, a plain black instrument case, which she brought to FUSE with her once a week, because she left directly from FUSE to go to her weekly music lessons. In other words, Andrea was interested in *Selfie Sticker,* because she wanted to make a sticker to put on her instrument case. The contrast between Johanna's and Andrea's expressed interests in Selfie Sticker, despite them jointly deciding to work on the challenge together, demonstrates how different interest pathways can intersect or overlap while still being unique.

A final interest that all three girls demonstrated and cultivated through their work in FUSE was an interest in collaboration. This was demonstrated by the fact that they chose to work together and continued working together throughout the entire school year. As a result of this interest, they also created opportunities both to deepen their pre-existing friendship and also to cultivate communication and collaboration skills, both with each other and with other students in the class. In contrast, in a classroom context where students are assigned to groups, where groups change between different activities, or where students are required to work individually, they likely would not have opportunities to develop communication and collaboration skills in quite the same way.

Similarly, in other STEAM learning contexts, where there is less (or no) choice between activities, the girls wouldn't have been able to pursue and cultivate STEAM interests in the same way they were able to in FUSE. For example, in other school learning contexts, Johanna might not have been given the opportunity to explore one or more potential career choices suggested by her parents (i.e., architect, sign maker). However, in FUSE she was easily able to explore proxies for these different careers in a relatively low stakes, low commitment way, to see if she liked them. This opportunity for interest exploration, paired with the feeling of competence she was able to achieve through successful completion of the FUSE activities, ultimately led to a more developed interest in a career in architecture that Johanna might not have achieved, if it weren't for her FUSE participation.

Finally, in contrast to a classroom environment where students are assigned activities, rather than given the freedom to choose them, the girls might not have been as motivated to persist in the face of frustration as they were in FUSE. Perhaps, more importantly, even if they did persist, we'd never know if they were persisting because they were required to or because they were genuinely interested in the subject matter. In contrast, in FUSE, because no one was forcing the girls to continue on and complete challenges, we can infer that it was their interest in the challenges that motivated them to persist in the face of frustration.

Case 3: Diving. My third case is a fifth grade student, who I'll call Carmen. Carmen's case is one of diving deeply into one particular challenge or activity; in Carmen's case it was 3D printing. Early in the year, Carmen expressed an interest in designing objects in a 3D CAD application, Tinkercad, and printing those objects using the 3D printer. This interest was expressed by: (1) choosing to do the Keychain Customizer challenge, which uses Tinkercad; and (2) observing and asking questions of other students and the FUSE facilitator as they designed in Tinkercad, printed their designs, or engaged in troubleshooting with the 3D printer. As the school year went on, Carmen moved from observing and questioning others to actively engaging in 3D printing, troubleshooting, and helping others learn to print. Consequently, Carmen demonstrated learning through iteration within challenge levels, and helping others with things with which she had previously struggled. Additionally, toward the end of the year, Carmen, demonstrated learning through integrating learning from FUSE with outside knowledge and interests, by making connections between what she had learned through her work with the 3D printer and her future career aspirations.

Demonstrating Learning at Different Levels: Iteration within Challenge Levels. One way in which Carmen demonstrated learning during FUSE was through iteration within challenge levels. The primary mode through which Carmen engaged in this learning was through watching others iterate and asking them questions as they did and then later doing the things she'd seen them do. For example, in mid October, Carmen spent almost an entire class period observing her FUSE facilitator helping another student, Anvi, print. She watched while the facilitator pried the previous print job off the printing platform, changed the printing filament to a different color, and set up the printer for printing. During her observation of this activity, she occasionally asked questions. Then, later, she began to offer help and answer other students' questions. In this way, her learning more closely resembled forms of learning documented in informal contexts, such as *learning by observing and pitching in* (Rogoff, 2014), than it does the learning through direct instruction that normally occurs in school. For example, while the facilitator changed the filament, Carmen read the directions that flashed on the printer screen. Then, when the new purple filament started to come out through the printing nozzle in a spiral, Anvi asked, "What is that?", and Carmen answered, "That's what makes it. That's your design? Oh it's purple! It melted the purple string?" These remarks demonstrate that, through her observations, Carmen was developing an understanding of how the 3D printer worked. Further, by engaging in this sort of learning through observation, she was showing initiative and self-direction by seeking out opportunities and resources to learn about an object of interest, the 3D printer. Finally, by choosing to learn about this object of interest, by observing others working with it and asking them questions, she was using and learning communication and collaboration skills.

Demonstrating Learning at Different Levels: Teaching Others Things with Which Learners Had Previously Struggled. As the year went on and Carmen learned more about the 3D printer, she demonstrated learning by teaching others things with which she had previously struggled. This included explaining how the printer worked to a substitute teacher and helping other students print and go through the process of troubleshooting with the 3D printer.

For example, Carmen helped Elena print by changing the printer filament to a different color and pulling up and inspecting Elena's CAD file, to make sure that it would print properly, a process she had previously observed the teacher doing. Later, when the printer malfunctioned, Elena called Carmen over to fix it. The transcript in Table 3.13 shows how Carmen diagnosed the problem.

Table 3.13
Carmen Diagnoses a Problem with the 3D Printer and Manages the Print Queue

Line	Person	Talk	Actions
1	Carmen:	Something must have went wrong with um, when it was pulling this in,[1] it must have gotten a little bit tangled.	[1]*Carmen pulls on guide tube surrounding filament.*
2	Elena:	Can I edit this?	
3	Carmen:	What? No you can't, Elena. Sorry. Unless you want to do it on this computer, and then let Diego print today, and then you can print next week.	
4	Elena:	I'm not going to print next week, unless I'm going, unless I go after Diego?	
5	Carmen:	You can go after Diego, right after Diego.	
6	Aaliyah:	This is probably going to take a little bit longer.	
7	Carmen:	So do you want to print after Diego or do you want to print now, with 'Focus'? Your choice.	
8	Aaliyah:	Just make it really big	
9	Researcher:	Is there something that you could do to fix it, so that it will print better next time, do you think?	
10	Elena:	Maybe like, I want to make it	
11	Carmen:	Something got tangled right here[1] in the string and it wasn't going in through it.	[1]*Carmen reaches for filament on spool.*

In, particular, in lines 1 and 11 of this transcript, we saw how Carmen presented a hypothesis as to what went wrong with the printer (i.e., “Something must have went wrong with um, when it was pulling this in, it must have gotten a little bit tangled.” and “Something got tangled right here in the string and it wasn't going in through it.”). Carmen’s ability here to diagnose and fix a problem with the printer shows adaptive problem-solving skills, while her ability to help others with their printing jobs and manage the print queue (line 7, “So do you want to print after Diego or do you want to print now, with ‘Focus’?”) shows collaboration skills.

Later in this same class session, Carmen demonstrated additional skills and knowledge of the 3D printer by explaining to the substitute teacher how it worked (see Table 3.14).

Table 3.14
Carmen Explains How the 3D Printer Works to a Substitute Teacher

Line	Person	Talk	Actions
1	Substitute:	I've never seen one of these in action before. So is it doing it layer by layer?	
2	Carmen:	[1]That that part[2] is just like the the platform for it[3] that holds it up and um in a couple of maybe hours, like at lunch time, it will probably be done and it will be 3D and you can actually see a skull.	[1]*Carmen nods.* [2]*Carmen points to the printing platform.* [3]*Carmen makes ball gesture with hands.*
3	Substitute:	Oh it's going to take that long?	
4	Carmen:	Yup, probably, maybe more than lunch.	
5	Substitute:	Yeah, maybe after lunch.	
6	Carmen:	Because it says six percent already. So it's kind of going a little bit fast, so maybe at lunch.	
7	Substitute:	Is that why you made the sign or Diego did?	
8	Carmen:	Uh yeah.	
9	Substitute:	And you guys come back and unplug everything after?	

10	Carmen:	We come back, we take the skull off, we turn this all off, we turn that computer off and then we go back.	
11	Substitute:	So I'll have to send you here at some point?	
12	Carmen:		*Carmen nods.*
13	Substitute:	I wish that we could sit here and watch it.	
14	Carmen:	[1]But we only have five more minutes. Time to flash the lights.	[1]*Carmen continues nodding.*
15	Substitute:	Flash the lights?	
16	Carmen:	Yeah, we flash the lights [inaudible]	
17	Substitute:	[1]She needs to run the class not me.[2]	[1]*Substitute turns toward researcher.* [2]*Substitute laughs.*

In this transcript, Carmen demonstrated relative expertise (Stevens et al., 2016) related to the 3D printer, by explaining to the substitute teacher how the 3D printer worked (line 2), how long it would take to print (line 2, 4, 6), and what the procedure was for coming back and retrieving printed items once they'd finished (line 8, 10, and 12). She also demonstrated mathematical thinking — by estimating the amount of time remaining for the print job based on the percent completion reported by the printer (lines 1 and 6) — and spatial thinking — by explaining how the printer builds a 3D object (line 1). Throughout this interaction, the substitute teacher positions her as the expert, asking her questions (e.g., lines 1, 3, 7, 9, 11) to which she seems genuinely not to know the answers (rather than the type of known-answer questions often asked by teachers). This positioning continues in the final lines of the episode (lines 13-17), when Carmen expands her sharing of expertise with the substitute to explaining that they only have five minutes left in the class (line 14) and explaining the procedure for letting the class know that (flashing the lights, lines 14 and 16). As a result, the episode concludes with the substitute teacher recognizing Carmen's expertise by saying "She needs to run the class not me" (line 17).

Demonstrating Learning at Different Levels: Integrating Learning from Multiple Challenges or Learning from Challenges with Outside Interests. Carmen also achieved a more distal form of learning, through her work with the 3D printer, integrating what she had learned while working with the 3D printer with outside interests, particularly her future career aspirations. The following excerpt from Carmen's end-of-year interview demonstrates the connection she made between her interest in and work with the 3D printer and her future career aspiration to become a doctor for kids with cancer:

> I like working on the 3D printer, and I like helping other people with the 3D printer so that they can print and they can have their prints and be happy with it. I am a generous person helping, and when I grow up I wish to help cancer kids and become a doctor for them. I'm starting now and helping people with the 3D printer…the 3D printer is like a cancer kid. I get to help it. If it's broken I get to cure it and fix it.

In this excerpt, Carmen made two connections between her activities in FUSE and her future career aspirations. First, she made a connection between helping other people with the 3D printer and helping cancer kids (e.g., "I like helping other people with the 3D printer so that they can print and they can have their prints and be happy with it. I am a generous person helping, and when I grow up I wish to help cancer kids and become a doctor for them.") Second, she made a connection between troubleshooting and fixing the printer and curing kids with cancer (e.g., "the 3D printer is like a cancer kid. I get to help it. If it's broken I get to cure it and fix it.") In making these connections, she demonstrated critical thinking skills, as the analogy she created between the 3D printer and a cancer kid and how she could troubleshoot or fix both shows a nuanced understanding of what is involved in working with and attempting to fix both technical tools and the human body.

Interest and Identity Development. Carmen's quote from her end-of-year interview also demonstrates how her FUSE experience led to interest and identity development for her. During her time in FUSE, Carmen was able to cultivate her interest in the 3D printer. She was also able to cultivate her identity as someone who enjoys helping other people. Then, later, she was able to take what she had learned about troubleshooting and helping others and connect it to her future career aspiration of becoming a doctor for cancer kids.

Carmen's interest pathway is all the more interesting, because it was somewhat unexpected. The connections that Carmen made between troubleshooting and helping others with the 3D printer and becoming a pediatric oncologist were connections that few people, other than Carmen, would be likely to make. Certainly, knowing of her career aspiration, it is unlikely that 3D printing would be the first activity a teacher would direct her to, in order to cultivate interests and skills related to that career. Consequently, if it wasn't for the fact that the choice-based nature of FUSE allowed Carmen to choose this pathway, she might never have ended up on it. Furthermore, if we hadn't given Carmen an opportunity to explain her interests, we might never have discovered the rich connections that she had made between her work in FUSE and her career aspirations. As a result, as a story of interest development, Carmen's case emphasizes the importance of Ingold's (2011) notion of "tracing the multiple trails of becoming, wherever they lead" (p. 14) or in other words, attending to and following student interest pathways, in order to understand student learning.

Case 4: Off-roading. The final case is Emil. Emil's case is primarily an example of off-roading, as he spends the majority of his time in FUSE engaging in activities that are related to, but go beyond the provided FUSE challenges. However, it can also be seen as an example of diving, because he engaged deeply and persistently in both FUSE challenges and his off-road activities.

Emil brought in and cultivated two notable interests in FUSE. The first was an interest in music and experience playing the piano, which he expressed by choosing to do the *Ringtones* challenge. This challenge allows learners to make music tracks using the sound mixing application, Soundation. Emil spent most of the Fall working on the *Ringtones* challenge. However, rather than stick closely to the instructions for the challenge, he discovered a piano keyboard tool within Soundation and spent a substantial amount of time using it to create original music tracks.

Emil's second interest was video games. Throughout the year, he discussed this interest with classmates and our research team. Beginning in January, it led him to try the *Game Designer* challenge, in which students use introductory programming techniques to modify and later create video games using the software program, Stencyl. As the transcripts and analysis presented in the following pages will show, soon after beginning *Game Designer*, Emil became interested in designing his own characters for his game. At first, he did this in a very basic application he found online that he reported having used at home previously. He then discovered a more sophisticated application called Piskel, which allows users to draw and animate pixelated characters and import them into Stencyl (See Figure 3.4).

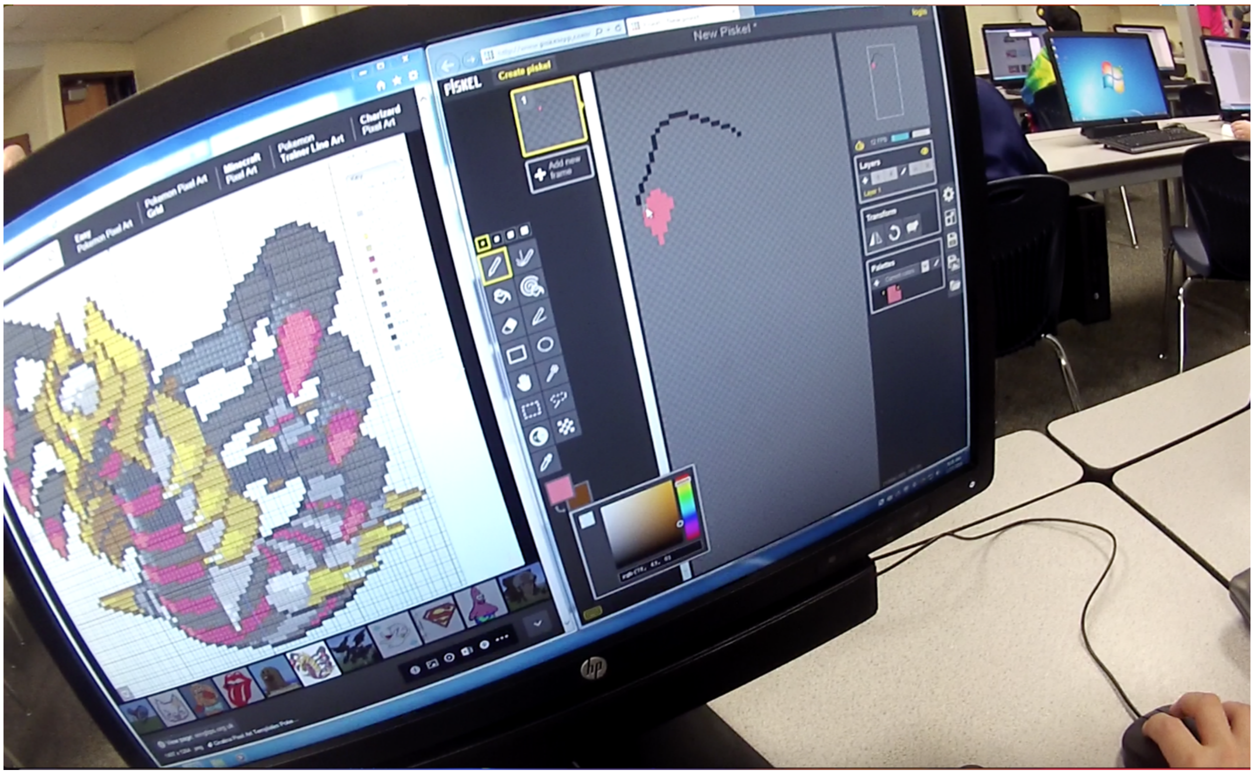


Figure 3.4. Emil works in Piskel to draw a character for his video game (right side of computer screen), using an image he found online as a guideline (left side of computer screen).

Emil became so excited about creating characters and other game elements in Piskel that he spent the rest of the school year working on this activity during FUSE studio time. He also reported working on this activity both during his school's after school FUSE club and at home, during his free time. Later, as other students in the class saw what Emil was doing in Piskel, they too became interested in using this tool both in conjunction with and separate from the *Game Designer* challenge. Many of these students asked Emil for help in learning how to create characters in Piskel, and he freely gave it too them. Emil also brought his interest in music and experience with the Ringtones challenge to bare on his work with Piskel and *Game Designer*, proposing to use Soundation to create a musical score for his video game. Therefore, Emil demonstrated learning at four different levels: (1) through iteration within challenge levels; (2) through teaching others things with which he had previously struggled; (3) through integrating learning from multiple challenges or learning from challenges with outside interests; and (4) through applying things learned in FUSE in other contexts.

Demonstrating Learning at Different Levels: Iteration within Challenge Levels. Through iteration within challenge levels, or really iteration within one offroad activity, Emil demonstrated the learning of many meta-disciplinary skills. First among these were creativity and adaptive problem-solving. He demonstrated these skills by identifying a problem in Game Designer (wanting to and not being able to draw his own characters) and seeking a novel solution to that problem (an online pixel drawing application). Then, when he found that that drawing application did not have all the features he desired, like the ability to easily erase the background behind a character, he sought out another online application with more affordances and found one in Piskel.

Through his work with Piskel, Emil demonstrated steady creative gains. At first, he was mostly copying images of characters he had found on the internet, pixel by pixel (see Figure 3.3), but later in the school year, he began creating characters and background images of his own design (see Figure 3.5). In both his move from playing video games to making them, and in this move from copying characters and backgrounds to designing them himself, we saw him moving from consumption to production and demonstrating corresponding increases in creative activity.

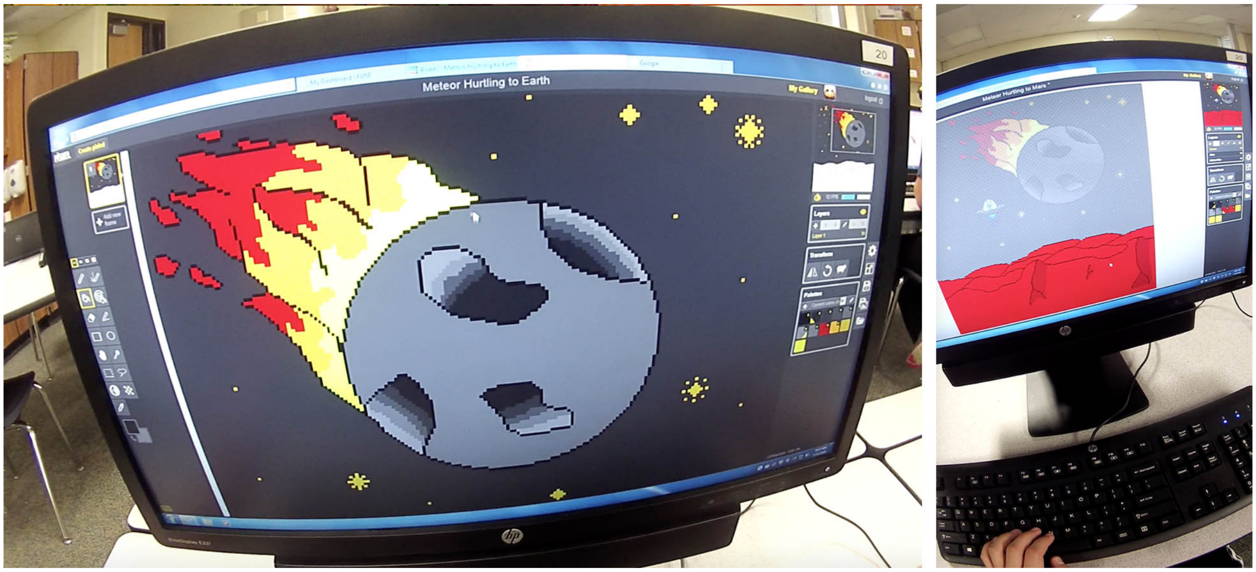


Figure 3.5. Emil creates a background image, “Meteor Hurtling to Earth”, drawn from his imagination, rather than copied from another image.

Through both his work designing his video game and designing characters for that game, Emil also showed continued use and learning of adaptive problem-solving skills, through iterative cycles of testing and modification to his designs. For example, after creating his first pixelated character and then importing it into Stencyl, he encountered a number of problems. First, because the initial pixelating program Emil had been using exported his character file as a jpeg, rather than a png file, when he imported it into Stencyl, it had had a white background behind it. To solve this problem, Emil found the Pencyl editing tool within Stencyl and used it to erase this background. He began doing this with a large, round eraser tool but quickly realized that as he got closer to his character, he would need to use a smaller, and squarer, eraser tool in order to create a clean edge. Then, once he had finally erased the background of the image, he tested it in his game, only to realize that it was also much too large to show up in the game. Rather than get discouraged, Emil simply took this next problem in stride, using tools in Stencyl to scale the image.

Emil's persistence in the face of bugs in his game or problems designing and importing characters and backgrounds into his game also provided him the occasion to demonstrates initiative and self-direction. He demonstrated these skills through his initial choice to go "off-road" by diverging from the prescribed FUSE activities, in service of a particular challenge-related goal. He also demonstrated initiative and self-direction by persisting in the face of frustration to solve the repeated problems with his Piskel characters and video game. For example, one day, he called me over to show me a revision he was going to make to his Piskel graphic. He planned to totally redraw the character, copying and pasting only small pieces of his old drawing into the new frame. In reference to this redesign, he said, "It's going to be a lot of work. I'm going to kill myself. My brain is going to die," but then he did it anyway, not because anyone was making him, but because he wanted to.

While iterating within his offroad activity, Emil also demonstrated math and spatial skills. For example, when he was redrawing pixelated characters in Piskel, he was doing so by using a numbered grid to map pixels from the original image onto the new one, as is shown in the transcript in Table 3.15.

Table 3.15
Emil Discovers a Web Application for Drawing Pixelated Characters and Begins Using It to Draw Characters for His Game Design Game

Line	Person	Talk	Actions
1	Emil:	Ooh! I'm going to create some[1]	[1]*Emil enters a new search into Google images. A bunch of pixelated video game characters come up.*
2	Emil:	I have an idea![1]	[1]*Emil opens an image of a Mindcraft axe, then closes it.*
3	Emil:	[1]Ok, do you know what I'm going to do?	[1]*Emil turns toward Zane.*
4	Zane:		*Zane doesn't respond.*

5	Emil:	[1]Oh my god I have to build this! Wait when do we have to go again? Because I	[1]*Emil opens a pixelated image of Link from Zelda.*
6	Researcher:	You want to build that? With blocks in the...	
7	Emil:	Yeah	
8	Zane:	Cool	
9	Emil:		*Emil Googles "pixel art grid". He views the options that come up and clicks on "pixel art maker". He shrinks and drags the image of Link to one side of his screen. Then he opens the "pixel art maker" and moves and stretches it to fill the other side of the screen.*
10	Emil:	Ta da! Now I'm going to go black, starting from here.[1]	[1]*Emil points to a black part of Link's shield.*
11	Zane:	You're a nerd.	
12	Emil:	[1]One, two, three, four, five, six…	[1]*Emil begins filling in pixels one at a time, counting as he does.*
13	Zane:	Whoah!	
14	Emil:	Seven	
15	Zane:	Are you even playing?	
16	Emil:	[1]One, two, three, four, five, six, seven. [2]One, two, three, four, five, six, seven, eight, nine, ten, eleven. [3]Eight, nine, ten, eleven.	[1]*Emil points to pixels he's just drawn on screen and counts.* [2]*Emil points to black pixels on Link's shield in original image and counts those.* [3]*Emil adds four more pixels to his own drawing, counting.*
17	Researcher:	That's really cool. How did you find out about this program?	
18	Emil:	Um, I tried it, like I tried it at home. Tried to find this.[1] One, two, three, four. One, two, three. One. One, two, three. One, two, three, four, five.	[1]Emil continues coloring in pixels.

The episode shown in this transcript is from when Emil first got the idea to draw pixelated characters and started drawing them in a pixel art web application (not Piskel yet, but another program like it). In the transcript, we can Emil's initial idea to create pixelated characters for his video game (lines 1-2) and the initial enthusiasm he expressed for this idea (line 5). The transcript also shows Emil performing the grid mapping and counting strategy to copy pixels from the original image of Link to his drawing (lines 12, 14, 16, and 18). Finally, it shows his friend Zane's reaction, initially calling him a "nerd" (line 11) but then seeming impressed with what Emil was doing (line 13, "Whoah!" and line 15, "Are you even playing?"). This transcript shows not only that Emil's work with pixel drawing application gave him an opportunity to pursue a project of interest and apply STEM content knowledge and spatial thinking to that project of interest, but also that his work was recognized as valuable by his classmates.

A second set of excerpts from later in the same class period shows how Emil continued to use this counting and grid mapping strategy to identify and fix a mistake he had made in his drawing (See Table 3.16 and 3.17).

Table 3.16
Emil Uses the Counting and Grid Mapping Strategy to Identify and Fix a Mistake He Had Made in His Drawing

Line	Person	Talk	Actions
1	Emil:	What? I messed up.[1]	[1]*Emil looks back and forth between his drawing and original Link image.*
2	Emil:	How did I mess up? [1]One, two, three, four, five, six. [2]One, two, three, four, five, six.	[1]*Emil counts the black pixels on the sword in the original image, running his fingers over them as he does.* [2]*Emil counts the pixels on the corresponding part of his drawing, running his mouse over them.*

Emil continued going back and fourth, counting until he found the problem. He then erased and redrew a line on the bottom of the sword. Then, apparently realizing he had made another mistake, he erased the whole bottom of the character.

Table 3.17
Emil Erases His Drawing and Starts Over

Line	Person	Talk	Actions
1	Emil:	Oh, man, I messed it all up.[1]	[1]*Emil erases everything in his drawing but the sword.*
2	Emil:	So I messed up. Now I have to start over.[1]	[1]*Emil begins drawing again.*
3	Emil:	Oh, this is so hard!	

In these excerpts, we saw Emil continuing to use the grid mapping and counting strategy to figure out where he had gone wrong in his drawing (Table 3.16, line 2). We also saw how his mistakes led to frustration with the task (Table 3.17, line 3). However, instead of giving up, Emil worked through the problem and eventually created an almost perfect replica of the Link image (see Figure 3.6). These transcripts demonstrate that through his application of the grid counting strategy, Emil was able to solve problems and learn from his mistakes.

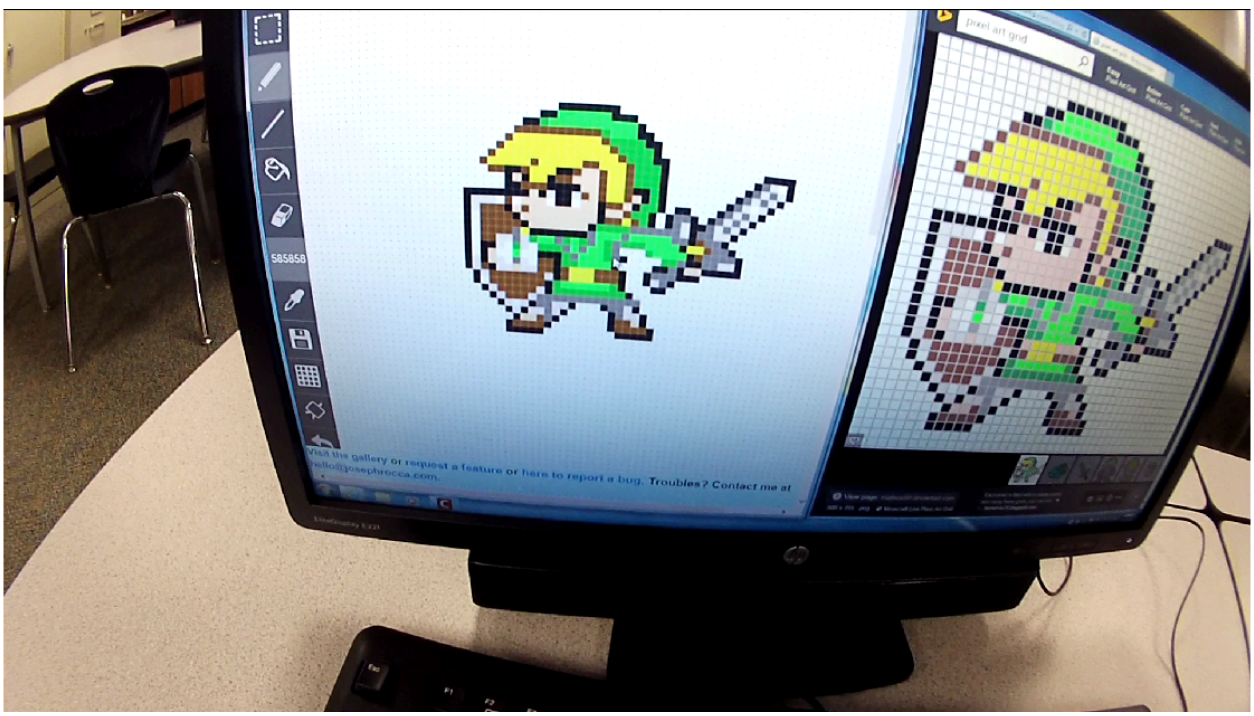


Figure 3.6. Emil finds a pixelated image of Link online (right side of the computer screen) and redraws an almost perfect replica of it (left side of computer screen).

In his end-of-year interview, Emil reflected on his use of math skills while working in Piskel (see Table 3.18).

Table 3.18
Emil Talks about FUSE Being Fun

Line	Person	Talk
1	Researcher:	Is Fuse fun?
2	Emil:	Yeah, definitely.
3	Researcher:	How come?
4	Emil:	It puts my imagination out there. For example, what I'm doing right now I'm just doing sometimes random things just from time to time. I just use my imagination. I just put it out there sometimes.
5	Researcher:	What does fun mean?
6	Emil:	For me, it's just enjoying something that's educational basically. This Piskel and FUSE and stuff is helping me be better in math. I almost feel like without it I wouldn't have had what I needed to do what I do in math.

Here, Emil begins by reflecting on how fun FUSE is for him (line 2) and why (lines 4 and 6), saying “It puts my imagination out there,” and “For me, it's just enjoying something that's educational basically.” The first of statements alludes to the creative skills he demonstrated and learned while working with Piskel in FUSE, while the second statement alludes to the disciplinary knowledge and skills he learned and applied during this activity. Then, in line 6, Emil makes a more explicit connection to math learning saying “This Piskel and FUSE and stuff is helping me be better in math. I almost feel like without it I wouldn't have had what I needed to do what I do in math.”

Finally, through iteration within challenge levels, Emil demonstrated the learning of art and design skills and technical skills. For example, in the following excerpt, another student, Dixon, called Emil over to help him create the color brown, so that he could add brown pixels to the image of a Squirtle (a Pokemon character) he was creating. This resulted in Emil and Dixon exploring how to make brown using the gradient color array provided in the software for choosing color swatches (see Table 3.19).

Table 3.19
Emil Helps Dixon Find the Right Shade of Brown for His Squirtle Character

Line	Person	Talk	Actions
1	Dixon:	How do you make brown?[1]	[1]*Dixon clicks through colors on gradient color array panel.*
2	Emil:	Oh, you gotta. Give me the mouse.[1]	[1]*Emil clicks somewhere between yellow and orange, then moves the bar on the side down to make a less saturated, darker yellow-orange.*
3	Dixon:	That's not brown enough.	
4	Emil:		*Emil clicks closer to red, then moves the color selector down to a color that is halfway down the saturation scale.*
5	Dixon:	A little browner.	
6	Emil:		*Emil moves cursor up the saturation scale.*
7	Dixon:	No, brown! Down, down.	
8	Emil:		*Emil moves cursor down.*
9	Dixon:	That's good.	
10	Emil:	Ta da!	

In this excerpt, we saw Emil figuring out the role of color mixing (lines 2 and 4) and saturation (lines 4, 6, and 8) in creating the color brown. We also saw him developing technical expertise in how to create colors using the gradient color array provided by graphic design software programs like Piskel. This development of technical expertise continued a few moments later, after Emil returned to his own computer to continue working on the image of Link (from Zelda) that he was drawing. Realizing that he also needed brown to color in part of his character, Emil asked Dixon for the number code for the shade of brown they had just found, so that he could enter and use it for the brown part of Link's shield and hair. Dixon gave him the code and Emil was able to use this brown color in his design. This exchange indicated that the boys had learned that digital colors have number codes associated with them, a useful piece of technical knowledge for working in graphic design software.

Demonstrating Learning at Different Levels: Teaching Others Things With Which Learners Had Previously Struggled. As we saw from the exchange between Emil and Dixon above, as Emil continued to work in Piskel, other students also became interested in using it. As they began designing things in Piskel, many went to Emil for help. Interestingly, unlike Johanna, Victoria, and Andrea, the girls who collaborated from the beginning of the year, Emil was, at first, a bit resistant to collaborating on Piskel. When the first other student, Dixon, began using Piskel, Emil complained to Zane that Dixon had copied him. However, he later changed his story, first by offering help to Dixon and other students, then, later, by acknowledging that copying his idea to work in Piskel wasn't the same as copying his designs. In his end-of-year interview, Emil reflected on his evolving thoughts on copying, collaboration, and Piskel (see Table 3.20).

Table 3.20
Emil Shares his Thoughts on Other Students Copying His Idea to Work in Piskel

Line	Person	Talk
1	Researcher:	Tell me again how do you feel about the fact that other kids are doing it?
2	Emil:	At first, I almost feel like they were taking my idea at first. Then, I see that they're doing their own things. They're not copying exactly what I'm doing. Some people just do it just for fun. I'm trying to make something here. At first, I thought they were just copying exactly what I was doing. Now I see that they're doing their own things.
3	Researcher:	Why would it have been bad if they were only copying what you were doing?
4	Emil:	Copying, not only are they taking my work, but also they're not trying anything new. They're just doing what another person is doing and not learning anything.
5	Researcher:	Why is that important to you?

6	Emil:	I don't want people to just cheat and do it just off of one person. I want them to actually learn how to do it and get to know by themselves.

In the excerpt above Emil expressed his initial frustration with students "taking my idea" by working in Piskel (line 2). However, he also explained how he came to realize that they weren't copying his projects, just the idea to use Piskel (line 2). Then, he went on to engage in some critical reflection, explaining why copying is bad, framed in terms of learning (lines 4 and 6). In other words, he expressed an explicit interest in other students' learning (i.e., "I want them to actually learn how to do it and get to know by themselves") and explained how copying denied them that learning opportunity ("Copying, not only are they taking my work, but also they're not trying anything new. They're just doing what another person is doing and not learning anything.") Through this transition, Emil showed that he had come to a new understanding the process of creative collaboration that he had not previously had.

Demonstrating Learning at Different Levels: Integrating Learning from Multiple Challenges or Learning from Challenges with Outside Interests. Emil also demonstrated learning through both integration of learning from multiple challenges and learning from challenges with outside interests. For example, Emil connected his work in Piskel and *Game Designer* to his interest in video games (e.g., Terraria, Halo, Zelda) and his work in *Ringtones* to his experience with music (i.e., playing piano). He also connected his musical interest and experience doing *Ringtones* to his work in Piskel, proposing to make a soundtrack for his game using the software from the *Ringtones* challenge. The transcript in Table 3.21, from Emil's end-of-year interview, summarizes these connections that he made throughout the year.

Table 3.21
Emil Talks about His Idea to Add a Soundtrack to His Video Game for the Game Designer Challenge

Line	Person	Talk
1	Researcher:	Would you say this is something that you're proud of?
2	Emil:	Yeah, I like it. I have a really big thing that I'm working on so far.
3	Researcher:	Can you tell me about that?
4	Emil:	First, I'm trying to make Bosses 2. Now I'm thinking what if I make ringtones and I add it into the Game Designer for a boss battle. When you enter the game it'll play that music. When you enter a different scene of the game it'll enter a different type of music.
5	Researcher:	What would be good about that?
6	Emil:	Again, the game I play at home, Terraria, that's how I get to know where I am in the game and you really understand the game. Right now, this is what I'm pixelating. This will be your character. I'm not done with it. I basically go on Google, solar flare armor and then here it is. Wait, let me go back, solar flare armor. I go to images, and now I find one that would be easy to, that I can see. I think I saved one right here, no. What about this one then? Let me try this.

In this interview excerpt, Emil referenced two specific video games (Bosses 2 and Terraria) that influenced his designs in Piskel and *Game Designer* (lines 4 and 6). He also drew on his experience playing these games to explain why music is important in video game design (i.e., line 6, "the game I play at home, Terraria, that's how I get to know where I am in the game and you really understand the game.") This demonstrates how he integrated outside interests and knowledge with things learned in multiple FUSE challenges, to shape design decisions for his video game.

Demonstrating Learning at Different Levels: Applying Things Learned in FUSE in Other Contexts. Finally, on multiple occasions, Emil demonstrated learning by applying things learned in FUSE in other contexts. For example, Emil got so excited about designing and animating characters in Piskel that he not only continued working on this activity, in conjunction with *Game Designer*, for the rest of the school year during FUSE but also regularly reported working on *Game Designer* or Piskel at home and during after-school FUSE club. The transcripts in Table 3.22 and 3.23 show Emil sharing something during FUSE that he had learned at home, while working on *Game Designer*.

Table 3.22
Emil Shares a Discovery He Made While Working on Game Designer at Home

Line	Person	Talk
1	Emil:	Dude, look look, I just want to show you this.
2	Zane:	Hold on.
3	Emil:	I just figured this out at home.
4	Zane:	You figured it out at home.
5	Emil:	Yeah.

After announcing to Zane that he had something to show him (line 1) that he had figured out at home (line 3), Emil then proceeded to show Zane and myself what he had figured out at home, by replicating it on his computer in the FUSE studio (Table 3.23).

Table 3.23
Emil Shows Zane and Me What He Discovered at Home, How to Run His Game Upside Down

Line	Person	Talk	Actions
1	Emil:	When created, turn actor 90 degrees, no 180.[1] Actor, choose actor. Mar...Oh! And now it will go upside down! Ready?	[1]*Emil types in "180."*
2	Emil:	[1]Ok, I think I figured out how to turn everything upside down.	[1]*Emil turns toward researcher.*
3	Researcher:	Cool	
4	Emil:	So I went to events, when created turn actor Mario by 180 degrees. So it'll go upside down.	
5	Researcher:	Oh, wow	
6	Emil:	I'm gonna test scene.[1] Please work.	[1]*Emil clicks "test scene".*
7	Computer:		*Stencyl shows loading symbol.*
8	Emil:	I don't know if it's going to work though.	

9	Computer:		*The updated game finally loads and runs upside down.*
10	Emil:	Oh! Oh! Oh!	
11	Researcher:	Alright![1]	[1]*Researcher laughs.*
12	Emil:	I don't know how to jump though.	
13	Researcher:	Uh oh.[1]	[1]*Researcher laughs.*
14	Emil:	That's what I need to fix.	
15	Researcher:	It doesn't work the same way it does when you're right side up?	
16	Emil:	Yeah, I tried that.	

In line 2 of this transcript, Emil shared what he had discovered at home by working on the *Game Designer* challenge there ("how to turn everything upside down"). He then explained how he had done it (line 4) and demonstrated that it worked by testing the scene he'd created for his game (lines 6-11). In doing so, he demonstrated that he had both learned how to do this well enough to replicate it, and that he was motivated enough to continue activities from FUSE in other out-school contexts, such as home.

This cross-context work also motivated and provided Emil with opportunities to engage in some interesting adaptive problem-solving. For example, wanting to work at home on things he had designed in Piskel at school, and vice versa, created a dilemma, because, ordinarily, files worked on at school would be saved on the school server and files worked on at home would be saved on his home computer (with neither set of files accessible from the other location). However, through an iterative problem-solving process, Emil was able to find a way around this. First, after his teacher reminded the class that they should be saving their work to the FUSE website, Emil had the idea that he could save his Piskel files to the FUSE site and then open them from the website at home. However, when Emil tried this approach, he encountered two problems. First, because Piskel wasn't one of the programs officially used for FUSE challenges, the FUSE website wouldn’t accept the file extension for Piskel files as an acceptable file upload. Second, in order to address the first problem, Emil tried exporting files out of Piskel as jpegs, an acceptable file type for the FUSE site. However, he then realized that he wouldn’t be able to reopen and continue editing them in Piskel. After realizing that it wouldn’t work to save his Piskel files to the FUSE site, Emil tried a different approach. He noticed that he could create an account on the Piskel website using his email address, so that files could be saved to that account, rather than the local computer. So he tried doing this with his own email address, but first couldn’t remember the password, then he got an error message saying that he needed to authenticate this email address using another email address. So, instead, he tried logging into Piskel with his dad’s email address, which finally worked. At this point, he expressed great excitement (exclaiming “Yes!” and throwing his hands up in the air), and he shared what he had discovered with a few other students. After this discovery, he began working fluidly on designing both at school and at home, saving all of his work to his online account. Again, what is most important to note here is that despite repeated setbacks, Emil engaged in adaptive problem-solving and persevered toward his goal, not for a grade or because the teacher had asked him too, but because of a genuine interest in the goal he was working toward.

In Emil’s end-of-year interview, he explained how this discovery had enabled him to work across contextual boundaries more easily (see Table 3.24).

Table 3.24
Emil Talks about Doing Piskel at Home, in His End-of-year Interview

Line	**Person**	**Talk** **Actions**
1	Researcher:	Do you do this at home too or just at school?
2	Emil:	I do it at home. That's why I log into my Google account here. If I go to my gallery, these are all Piskels that I created.

3	Researcher:	How much time do you spend at home doing this?
4	Emil:	It depends on the day. Sometimes I have time to do it. Sometimes I don't. It depends, a usual half an hour or an hour. If I'm in a rush or if I have a lot of homework, I'll do half an hour. If it's very easy and I don't have to go anywhere, I'll do an hour or so with this. Here's one that I pixelated, the burning wolf. It slowly starts to burn and then falls into ash.

In this excerpt, Emil explained how he was able to use his Google account to log into Piskel at home and at school to see and work on his gallery of Piskel creations (line 2). He also reflected on how much time he had spent working on Piskel at home (line 4), "half an hour or an hour" a day. The amount of time Emil reported spending on Piskel at home, paired with the work he put into figuring out how he could access files both at school and at home, shows that he was interested enough in Piskel to put in the work required to carry this activity across contextual boundaries.

Emil's cross-context work on Piskel and *Game Designer* also opened up additional opportunities for collaboration that extended beyond the FUSE studio. For example, late in the year, Emil discovered a tool called Stencyl Forge, located within Stencyl, the application for the *Game Designer* challenge. This tool allows users to upload and share games or resources (backgrounds, objects, characters) they've created in Stencyl. He explained to me that, using this tool, you could download and play a game or download and use resources others had created. When I asked him how he found it, he told me that a friend in another class had told him about it, because he had uploaded a game there that he wanted Emil to play. Upon discovering and then exploring this tool in Stencyl, Emil said, "This is Epic!…Epic!…This is everything I need." His discovery of this tool for sharing game designs, through conversations with friends, outside of the FUSE studio, demonstrates how applying things learned in FUSE in other contexts opened up new opportunities for Emil to engage in both collaboration and, consequently, learning.

Interest and Identity Development. At multiple points during the year, Emil connected his work in FUSE to outside interests. For example, when working on *Game Designer*, he mentioned drawing design inspiration from a number of specific video games that he liked to play in his spare time. The transcript in Table 3.25 shows one example of how being able to design a game containing elements of other video games that he enjoyed enhanced his interest and engagement in the Game Designer challenge.

Table 3.25
Emil Searches for Futuristic Terrain Images for the Background of His Video Game, So That He Can Model It After Halo

Line	Person	Talk	Actions
1	Emil:	I'm trying to find a terrain, like a future	
2	Researcher:	Trying to find what?	
3	Emil:	Terrain, because Halo's all futuristic. So I'm trying to find future terrain.	
4	Researcher:	Oh, sure.	
5	Emil:	And then, I just need to find it[1]	[1]*Emil scrolls through images that he's pulled up via an image search.*
6	Emil:	Yes.	[1]*Emil opens an image.*
7	Researcher:	So then you can bring that into Stencyl?	
8	Emil:	Yeah, what I need = Oh man this doesn't work. I'm gonna try this one.[1] Doesn't work. Try this one.[2] It doesn't work. Try this one.[3] It doesn't work. Try this one.[4] It doesn't work. Why won't you guys work?[5]	[1]*Emil clicks on the image to enlarge it. It isn't big enough.* [2]*Emil clicks on the image to enlarge it. It isn't big enough.* [3]*Emil clicks on the image to enlarge it. It isn't big enough.* [4]*Emil clicks on the image to enlarge it. It isn't big enough.* [5]*Emil continues scrolling through and trying different images. He finally finds one that will work.*
9	Emil:	Ooh! Ooh! Ooh! Okay, snipping tool.[1]	[1]*Emil opens the snipping tool and snips the image. Then he saves it under a new name in his folder.*
10	Zane:	Oh, like so that picture's just going to be the background now?	

11	Emil:	Yes!
12	Zane:	And that's fun because?
13	Emil:	I wanted to!

As we saw in the transcript above, Emil specifically referenced Halo (line 3) as the inspiration for the terrain for his video game. After an initial period of searching (line 8), when Emil finally found an image that he was able to import into Stencyl, he expressed great excitement ("Ooh! Ooh! Ooh!", line 9). Then, when his friend Zane asked him what he was doing (line 10) and why that was fun (line 12), Emil responded by saying "I wanted to!" (line 13), indicating that the element of choice was an important factor in why this was fun (or interesting) for him.

Emil's FUSE facilitator also noticed his engagement in FUSE, mentioning Emil in an end-of-year interview (see Table 3.26).

Table 3.26
Mr. Williams Identifies Emil as the Student Who Started Piskel Activity in His Class

Line	Person	Talk Actions
1	Researcher:	Who were then the fifth- or sixth-grade students that you saw that were engaged a lot last year?
2	Mr. Williams:	The sixth-graders that continue to be? Well, Emil, Emil kind of did his own thing, but I think he led the whole Piskel thing for a lot of people.

After Mr. Williams talked about a few other students, the conversation about Emil continued (see Table 3.27).

Table 3.27
Mr. Williams Talks about Emil's Excitement around Piskel and His Work with It Outside of the FUSE Studio

Line	Person	Talk
1	Researcher:	How about Emil? You mentioned Emil already before, with his Piskel activity.
2	Mr. Williams:	Emil is really = It's so refreshing when I see him really excited about something. He would tell Kay what he did at home. 'At home I got this working,' and he'd come here and try to do it here, or continue on what he was doing at home. He's kind of funny because he = I've had Emil for two

		years, and when he's excited, he talks higher, the pitch of his voice gets higher, and it's kind of more exciting for him. He seems pretty into this. I don't know, last year he worked on some challenges. This year, I would say the majority of the time, he wasn't on a regular challenge that was written by Northwestern. He kind of went on the Piskel, and did kind of his own things, but he would get those figures to move. A lot of them, they end up coloring, or making a new one, same type of = They'll look at one as a model, and then maybe they'll change the colors, maybe one pixel at a time, where he tries to go beyond a little bit, and that's how he is. He tries to go beyond in a lot of other things. He really seemed to be more, I don't want to overuse the word engaged, but he was a little bit more engaged into that than others.
3	Researcher:	How do you remember him coming upon the whole Piskel software?
4	Mr. Williams:	I think he came upon that at home, and then early on, he asked, can we do that here, and I didn't know exactly what I was doing, so I looked at it for a while, and I'm like, yeah. It's not unlike other things in here. That's the appropriate place to do it, here, so I just kind of let him go, and he's one that I can trust to make sure that he is on the right thing, right topic. He was in FUSE Club too, until track started, and then he quit FUSE and went, so he would continue on where he left off, a lot of times, in here, doing the same thing.
5	Researcher:	Kind of continuing.
6	Mr. Williams:	Yeah, and he was excited. He draws other people in with his excitement a little bit, so I think that he was the one, I think, from my class that started that whole Piskel thing, and then they kind of found, because he showed his excitement and got the others excited about it.
7	Researcher:	It was contagious, in that sense.
8	Mr. Williams:	I think so. He was the one that started it, and then it kind of permeated from him.

In this interview excerpt, the teacher identified four important features of Emil’s FUSE participation. First, he identified the off-road nature of Emil’s FUSE activity (lines 4 and 6). Second, he identified Emil’s high level of engagement during FUSE time (line 4). Third, he identified the way in which Emil continued his FUSE activity in other spaces (e.g., at home and during after school FUSE club, line 6). Finally, fourth, he identified how Emil sharing his enthusiasm for Piskel with his classmates led to others taking up this activity as well (lines 8 and 10).

This excerpt from the interview with Emil's teacher is interesting for at least three reasons. First, it serves as triangulation or confirmation of conclusions I had come to, independently, about Emil's engagement in FUSE. Second, it shows that teachers can do a form of the analysis I have proposed here, for assessing learning in an environment like FUSE. By simply observing Emil during FUSE time, this teacher was able to identify the nature of Emil's FUSE participation (going beyond the challenges), the fact that he was making connections across contexts (working on Piskel at home and during after-school FUSE club), the fact that he was highly engaged in his FUSE activities (interest), and the fact that he shared his interest with other students (collaboration).

We received further confirmation of Emil's interest development during FUSE, particularly in Game Designer and Piskel, through things Emil himself said throughout the year. For example, as the year went on, on more than one occasion, Emil explained how his love of video games and the skills he had built while doing Game Designer and working in Piskel in FUSE had impacted his future career plans. Specifically, he told me and other members of our research team that he was interested in pursuing a career as a video game designer. The transcript in Table 3.28 from mid-April shows Emil's first expression of interest in being a professional game designer.

Table 3.28
Emil Talks about His Career Aspiration to Be a Game Designer or Youtuber

Line	**Person**	**Talk**	**Actions**
1	Researcher:	What do you want to be when you grow up?	
2	Emil:	A game designer slash Youtuber.	
3	Researcher:	So you can what?	
4	Emil:	A game designer slash Youtuber, like and like go make youtube videos and be a game designer.	

5	Researcher:	Oh Youtuber, oh sorry, I just didn't hear what you said, yeah.	
6	Emil:	Ok	
7	Researcher:	Got it. So you want to make Youtube videos about game design or about	
8	Emil:	Well, just about like the game itself, like I'll play the game I make, like but what I want to do is create like the characters for the game.	
9	Researcher:	Sure.	
10	Emil:	And then let the other people create the game.	
11	Researcher:	Sure.	
12	Emil:	'Cause you look at Minecraft and Terraria, they make a lot of money, like they made a lot of money with all the, how much they sold.	
13	Researcher:	Yeah, there's definitely a lot of careers in game design.	
14	Emil:	Yeah, I don't know, but my mom isn't going to let me be a game designer.	
15	Researcher:	Your mom's not going to let you be a game designer?	
16	Emil:	No.	
17	Researcher:	No? What does your mom want you to be?	
18	Emil:	A dentist or something.	
19	Researcher:	[1]Yeah? And you don't want to be a dentist?	[1]*Researcher laughs.*
20	Emil:	No. I want to be like, I want to actually enjoy the job I have.	

In the transcript above Emil expressed an interest in being a game designer (lines 2 and 4) and also a more specific interest in the aspect of game design he had been working on in Piskel, creating characters (line 8). He also cited video games he's played, like Minecraft and Terraria, as inspiration for this career interest (line 12). Finally, he made an interesting distinction between what his mom wanted him to do for a career (be a dentist, line 18), and what he wanted to do ("I want to actually enjoy the job I have", line 20), indicating the importance that he places on interest in choosing a career and therefore implying that he enjoys game design.

In Emil's end-of-year interview Emil reiterated this interest in game design as a future career (Table 3.29).

Table 3.29
Emil Reiterates his Interest in a Career in Game Design, in his End-of-year Interview

Line	**Person**	**Talk**
1	Researcher:	Are you doing this for a grade?
2	Emil:	There isn't much of a grade for FUSE, but I just like adding new stuff. I might even make it for my future job. I want to be a game designer or programmer or something.
3	Researcher:	Where did you get the idea to be a game designer?
4	Emil:	I just like it, because you look at some of the people, the major game designers like Minecraft and stuff like that. You see what they can make. It's such a simple game, but it turned out into a major seller.
5	Researcher:	Do you think FUSE would help you become a game designer?
6	Emil:	Yeah, with what I'm doing right now I think so

In this transcript, Emil not only expressed an interest in being a game design (lines 2 and 4), but he connected this interest to the work he had done in FUSE (line 6). In line 2, he also explained that it was his interest in game design and possible interest in a future career as a game designer that motivated his work in FUSE, rather than a grade ("There isn't much of a grade for FUSE, but I just like adding new stuff. I might even make it for my future job. I want to be a game designer or programmer or something.")

Again, this is very different from the type of rationale a student might give for doing work in regular school classroom, where everything is required and graded, and there isn't much room for choice or pursuit of individual interests. Emil's case, like the other three student cases, demonstrates the power of a choice-based learning environment like FUSE for allowing students to pursue and further develop STEAM-related interests. It also shows, yet again, the importance of attending to student interest pathways in order to understand learning and the ways in which unique interest pathways can lead to different, but equally interesting an important forms of learning.

Summary

The four cases presented here capture just a few of the unique interest pathways students travelled in FUSE. However, I believe that they represent the primary modes or patterns of interest development and learning we've seen in FUSE. For example, of the 59 focal participants I observed and collected video data on over the course of the full 2015-16 school, I coded 15 as being on a sampling pathway, 22 as being on a completing pathway, 19 as being on a diving pathway, and 3 as being on an off-roading pathway.

These cases also represent the important aspects of what it means to be on each of these pathways. Table 3.30 summarizes each case in terms of the type of interest pathway the learner followed, the interest and identity development that occurred on that pathway, the specific challenges learners chose to work on, the learning that occurred, and the levels at which learning was demonstrated (promixal to distal). It also describes how the levels of learning framework could be adapted to analyze learning in other makerspaces. I included this last column, because traditional makerspaces don't have the challenge-based or leveling-up structure that FUSE does. Therefore, applying this framework to other makerspace contexts would likely require merging categories one and two. Also, rather than discussing "challenges" as the meaningful contexts for achieving proximal learning goals, we would likely want to think about that learning as situated within projects or work with particular tools, instead.

Table 3.30
Summary of Interests, Challenges Pursued, Skills learned, and Types of Learning Demonstrated in Each of the four Student Cases

Case	**Type of Interest Pathway**	**Challenges Selected to Work On**	**Interest and Identity Development**	**Skills Learned**	**Levels at Which Learning was Demonstrated (Proximal to Distal)**	**Equivalent Categories for Other Makerspaces[1]**

Amadia	Sampling	Laser Defender, Dream Home, 3D You, Keychain Customizer, Minime Animation, Jewelry Designer, Selfie Sticker	Amadia showed and explicitly expressed greater interest in FUSE than in other school courses. She cited the choice-based nature of FUSE as a reason for her engagement, in addition to expressing interest in specific challenges.	Adaptive Problem-solving; Communication & Collaboration; Creativity & Innovation; Information, Media, and Technology Literacy; Initiative and Self-direction; Spatial Skills	1. Iteration within challenge levels in order to achieve a goal 3. Applying learning from one challenge sequence to another	1 & 2. Iteration within a project or work with a particular tool, in order to achieve a goal 3. Applying learning from one project to another subsequent project
Johanna, Andrea, and Victoria	Completing	Dream Home, Dream Home 2, Selfie Sticker	Johanna mentioned wanting to be an architect. All girls mentioned an interest in working collaboratively and in different aspects of arts and design.	Critical Thinking; Adaptive Problem-solving; Communication & Collaboration; Creativity & Innovation; Information, Media, and Technology Literacy; Initiative and Self-direction; Spatial Skills; Math Skills	1. Iteration within challenge levels in order to achieve a goal 2. Applying learning from one challenge level to another 3. Applying learning from one challenge sequence to another 4. Teaching others things with which learners had previously struggled	1 & 2. Iteration within a project or work with a particular tool, in order to achieve a goal 3. Applying learning from one project to another subsequent project 4. Teaching others things with which learners had previously struggled
Carmen	Diving	Keychain Customizer, Ringtones, 3D Printing	Enjoys 3D printing and helping, wants to be a doctor, made a connection between fixing the 3D printer and fixing a cancer patient as a doctor	Critical Thinking; Adaptive Problem-solving; Communication & Collaboration; Information, Media, and Technology	1. Iteration within challenge levels in order to achieve a goal 4. Teaching others things	1 & 2. Iteration within a project or work with a particular tool, in order to achieve a goal 4. Teaching others things

				Literacy; Initiative and Self-direction; Spatial Skills, Math Skills	with which learners had previously struggled	with which learners had previously struggled
					5. Integrating learning from multiple challenges or learning from challenges with outside interests	5. Integrating learning from multiple projects or tools or learning from these projects or tools with outside interests
Emil	Off-roading	Ringtones, Print My Ride, Dream Home, Game Designer	Prior music interest (plays piano), prior video game interest, by Spring says he wants to be a game designer	Critical Thinking; Adaptive Problem-solving; Communication & Collaboration; Creativity & Innovation; Information, Media, and Technology Literacy; Initiative and Self-direction; Spatial Skills, Math Skills	1. Iteration within challenge levels in order to achieve a goal	1 & 2. Iteration within a project or work with a particular tool, in order to achieve a goal
					4. Teaching others things with which learners had previously struggled	4. Teaching another student something with which the learner had previously struggled
					5. Integrating learning from multiple challenges or learning from challenges with outside interests	5. Integrating learning from multiple projects or tools or learning from these projects or tools with outside interests
					6. Applying things learned in FUSE in other contexts	6. Applying things learned in the makerspace in other contexts

The findings summarized in Table 3.30 demonstrate both important similarities and important differences between the students on different interest pathways. For example, different types of pathways (sampling, completing, diving, or off-roading) corresponded to different levels at which learning was demonstrated (proximal to distal; see also Table 3.31). In other words, Amadia, who engaged in sampling, demonstrated learning through iteration within challenge levels and by applying learning from one challenge sequence to another, but not by applying learning from one challenge level to another, because she wasn't often doing more than one level of a challenge. In contrast, Johanna, Victoria, and Andrea, who completed all levels of each challenge systematically, had plenty of opportunities to demonstrate learning from one challenge level to the next. Finally, Carmen and Emil, who engaged in diving and off-roading, integrated learning from challenges with outside interests, and in Emil's case, applied things learned in FUSE in other contexts, in a way that Amadia and Johanna, Victoria, & Andrea did not.

Table 3.31
Ways in which Students on Different Interest Pathways Demonstrated Learning During FUSE

Ways in Which Learning is Demonstrated	**Amadia (Sampling)**	**Johanna, Victoria, & Andrea (Completing)**	**Carmen (Diving)**	**Emil (Off-roading)**
Learning through iteration within challenge levels in order to achieve a goal	X	X	X	X
Applying learning from one challenge level to another		X		
Applying learning from one challenge sequence to another	X	X		
Teaching others things with which learners had previously struggled		X	X	X
Integrating learning from multiple challenges or learning from challenges with outside interests			X	X
Applying things learned in FUSE in other contexts				X

In contrast, the different interest pathways did not seem to correspond to differences in the types of skills learned, at least for meta-disciplinary skills (See Table 3.32). This is important, because it means that we should not privilege one form of engagement in a makerspace environment like FUSE over another, but rather recognize and encourage the rich learning that can occur along all of these different types of interest pathways.

Table 3.32

Different Meta-disciplinary Skills Learned by Students on Different Interest Pathways

Meta-disciplinary Skill	**Amadia (Sampling)**	**Johanna, Victoria, & Andrea (Completing)**	**Carmen (Diving)**	**Emil (Off-roading)**
Critical Thinking		X	X	X
Adaptive Problem-solving	X	X	X	X
Communication & Collaboration	X	X	X	X
Creativity & Innovation;	X	X	X	X
Information, Media, and Technology Literacy	X	X	X	X
Initiative and Self-direction	X	X	X	X

Discussion

The cases presented here not only capture the range of interest pathways students travelled in FUSE. They also emphasize how learning in makerspaces is different from traditional classrooms with one-size-fits-all curricula. Unlike traditional classrooms, makerspace environments like FUSE allow students' unique interests to shape diverse interest pathways. This is important, because, as these cases demonstrate, genuine student interest promotes persistence, iteration, and learning within activities and connections between activities and contexts.

These cases also demonstrate the importance of carefully considering what types of learning we attend to in makerspaces and how we assess this learning. These types of activities are inherently interdisciplinary. Therefore, one of their unique affordances is the promotion of meta-disciplinary skills, such as collaboration, creativity, self-directed learning, adaptive problem-solving, and spatial skills. We provide a framework for examining this learning qualitatively, rather than using a one-size-fits-all assessment. The cases show that this method better suits the personalized nature of learning in these contexts and the complex nature of what is being learned. The framework used here is also simple enough that it could be mobilized by educators as a way to notice, understand, and evaluate student learning in a makerspaces, purely through a combination of observations and self-reports. As we saw from the cases presented here, Mr. Williams already engaged, informally, in some of the same types of evaluation highlighted by this framework, in recognizing and valuing Emil's work with Piskel, and noticing differences in Amadia's engagement in FUSE and her engagement in other school subjects. The fact that Mr. Williams — a teacher who had initially been identified as only moderately well aligned with the culture of FUSE — recognized, and seemed to value, the excitement about schoolwork that Emil demonstrated in FUSE, shows what the culture of FUSE allows, what it normalizes, and how relatively easily the type of teacher thinking required to evaluate student learning using this framework would be to cultivate in this sort of context.

The successful application of this framework to the activities in FUSE also leaves an open question about whether similar forms of qualitative assessment could be used in other school learning contexts. Arguably, the basic questions posed by this framework — what is learned within activities, across activities, and across contexts, and where we can see evidence of learning endogenously in students' activity — haven't really been asked, in qualitative ways, about other forms of school learning. In some ways, FUSE is an easier context, in which to ask these sorts of questions and demonstrate learning in these ways, because of the leveling-up structure of challenges, choice, and the absence of carrots and sticks present in conventional classrooms (e.g., grades, assignments, due dates). However, showing that we can evaluate learning in this way in a non-standard context like FUSE, raises the question of whether such a framework might be applied to traditional learning in schools as well, and whether that might have advantages over our current system of exogenous assessments (e.g., written reflections, worksheets, classroom exams, and standardized tests).

The cases presented in this chapter also enhance our understanding of interest and what it looks like in a choice-based makerspace environment like FUSE. The cases show that the way interest develops — what it is initially tied to and how it influences activity, engagement, and identity — is somewhat unique to each individual. For example, an initial interest in the Keychain Customizer challenge and 3D printing led Amadia to simply make a keychain, then move on to another challenge. In contrast, for Carmen, it led to a specific and prolonged interest in the 3D printer and later to a desire to help people by becoming a pediatric oncologist. However, they also show interest playing at least five recurring, and critical, roles in learning in this sort of context. First, interest served a spark that influenced the choice of particular projects or challenges. Second, interest was the motivator that pushed students to continue with projects or challenges, even when they presented obstacles or difficulties, and to put in the work of adaptive problem-solving or organizing people and material resources to make sure students could complete the task at hand. Third, interest distinguished FUSE activities as more engaging than regular school. Fourth, initial interest in challenges helped shape later STEAM career interests and identities. Finally, as interest developed, it became the motivator for engagement in activities that extended beyond the makerspace activities and context.

Thinking about interest as playing these different roles in learning has important implications for how we think and talk about other current issues in learning. For example, one concept that has gotten a lot of attention, both in education research and in the popular media, recently, is *grit* (Duckworth, Peterson, Matthews, & Kelly, 2007), or the ability to persevere in the face of challenge or difficulty. I believe the findings presented here suggest that rather than focusing on grit as a personal quality that should be encouraged in students, what we should be focusing on is interest, and how educators can help cultivate it. I say this because in the cases shared here, and in other cases from the FUSE data corpus, there are many examples of *productive frustration* (Illeris, 2006) or students encountering a problem, getting frustrated, and sometimes complaining about how hard things are, but then working through that frustration, and in the end, reflecting positively on their experiences. Because I have seen this across multiple students during their engagement in FUSE and, in cases such as Amadia's, can directly contrast this orientation to FUSE with a very different orientation to regular school, it doesn't seem quite right to attribute this to an individual personality attribute like grit. Instead, the data suggests that it is attributable to interest. What determines whether students will persist in the face of difficulty is their interest in the task they're completing or goal they're trying to achieve, not some static personality trait within the student. If they're not persisting in this way during their work in other school classes or subjects, it's likely because they're not interested, and consequently not motivated to do so. In other words, if children are interested in what they're doing and have some control over the goals they're working toward, they will be willing to work hard to achieve those goals. It is when they're forced to engage in tasks they didn't choose, don't understand, or don't value that persistence or "grit" becomes a problem. This has important implications for educational design, suggesting that if we care about persistence and the skills such as critical thinking and adaptive problem-solving that go with it, we should be thinking in terms of designing learning activities and environments that invite, spark, and allow room for the development of student interest.

These cases also provide us with a better understanding of how interest might develop in a makerspace environment like FUSE. FUSE allows learners to bring in and incorporate interests and practices from other areas of their lives. As a result, those interests become paired with and changed by learners' experiences in FUSE. Further, the same permeable membrane that allows learners' interests into FUSE, makes it easier for learners' to extend the interests developed in FUSE out into other contexts. In the last analysis chapter of this dissertation, Chapter 5, I elaborate more on this model, by following students across contextual boundaries, to see what interests and practices make it across these boundaries. However, here, I want to highlight the importance of the principles of choice and permeability of context, as possible mechanisms for interest development. This is an important contribution to the literature on interest, as there are many paper on interest, but very few that account for the mechanisms underlying interest development. It also has important implications for the design of maker spaces or other activity systems for learning, because it suggests that systems that allow interests in and make space for the development of those interests may make it easier for learners to extend those interests, and the learning and practices that get paired with them, out into subsequent STEAM learning contexts.

The cases described in this chapter, of students on different interest pathways, engaging in FUSE activities in different ways, also speak to an ongoing tension in research on the design of making activities. This tension is between designing making activities that promote a prescribed, planful, engineering design approach or those that promote a more open-ended tinkering approach to making. The different types of interest pathways presented here correspond to these different orientations towards making. For example, learners on a completing pathway seem more driven by a desire to complete prescribed challenge levels or challenge sequences in the suggested order (more of an engineering design approach). In contrast, learners on a sampling pathway seem to be more concerned with exploring possible options or tinkering with tools and materials, rather than being overly constrained by prescribed goals (more of a tinkering approach). Meanwhile, learners on a diving or off-roading pathway may have more of an engineering design mindset, but one that stems authentically from their own goals and interests, rather than a set of goals and interests prescribed by an instructor.

Given that the cases presented here demonstrate that there is rich learning and interest development occurring along each of these pathways, there is a strong case to be made for designing makerspaces in the way FUSE is designed, which allows for both types of engagement within the same activity system, rather than privileging one over the other. In other words, the data presented here suggest that, rather than debating the relative merits of engineering design versus tinkering approaches to making, we should acknowledge that different learners, much like different educational designers, may prefer one or the other, and design activity systems that allow for both.

This leads to one last, important, implication of the findings presented here. That is the way in which these findings speak to issues of equity and inclusion in the design of making activities and makerspaces. Of the focal students described in the cases presented here, five of six are female students and four of six (Amadia, Andrea, Victoria, and Carmen) are from historically underrepresented minority groups. My analysis of their cases shows at least two important things about FUSE and about designing makerspaces for equity and inclusion. Not only did FUSE not provide some of the barriers to entry that other out-of-school makerspaces provide to these students (Lewis, 2015), but it also provided a space in which they were able to meaningfully engage and cultivate STEAM-related interests, skills, and practices. I would argue that this is the result of two key features of the FUSE environment. The first is the choice-based nature of FUSE, which allows learners to pursue projects of interest to them in ways that work for them (working either alone or with others, taking either an engineering design or tinkering approach, etc.) The second is by supporting novices and experts working side-by-side, assisting one another, and continually shifting roles in ways that challenge deficit views and support more inclusive learning and development. Therefore, as we think about designing makerspaces, as well as other learning activities and environments for equity and inclusion, considering the role of interest in learning and designing for choice, both in activity and approach, should be primary design concerns.

Chapter 4. Spatial Thinking and Learning in Makerspace Activities

In Chapter 3, I presented examples of different learning pathways through FUSE, exploring the ways in which individual interests led to different types of learning in FUSE. Here, I will look at the challenges themselves, examining how specific challenges tend to facilitate particular types of thinking and learning. In this investigation, I will focus on one particular set of skills, spatial skills. Spatial skills are far from the only skills learned in FUSE or other makerspaces. However, they serve as one example of a set of meta-disciplinary skills that are developed in FUSE, and this chapter provides an example of how to look across FUSE activities (i.e., challenges) to show their development. I chose spatial skills in particular, as a focal case of meta-disciplinary skill learning, as prior research suggests that the types of hands-on activities found in makerspace contexts like FUSE should do a particularly good job of cultivating these skills (e.g., Levine, et al., 2011; Ping, et al., 2011; Ramey & Uttal 2017; Ramey & Uttal, 2017). However, they are conspicuously absent from the literature on learning in makerspaces.

In other words, unlike traditional textbook learning, hands-on, project-based, learning activities, like the ones found in FUSE, have the potential to spatialize (Newcombe, et al., 2013) STEM content, by situating learning within work with physical and digital objects and spatial representations, rather than limiting it to the verbal and analytic domains. This is important for at least three reasons. First, spatial skills, in the psychometric sense, uniquely predict performance in college STEAM courses (e.g., Hsi et al., 1997; Sorby, 1999; Sorby, 2009; Sorby & Baartmans, 2000; Sorby, et al., 2013; Tseng & Yang, 2011) and entry into STEAM disciplines (e.g., Humphreys et al., 1993; Lubinski, 2010; Shea et al., 2001; Wai et al., 2009). Second, spatial thinking and problem-solving, in the situated and distributed sense, play a central role in the practices of STEAM professionals (e.g., Dogan & Nersessian, 2010; Stevens & Hall, 1998) and are often used in everyday thinking and learning (e.g., Hutchins, 1995a; Scribner, 1984; Wagner, 1978). Finally, recent research has demonstrated that spatial skills are highly malleable (e.g., Uttal et al., 2013) and thus can be improved through instruction or hands-on experience. Unfortunately, traditional, textbook learning often de-emphasizes spatial thinking, in favor of verbal or analytic approaches to knowledge. As a result, spatial skills are systematically undervalued and underdeveloped in our schools (e.g., NRC, 2006; Schultz, et al., 2003; Newcombe et al., 2013).

Spatial Thinking with Other People, Tools, and Representations

Both cognitive developmental studies and sociocultural research provide insights into why makerspaces like FUSE might facilitate spatial thinking. For example, object manipulation, in the form of puzzle play or manual rotation, has been shown to improve preschoolers' spatial transformation or mental rotation skills (Levine, et al., 2011; Ping, et al., 2011). Developmental studies also suggest that engaging young children in talk and gesture about spatial ideas may improve spatial skills (Ping et al., 2011; Pruden, Levine, & Huttenlocher, 2011). Because making activities provide opportunities for discussing and manipulating spatial objects and ideas, these activities may have similarly advantageous outcomes for improving spatial skills, but little work has tested this hypothesis directly.

Situated and distributed accounts of learning (e.g., Cole, 1996; Hutchins, 1995a; 1995b; Lave & Wenger, 1991) also suggest that objects, representations, and collaborations with other people in the activity system (Engeström, 1987), will play as important a role in spatial thinking and learning as internal cognitive processes. For example, Stevens & Hall, (1998) described a case of a student working with a tutor to learn about Cartesian geometry. Working together, they used a combination of paper and pencil, computer software, and gesture to work through and make sense of a series of calculations and graphing activities. These tools, and the spatial understanding of Cartesian grids and graphing translations that they facilitated, became central to the student's understanding of these mathematical concepts. The authors went on to demonstrate how professional engineers coordinated arrangements of people, tools, and representations in similar ways while designing a roadway. They then contrast this to the ways in which math problems are taught and assessed in schools, where analytic approaches (i.e., formulas and calculations) are emphasized over spatial ones (i.e., graphs) and where students are deprived of the very tools (e.g., CAD software, coordinate grids) and collaborative structures (e.g., talking and gesturing through spatial ideas) that might best assist them in solving these sorts of problems. In other words, the case of the student using paper space to make geometric inferences, while working with his tutor, may more closely resemble the daily work of engineers than what we typically think of as engineering or math problem-solving. Stevens and Hall's (1998) findings have important implications, not only for how we think about teaching STEM content in schools but also for how researchers go about examining spatial thinking and learning. Primary among these is that any investigation into spatial thinking and learning should attend to ways in which this thinking and learning might be supported by both collaboration and the use of specific tools and representations.

Focusing on the role of specific tools and technologies in shaping spatial thinking may be particularly important in learning environments like makerspaces, where many activities depend on new hardware and software tools, like 3D Printers, Arduinos, and CAD and computer programming software. While on the one hand, providing access to such tools has the potential to engage and empowers learners and help prepare them for future educational and career endeavors using similar tools and technologies (Dewey, 1897; Papert, 1980; Resnick et al., 2009; Rogoff, 2003), these new learning tools and technologies also leave us with interesting open questions regarding the skills and practices they facilitate.

Despite the overall lack of research, prior studies do suggest ways in which specific tools and technologies available in makerspaces might shape spatial thinking. For example, studies on both K-12 and college students show that designing 3D objects in CAD software is both spatially demanding and, if done in particular ways, can lead to improvements in spatial visualization skills (Basham & Kotrlik, 2008; Onyancha, Derov, & Kinsey, 2009; Shavalier, 2004). Some studies suggest that allowing opportunities for mapping between 3D CAD models and physical models (created by instructors) or between CAD models and sketches (created by students) can be particularly instrumental for improving spatial visualization skills (e.g., Onyancha et al., 2009; Sorby, et al., 2013). However, few of these studies have examined the *how* of spatial thinking and learning with technology tools such as CAD software and 3D printers. This leaves open questions regarding how students make sense of CAD models, and what types of spatial skills, other than spatial visualization, they might employ to do so.

Situating Spatial Thinking Research Within Real-world Making Activities

Another takeaway from Stevens and Hall's (1998) work is that to fully understand how students make sense of the types of spatial problems that arise during making activities and how they use various tools, representations, and other people to do so, it is necessary to examine their thinking, learning, and problem-solving in the context of real-world making activities. Traditional laboratory and psychometric assessments of *spatial skills* deprive participants of many or all of the tools and collaborative structures available in everyday problem-solving contexts. Thus, traditional laboratory studies cannot help us understand *why* spatial thinking matters or *how* individuals learn STEAM-relevant *spatial skills* and *spatial practices* in real-world learning contexts. To investigate these questions of mechanism, we need to look at these activities in context, through a more situated and distributed lens, taking an *endogenous*, rather than *exogenous* approach to studying spatial thinking in use (Hall & Stevens, 2015; Stevens, 2010).

Such a situated account has the added advantage of helping us understand what other meta-disciplinary skills and practices making activities facilitate, either in addition to or in coordination with spatial thinking and problem-solving. Lemke, Lecusay, Cole & Michalchik (2015) propose a potential set of answers to this question, based on a review of research on informal, media-rich, inquiry-based, learning activities (such as science learning in a museum or computer-programming in an after-school program). They suggest that such activities tend to promote a combination of cognitive and socio-emotional learning outcomes, and help learners develop practices related to independent inquiry, collaboration, design iteration, and the ability to draw on social and material resources to solve problems.

One open question is how spatial thinking and problem-solving might play a role in the development of these other meta-disciplinary skills in makerspaces. From work by Stevens (2000) on professional architects' and architecture students' collaboration and distribution of labor, we might conclude that particular tools and representational forms found in makerspaces (e.g., CAD software versus pencil and paper drawing) would provide different affordances and constraints for collaboration. In other words, the particular tools and technologies being used in different making activities would strongly influence what skills are learned and how they are learned. Given that much of the work of design iteration and inquiry in makerspaces relies upon spatial representations and tangible tools (like CAD software and 3D printing), we have reason to believe that spatial thinking would be both critical to the learning of these other skills and practices and strongly shaped by the particular tools and technologies available within the makerspace context.

In examining the interplay between people, objects, and different representational or semiotic forms in makerspace classrooms, I draw on prior work from Hutchins (e.g., Hutchins, 1995a; 1995b; Hutchins & Klausen, 1996), Goodwin (2000), Latour (2005), and Stevens and Hall (Hall & Stevens, 2015; Stevens, 2010; Stevens & Hall, 1998). From Hutchins, I draw the notion of tracing the propagation of representational states (in this case spatial representations) across different representational media in a distributed cognitive system. From Goodwin, I draw the similar idea that human action is built through the coordination of a range of different semiotic resources and that tools and representations can provide semiotic structure to the actions being invoked. From Latour, I draw the importance of attending to the role of both human and non-human actors in sensemaking or problem-solving processes and the ways in which these human and non-human actors are assembled into networks, in context. Finally, from Stevens and Hall, I draw framing on how to use these situated and distributed lenses specifically to examine learning, specifically learning how to read and work with spatial representations. Applying these prior theoretical lenses to looking at spatial thinking in makerspaces, we must conclude that it is critically important not only to examine spatial thinking within the sociomaterial context in which it is authentically learned and applied but to: (1) examine the specific interactions between people, tools, and representations through which spatial thinking and learning are enacted and developed; and, (2) to trace specific spatial representations across representational media (e.g., from external representation to mental representation to representation through talk or gesture, etc.), in order to understand how spatial understandings are distributed to or co-constructed by learners and their sociomaterial context.

This approach seems an obvious one for understanding spatial thinking, particularly if we are interested in how specific tools, representations, and collaborative forms available in a particular learning environment might shape spatial thinking and learning, as so much of spatial thinking seems to be dependent upon the coordination of internal and external spatial representations. However, it stands in sharp contrast to the ways in which spatial thinking has generally been studied (in laboratories or through correlational studies). The analyses presented in this chapter are part of a line of work (see also Ramey & Uttal, 2017) which frames spatial thinking not just as a set of cognitive processes or skills but also as a set of distributed practices, which draw on context- and activity-specific social and material resources (i.e., *distributed spatial sensemaking*). This line of work fills a gap in prior literature in understanding how spatial thinking is used, learned, and can be evaluated, endogenously, within the context of STEAM learning activities. The analyses presented in this chapter extend this line of work by examining how learners make sense of the spatial problems that arise in makerspaces like FUSE, what resources and practices they draw on to do so, and how we might design or redesign future making activities or spaces to better cultivate a range of spatial skills and practices.

Focusing on Student Thinking and Learning Rather than Teaching

In embarking on that effort, I believe it is also important to highlight an additional mismatch between prior literature on the relation between spatial thinking and learning the type of investigation I have undertaken here. The vast majority of the previous studies that have addressed the role of gesture, tools, and representations in shaping spatial thinking and STEM learning have done so in the context of didactic, teacher-led instruction on specific, narrowly constrained STEM topics or problems (for one notable exception, see Kolvoord, Uttal, & Meadow, 2011). In some of this work, instructors or researchers have presented specific STEM content paired with specific gestures, actions, or representations, in order to improve student understanding of things like topographic maps (Atit, Weisberg, Newcombe, & Shipley, 2016) and elementary mathematics (Congdon & Levine, 2017). In other work, students themselves have been trained to use specific gestures or actions with tools or representations, in order to understand STEM concepts, such as measurement (Novack, Congdon, Hermani-Lopez, & Goldin-Meadow, 2014) or the structure of molecules (e.g., Stull & Hegarty, 2016). In contrast, learning in makerspaces (and particularly in choice-based makerspace environments like FUSE) tends to be more student- and inquiry-driven and spans a wide variety of tools and concepts. This necessitates a shift in focus away from the ways in which didactic instruction can be modified to convey spatial information or ways in which students can be trained to approach specific problems more spatially and toward: (1) understanding the ways in which students spontaneously engage in spatial thinking and problem-solving; (2) examining how they draw on social and material resources and practices to do so; and then (3) designing activities that provide them with the right task constraints to encourage particular types of spatial thinking and the right array of resources to draw upon to do so productively.

This shift in focus is doubly important, because even within the spatial training literature, one of the big open questions about spatial training interventions is whether they lead to durable and transferable improvements in spatial skills (NRC, 2006; Uttal et al., 2013). Although some interventions do seem to lead to at least limited durability and transfer, our understanding of what and how spatial skill improvements last is limited by the ways in which they're measured in such studies (Uttal et al., 2013). We might expect that more learner-driven, interested-based spatial problem-solving would lead to deeper, more long-lasting learning (e.g., Lemke et al., 2015; Papert, 1980; Resnick et al., 2009), but then the question becomes how to seed such open-ended learning environments with the types of spatially-rich activities and problems through which learners might develop these spatial skills. We might also expect that when the outcome we're interested in is real-world spatial problem-solving, not performance on a psychometric assessment, then the availability of and a learner's ability to draw on external, social and material resources may become as or more important than his or her cognitive spatial skills (e.g., Cole, 1996; Hutchins, 1995a; 1995b; Stevens & Hall, 1998). However, we know relatively little about how or whether spatial thinking and learning might occur within the context of more open-ended, student-driven activities, such as those found in makerspaces, and what their real-world consequences, in terms of spatial thinking and problem-solving, are (beyond performance on psychometric tests).

Examining Distributed Spatial Sensemaking in Makerspace Classrooms

The present study seeks to address some of these open questions regarding spatial thinking in learning in makerspaces, specifically:

1. How do students make sense of spatial phenomena or spontaneously engage in spatial thinking and problem-solving, in the context of making activities?
2. What role do specific tools, representations, collaborative forms, and activities play in shaping spatial thinking and learning in a makerspace?
3. How might spatial thinking and problem-solving play a role in the development of other disciplinary and meta-disciplinary skills in makerspaces?

In answering these questions, I draw on prior work by Ramey and Uttal (2017), applying the concept of *distributed spatial sensemaking* — the idea that learners both employ cognitive spatial processes and draw on context- and activity-specific social and material resources to co-construct understandings of spatial phenomena — to shed light on how learners make sense of the spatial problems that arise in makerspace environments like FUSE. I draw upon this prior work by using our analytic techniques — coding multiple modalities of thought and communication, such as talk, gesture, and object manipulation for evidence of various types of spatial thinking. However, I also expand upon their prior work by applying their theory and analysis to understanding spatial thinking within a different context and set of activities (a more choice-based, student-driven makerspace environment, rather than an instructor-led engineering camp).

In doing so, I draw on our finding that different types of activities (engineering design versus construction kit) facilitated different types of spatial thinking and that these differences were related to the types of representations (verbal versus diagrammatic instructions) learners needed to make sense of to complete these different activities. I apply these insights by focusing my examination of spatial thinking in the makerspace context on the ways in which different making activities and different tools, representations, and collaborative forms shape the ways in which spatial thinking unfolds in context. The wide variety of challenges available in FUSE, the similarity in structure between the challenges, and the way in FUSE allows students to draw on heterogeneous resources for problem-solving makes this sort of activity comparison possible. Such a comparison provides insight into the specific making activities educators might use in order to promote specific types of spatial thinking. It also provides insight into ways in which existing activities could be augmented with particular tools, representations, or enticements toward particular collaborative forms that might better facilitate spatial thinking and learning or learning of related STEAM skills and practices.

I also expand upon Ramey and Uttal's (2017) prior work by explicitly focusing on learning, examining how spatial thinking changed over time during participation in different FUSE activities, and how spatial thinking led to other types of problem-solving insights and the development of related STEAM skills and practices. This investigation provides insight into how making activities might be used not only to elicit spatial thinking and problem-solving but also to improve STEAM-related spatial thinking and problem-solving skills and practices.

Data Analysis

In this investigation, I used an analytic approach informed by the one used by Ramey and Uttal (2017), which integrates insights from cognitive, situated, and distributed perspectives and attends to evidence of both cognitive spatial processes and socially and materially-distributed sensemaking practices. However, I also expanded upon and modified this prior analytic approach in a few specific ways to better fit the data analyzed here. First, where Ramey and Uttal focused their analysis on *episodes* of distributed spatial sensemaking, here, I applied their qualitative categorical coding scheme to multimodal *idea units* (Chafe, 1979; 1980). Importantly, by *idea units*, here I refer not only to such units as they are defined by discourse analysts, as audible chunks or divisions in the flow of talk, marked by rising and falling intonation and pausing (akin to commas and periods; Gee, Michaels, & O'Connor, 1992), but also to idea units expressed through modalities other than talk, such as gesture and object manipulation, and separated by visible pauses or by distinct, independently meaningful (to participants) strokes. I used multimodal idea units as my unit of analysis in order to understand not just how spatial thinking was used to solve spatial problems (the focus of Ramey and Uttal's analysis) but also how spatial thinking was used throughout FUSE activities to potentially solve a variety of different types of problems. Then, in my analysis of episodes, I used interaction analysis (e.g., Goodwin, 2000; Hall & Stevens, 2015; Jordan & Henderson, 1995; McDermott, et al., 1978; Mehan, 1982) in combination with Ramey and Uttal's categorical coding scheme in order to better understand not just *what* cognitive processes and practices were being used, but *how* they were being used in interaction and what it was about the specific sociomaterial conditions and task constraints of the FUSE activities that led to their use. Finally, in the places where I did use Ramey and Uttal's coding scheme I added, subtracted, and modified certain categories to better fit the data analyzed here. In the sections that follow, I detail both the parts of this prior analytic approach that I've used and the ways in which I've expanded upon or modified it for my purposes here.

Case Selection. To analyze sensemaking across the 24 different FUSE challenges available to students during my observations, I first content-logged all of the video I collected for which challenge(s) students were working on during a given video file. For each activity, I then selected two different, contrasting, cases of a student or group of students doing the activity. In selecting these cases for analysis, it became clear that some activities had been much more popular with students in my sample than others. For example, while almost every student in my sample did the *Dream Home* challenge, there were six challenges (*Crystal Ball, Party Lights, Music Amplifier, Just Bead it, How to Train your Robot*, and *Jewelry Designer*) for which I had either no video data of students doing that challenge or video data of only one student or group of students doing the challenge. Therefore, I eliminated these six challenges from my analysis, in order to have a firmer base upon which to construct the case for ways in which particular challenges afford the development of specific spatial skills.

For the remaining 18 challenges, I selected student cases based first upon the amount and quality of the video I had on each case. For example, in my selection of a first case for analysis for each activity, I privileged cases where students actually worked most or all the way through the challenge and where I had video data on most or all of that process. Then, in selecting the second student case from each challenge, I chose a case that contrasted with the first case along one or more theoretically important dimensions. For example, if the first student case was an individual student working on a challenge alone, I looked for a second case where a group of students worked on that challenge together. Similarly, if one case was a fifth grader doing a challenge, for the second case, I looked for a sixth grader. Finally, if the first case was a student who worked systematically through multiple levels of a challenge, for the second case I looked for students who took more of a sampling or tinkering approach to the challenge (just trying it out, but not systematically going through levels or adhering more loosely to challenge instructions). For each of these cases, I analyzed all of the video data I had on them doing a given challenge. As a result, the video that I analyzed for each student case ranged in length from one (30-60 minute) class period to fifteen class periods (i.e., up to 15 total hours of video).

Coding Process. I coded this video data from student cases in two stages, to allow for iteration in my coding scheme and later analysis. In the first stage, I took one batch (approximately one third) of the video and created multimodal transcripts of the data, then coded that data using the coding scheme derived from Ramey & Uttal (2017). However, during this first round of coding on transcripts, I also made iterative changes to that coding scheme based on new information or patterns I observed in the data that weren't accounted for in my initial coding scheme. Then, once I was confident that my coding scheme was solidified, in the second round of analysis, I imported this coding scheme into the video analysis software program, Studiocode and coded the remaining video directly on the video record (without the intermediate step of transcription). I broke up the process in this way, because while, on the one hand, coding from transcripts is much more time consuming than coding directly on video, on the other hand, it is also somewhat easier to go back and revise codes on transcripts than it is on video, in Studiocode. Thus, starting with a set of transcripts, while I was finalizing my coding scheme, then moving to Studiocode, once that coding scheme was finalized, allowed for the greatest balance of efficiency and flexibility in my coding process. Finally, during these first two rounds of categorical coding, I also selected clips for more detailed interaction analysis (e.g., Goodwin, 2000; Hall & Stevens, 2015; Jordan & Henderson, 1995; McDermott, et al., 1978; Mehan, 1982; Schegloff, 1992). I present transcripts of many of these clips in the findings section of this chapter, because they demonstrate *how* students used the spatial processes, sensemaking practices, resources I coded for to solve problems in the context of the different FUSE activities.

Categorical Coding Scheme: Analyzing Cognitive Spatial Processes. To analyze the types of cognitive spatial processes learners engaged in during FUSE activities, I maintained Ramey and Uttal's (2017) use of a recent taxonomy, derived from cognitive, psychometric, and linguistic research (Newcombe & Shipley, 2015; Uttal, et al., 2013), which classifies cognitive spatial processes along two orthogonal dimensions: intrinsic-extrinsic and static-dynamic. Intrinsic-extrinsic refers to whether the spatial information pertains to an individual object or relations among multiple objects or reference frames (Uttal et al., 2013), while static-dynamic refers to whether or not the information that is coded involves motion or transformation or not (Uttal et al., 2013). Using these dimensions, it is possible to divide spatial processes into four categories (See Figure 4.1): intrinsic-static (e.g., categorizing space), intrinsic-dynamic (e.g., mental rotation), extrinsic-static (e.g., locating an object or self with respect to a frame of reference), and extrinsic-dynamic (e.g., perspective taking).

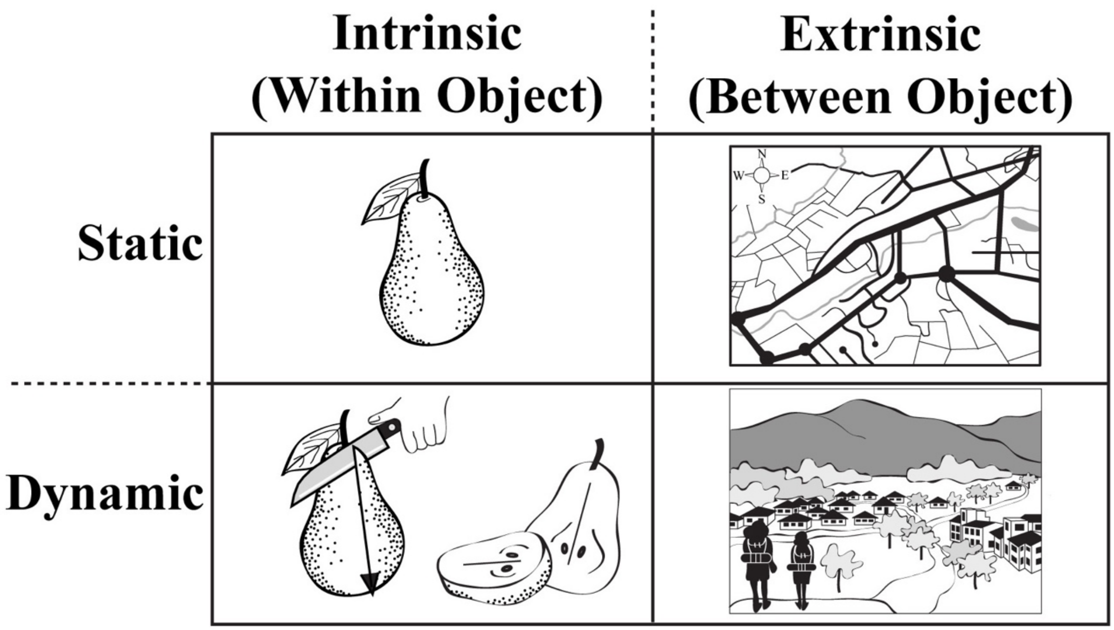


Figure 4.1. A 2 x 2 classification of spatial skills and examples of each spatial process.

This taxonomy helps us to identify cognitive processes that may be relevant to learning in making activities. For example, intrinsic-dynamic spatial processes, such as mental rotation, spatial visualization, 2D to 3D translation, cross-sectioning, and mental simulation, have been identified in laboratory and correlational studies as particularly predictive of engineering success (e.g., Hegarty, 1992, 2004; Hsi et al., 1997; Sorby, 1999, 2009; Sorby & Baartmans, 2000; Sorby et al., 2013; Tseng & Yang, 2011). However, as Ramey and Uttal (2017) found, attending to the full taxonomy also helps us identify cognitive spatial processes from other quadrants that might be important in STEAM learning but overlooked by studies which use only the standard intrinsic-dynamic psychometric assessments to measure spatial thinking and learning.

Using the model laid out by Ramey and Uttal (2017), in applying this taxonomy to interactional data from classroom video, I used definitions of different spatial skills from the literature to derive qualitative codes for different types of spatial thinking. This coding was done in an iterative fashion, with categories solidified through conversation between the data and the relevant literature. As a result, the final coding categories used in the analyses presented here diverge slightly from those used by Ramey and Uttal (2017), with some of their categories not appearing, because they didn't fit this dataset and others being added to their scheme in order to provide more thorough or nuanced descriptions of this dataset. Additionally, certain codes were derived purely from the data, rather than from the literature, as categories of spatial skills described in the literature seemed either to broad or ill-fitting of the data at hand (See Table 4.1).

Table 4.1
Cognitive Spatial Processes Identified as Part of Distributed Spatial Sensemaking

Category	Definition	Cognitive Process	Definition
Intrinsic-Static	"Perceiving objects, paths, or spatial configurations amid distracting background information" (Uttal, et al., 2013, p. 4)	Disembedding (Newcombe & Shipley, 2015)	Distinguishing shapes or objects from distracting background information
		Categorizing Space (Newcombe & Shipley, 2015)	Describing or labelling individual shapes or objects
		Quantifying space	Attaching numerical measurements, dimensions, or counts to objects
Intrinsic-Dynamic	"Piecing together objects into more complex configurations, visualizing and	2-D to 3-D Translation (Newcombe & Shipley, 2015)	Relating or translating between 2-D and 3-D representations
		Mental Rotation	

	mentally transforming objects, often from 2-D to 3-D, or vice versa. Rotating 2-D or 3-D Objects" (Uttal, et al., 2013, p. 4)	(Newcombe & Shipley, 2015)	Mentally representing and rotating 2D and 3D objects in space
		Mental Simulation (Hegarty, 2004)	Visualizing dynamic motion of a static object or representation
		Scaling or Scale Changes	Visualizing scale changes of objects
		Mental Folding (Harris, Hirsh-Pasek, & Newcombe, 2013)	Spatial visualization involving the folding of 2D patterns or materials into 3D objects and representations
Extrinsic-Static	"Understanding abstract spatial principles, such as horizontal invariance or verticality" (Uttal, et al., 2013, p. 4)	Spatial Relations (Newcombe & Shipley, 2015)	Visualizing or describing relatio between objects or between self objects
		Describing Relative Size	Similar to spatial relations but specifically about the relative size of objects (e.g., big, small, bigger, smaller), in other words, relative properties of objects versus relative location of objects
Extrinsic-Dynamic	"Visualizing an environment in its entirety from a different position" (Uttal, et al., 2013, p. 4)	Perspective Taking (Newcombe & Shipley, 2015)	Updating static representations given self-movement
		Dynamic Spatial Relations	Updating static representations given movement of objects

The resultant set of codes were applied to multimodal idea units (Chafe, 1979; 1980), or idea units expressed through any external modality of thought and communication, including talk, gesture, and object manipulation, and coded in the context of the rest of the transcript or interaction, rather than in isolation. In conducting this analysis, I drew particularly on prior work in which talk, gesture, object manipulation, or sketching have been used as evidence of mental models of spatial phenomena (e.g., Sauter, Uttal, Alman, Goldin-Meadow, & Levine, 2012; Singer, Radinsky, & Goldman, 2008; Vosniadou & Brewer, 1992) and on work demonstrating cognitive and developmental links between spatial thinking and spatial talk, gesture, or object manipulation (e.g., Göksun, Goldin-Meadow, Newcombe, & Shipley, 2013; Levine, et al., 2011; Ping et al., 2011; Pruden et al., 2011).

Categorical Coding Scheme: Analyzing Sensemaking Practices and Resources Used. Again, drawing upon and modifying Ramey and Uttal's (2017) prior analysis, I also coded students' contextualized, multimodal, idea units for a number of sensemaking practices. The first of these was object manipulation, which I divided into categories of epistemic (for the purpose of understanding something) and explanatory (for the purpose of explaining or demonstrate something to someone else), both of which are distinct from pragmatic object manipulation (for the purpose of moving physically or digitally closer to a construction goal; Kirsh & Maglio, 1994; Ramey & Uttal, 2017). The second was gesture, which I divided into pointing or diectic (e.g., Goodwin, 2000) gestures, gestures representing static spatial arrangements (note that the gestures themselves are not static, just the arrangements they're representing), and gestures representing dynamic spatial processes. The third was sketching, and the fourth was spatial analogical reasoning or "comparing one set of spatial properties or relations to another, attending to similarities and/or differences" (Ramey & Uttal, 2017, p. 290). Drawing on the structure mapping theory of analogy (e.g., Gentner, 1980; Gentner & Markman, 1997), I divided these spatial analogies analogies into those conveyed purely through talk and facilitated by physical alignment of objects with one another or objects with diagrams.

Then, expanding upon Ramey and Uttal's (2017) coding scheme, and drawing on prior work by Hutchins (1995a, 1995b), Goodwin (2000), and Latour (Johnson, 1988; Latour, 2005), I also coded participants' idea units for both the human and non-human resources they were drawing on to aid in spatial sensemaking and problem-solving. In the FUSE activities, these resources included diagrams, instructional videos, written instructions, other students' descriptions (multimodal), instructors' descriptions (multimodal), and tinkering with or exploring materials.

Interaction Analysis. Finally, in addition to categorical coding, I applied interaction analysis (e.g., Goodwin, 2000; Hall & Stevens, 2015; Jordan & Henderson, 1995; McDermott, et al., 1978; Mehan, 1982; Schegloff, 1992) to selected episodes of spatial thinking and learning. This is a method for "the empirical investigation of the interaction of human beings with each other and with objects in their environment…[investigating] human activities, such as talk, nonverbal interaction, and the use of artifacts and technologies, [and] identifying routine practices and problems and the resources for their solution" (Jordan & Henderson, 1995, p. 39). I chose to employ this particular analytic method, in conjunction with categorical coding, because it is the methodological consequence of seeing cognition as socially and ecologically distributed (Jordan & Henderson, 1995). As Jordan and Henderson (1995), write,

> Interaction analysis finds its basic data for theorizing about knowledge and practice not in traces of cranial activity (e.g., protocol or survey interview data), but in the details of social interactions in time and space and, particularly, in the naturally occurring, everyday interactions among members of communities of practice (p. 41).

As a consequence, interaction analysis not only aligns with a situated and distributed theoretical lens on learning but has unique affordances for understanding how thinking and learning unfold in moment-to-moment, multimodal interactions between people, objects, and representations. In other words, while the categorical coding scheme I've used allowed me to determine *what* spatial processes, sensemaking practices, and resources were used by students during FUSE activities, by using interaction analysis and applying Schegloff's (1992) principals of *relevance* and *procedural consequentiality*, I was able to look at which of those processes, practices, and resources actually mattered for sensemaking, and through a turn-by-turn analysis of the interaction demonstrate *how* they mattered.

Findings

My analyses yielded several findings related to spatial thinking and STEAM learning in the context of FUSE activities. In the sections that follow, I detail these findings, focusing on three primary assertions. First, in making sense of and working through FUSE challenges, students engaged in frequent and diverse forms of spatial thinking and drew on a variety of both social and material resources, often in coordination with one another. Second, the different sociomaterial contexts and task constraints of different FUSE challenges facilitated different types of distributed spatial sensemaking. Third, over time, the spatial thinking occurring during different FUSE challenges led not only to improvements in spatial thinking, but also to problem-solving insights and STEAM learning.

Spatial Thinking in Making. Across all the data I analyzed of students working through FUSE challenges, I found 9393 instances of spatial thinking demonstrated through talk, gesture, or object manipulation. Among these, I found evidence of students engaging in 13 different types of spatial thinking, spanning all four quadrants of the two by two grid (i.e., intrinsic-static, intrinsic-dynamic, extrinsic-static, and extrinsic-dynamic). The most commonly demonstrated set of spatial skills was extrinsic-static skills (57 percent of total instances of spatial thinking), including thinking about spatial relations between objects or between self and objects (54 percent) and describing relative size (3 percent). These were followed by the intrinsic-static skills (24 percent), including disembedding (17 percent), quantifying space (5 percent), and categorizing space (2 percent), then extrinsic-dynamic skills (11 percent), including perspective-taking (6 percent) and thinking about dynamic spatial relations between objects (5 percent), and finally intrinsic-dynamic skills (8 percent), including Mental Rotation (3 percent), 2D to 3D translation (3 percent), scaling or scale changes (1 percent), mental simulation (1 percent), and mental folding (less than 1 percent).

There are two things that are important to highlight in these findings. The first is the amount of spatial thinking going on during these activities (9393 instances). The second is the broad range of different spatial skills students demonstrated, and in particular, the relative infrequency of intrinsic-dynamic spatial thinking (8 percent or 713 instances), relative to other types of spatial thinking. This is important, because most of the psychometric tests used in correlational studies, test primarily for these intrinsic-dynamic skills. So, by relying only on those, it's clear that we're missing a lot of the spatial thinking that's actually going on in real-world problem-solving contexts.

Conversations with People and Tools. Another important aspect of spatial thinking in real-world learning contexts that laboratory and correlational studies fail to account for is the heterogeneity of social and material resources that students draw on to make sense of spatial concepts and how the use of those resources shapes spatial thinking. In making sense of the spatial aspects of the various FUSE challenges, students used a variety of both social and material resources, often in coordination with one another. Social resources included both the adults serving as FUSE facilitators and other students in the classroom. Material resources included diagrams, help videos, and written instructions from the FUSE website, as well as physical or digital materials specific to each challenge. Across the challenges, the most commonly used resource was other students (44 percent of total resources used). The second most common resource was the digital or physical materials themselves (i.e., learning or problem-solving through tinkering or exploring materials, 28 percent). This was followed by instructional videos (10 percent), the FUSE facilitator (9 percent), written instructions on the FUSE website (7 percent), diagrams on the FUSE website (3 percent), and sketching or sketches (less than 1 percent).

There are three things that are important to note in these numbers. First, that many of the resources students drew upon, such as help videos, diagrams, sketches, and tinkering with materials had strong, inherently spatial components, whereas others, such as other students, facilitators, and written instructions, were not inherently spatial but were able to convey spatial information through practices such spatial language, gesture, and object manipulation. The second thing worth noting is how infrequently students drew on the facilitator as a resource, relative to other resources available in the classroom. This contrasts with the structure of a traditional school classroom, where the teacher is the primary resource from whom knowledge is dispensed. This difference is important, as is emphasizes the need, when thinking about learning in makerspace environments, to move away from those traditional, didactic approaches to studying and improving spatial thinking and learning and toward looking at students' own spontaneous thinking and problem-solving with a variety of social and material resources.

Finally, a third thing that is interesting here is the interchangeable roles that people and materials often played in facilitating sensemaking and problem-solving during the various challenges. One way in which physical and digital materials served similar functions to people in interactions in FUSE studio was by giving learners feedback on whether they had executed the steps of a challenge correctly. For example, if an object wasn't designed properly in the CAD design software program Sketchup, a tool in the software would tell the student that it wasn't printable on the 3D printer. Similarly, during the *Solar Roller* challenge, if students didn't connect the wires or gears of their solar car correctly, it wouldn't run when placed under a light source. In fact, one group of students that I observed doing the *Solar Roller* challenge took the notion of the solar car serving the function of a person giving them feedback so literally that they started referring to it as "Mr. Solar Panels."

Another set of tools which served the role of people in distributed spatial sensemaking interactions was the help videos on the FUSE website. For example, I frequently observed students using the help videos on the FUSE website in much the same way that they used other students or facilitators, as just-in-time help resources. The following excerpt (Table 4.2) shows how two fifth grade students, Erin and Ajay, engaged in distributed spatial sensemaking with each other, a help video, and an array of materials, in order to assemble their solar car for the *Solar Roller* challenge.

Table 4.2
Erin, Ajay, and a Help Video Do the Solar Roller Challenge

Line	**Person**	**Talk**	**Actions**
1	Video:	The long leg of the capacitor is its positive end.[1] Okay? The red end[2] of the solar panel is its positive. Now the motor does not have a positive and negative.[3] So either one could be positive or negative. It's up to you. Alright to connect them all together, let's start with the capacitor. I'm going to uh just plug the capacitor right into the bread board.[4] Um, and you want to plug it in so that you're plugging into the long way[5] of the	[1]*Hands hold up capacitor, points to long leg.* [2]*Hands hold up red alligator clip and points to it.* [3]*Hands hold up IC hooks attached to motor.* [4]*Hands hold capacitor over breadboard.* [5]*Hand points to breadboard and draws vertical line with finger.*
2	Erin:		*Erin pauses video.*

3	Ajay:	Ok, now this is confusing.	
4	Erin:	I know it is.[1]	[1]*Erin plugs capacitor into bread board*.
5	Ajay:	We're missing parts.	
6	Erin:	[1]Ok, it's good.[2]	[1]*Erin finally gets capacitor in*. [2]*Erin resumes video.*
7	Video:	bread board like that[1]. Ok, now on the bread board each row of 5 holes is connected. So each of these 5 holes in this row is connected.[2] Each of these 5 rows in this, uh each of these 5 holes in this row are connected.[3] Um, so, to assemble it	[1]*Hand plugs capacitor into breadboard.* [2]*Hand points to holes.* [3]*Hand points to holes.*
8	Erin:	[God this is so hard.	
9	Video:	[what we want to do is connect all the positive ends. So this is the positive end of the panel.[1] It goes into the long leg row, which is the	[1]*Hand holds up red alligator clip and wire over breadboard.*
10	Erin:	[1]Ok, so the long leg. This is basically the long leg thing, so.	[1]*Erin pauses video.*
11	Ajay:	So put it in the same exact row.	
12	Erin:	In there, wait no, that's not, god! I'm so stupid.[1] Wait, yeah they meant this, so. So you put the,[2] where did it	[1]*Erin laughs*. [2]*Erin holds up a black wire and alligator clip*.
13	Ajay:	Where did the	
14	Erin:	Ah![1] Ok, just get in.	[1]*Erin looks under table*.
15	Ajay:	No, that's not it. Should I keep trying?	
16	Erin:	No just, let's get another one. I know there's another one somewhere near the edges[1] right here. Okay, goody![2] Okay, alrighty. So this goes in the po-si-tave row.[3] Ick, and this goes in the neg-at-ave row. I can't see it! Ok, that's good!	[1]*Erin rummages through kit box*. [2]*Erin turns back around.* [3]*Erin inserts red wire from solar panel into positive row of bread board*.

We can see, in the transcript of this interaction, that the students used the video as a just-in-time help resource, playing only small segments of it at one time, then doing what the video instructed. We can also see that many of the instructions provided by the video were spatial in nature, describing the relative size and position of pieces that needed to be assembled for the car to work properly (e.g., line 1, "The long leg of the capacitor is its positive end" or line 9, "what we want to do is connect all the positive ends"). Making sense of these spatial instructions was a large part of the problem-solving work the students needed to engage in to put together their solar car. Further, the way that they were using the video was as if the video was a person in the sensemaking and problem-solving interaction — for example, Erin responding directly to things said or shown in the video through her talk and actions (lines 4 and 10), then "asking" the video for the next step by resuming it (line 6).

We can better understand the human role of the video in the interaction between Erin, Ajay, and the help video by comparing it to a similar interaction where a different, student, Amadia, used her classmate, Evan, in the same way while working on the Minime Animation challenge (see Table 4.3).

Table 4.3
Amadia uses Evan as a Just-in-time Help Resource as She Does the MiniMe Animation Challenge

Line	Person	Talk	Actions
1	Amadia:	Wait, Evan, what's the name of that software that that's on?	
2	Evan:	Oh[1]	[1]*Evan comes over.*
3	Amadia:	Cuz I didn't save it.	
4	Evan:	[1]Boom! Let's go to challenges. Oh they're going. Just click this.[2]	[1]*Evan takes Amadia's mouse.* [2]*Evan clicks link to open file and application for Minime from FUSE challenge page, already open.*
5	Amadia:	Oh seriously? That's it?	
6	Evan:	Play, then open.	
7	Amadia:	Seriously? That's it? That's it?	
8	Evan:	Wait, and then hold on.[1] Click. Do you want to pose him now?	[1]*Evan puts hand on Amadia's mouse again and clicks on character.*
9	Amadia:	Yeah, pose him. Wait first I want to change his color.	
10	Evan:	Okay	
11	Amadia:	Then when I'm done, come back and help me.	

Here, Amadia used Evan as a just-in-time help resource, having him show her how to do one step at a time (line 1 and line 9), then asking him to come back and show her the next one after she'd finished that step (line 11). We can imagine Evan being replaced by a help video in this interaction or the video in the *Solar Roller* interaction being replaced by Evan, as both are being used as resources in similar ways. Of course, they are not completely analogous, as Evan can elaborate, in response to questions, in a way that the help videos cannot, while help videos may be more carefully curated to convey important information in specific ways than Evan's talk and actions.

There were also other ways in which students used other students as resources in the FUSE studio. In many cases, students offered help or advice to another student working on their own project without being asked. In other cases students worked collaboratively on the same project and used each other as resources by distributing the mental or physical work of the challenge between them.

Epistemic and Explanatory Object Manipulation. We can also see from these two episodes that talk was not the only modality through which spatial ideas were worked out or communicated. As we can see in lines 4 and 8 of the transcript of the interaction between Evan and Amadia, students also communicated spatial information and furthered spatial sensemaking through actions on physical or digital objects. In my analysis, I separated actions of this type (serving epistemic purposes or explanatory purposes) from pragmatic actions (apparently taken only to move the actor closer to a construction goal), which were nearly ubiquitous in the dataset I analyzed. I coded 303 instances of object manipulation of the type Evan demonstrated in lines 4 and 8 of the transcript above, explanatory object manipulation. I also coded another 198 instances of epistemic object manipulation (physical or digital) in the dataset. In some cases actions, evidence from the surrounding interaction suggested that actions served both purposes, both helping a student understand a spatial concept and also helping them explain that concept to another student, and thus they were coded as both.

The following set of examples demonstrate how epistemic object manipulation looked different from pragmatic object manipulation or explanatory object manipulation. In the first episode, which provides examples of epistemic, explanatory, and pragmatic object manipulations, Adele was working with another student, Ava, on building a structure for the *Spaghetti Structures* challenge (see Table 4.4). The girls had previously created two pyramid-shaped structures out of spaghetti and marshmallows, which were joined together at one corner. In this episode they were discussing what to do next to advance the construction of their spaghetti structure.

Table 4.4
Ava and Adele Use Object Manipulation to Work Through the Spaghetti Structures Challenge

Line	Person	Talk	Actions
1	Ava:	Turn it. Now what?	
2	Adele:	Uh, ok. Hmm...	
3	Ava:	Connect it there?[1]	[1]*Ava points to top of structure.*
4	Adele:	Hold on[1], o::p.	[1]*Adele picks up structure and turns it sideways. A piece comes loose.*
5	Ava:	[1]Ok, now go.	[1]*Ava reconnects piece.*
6	Adele:	Maybe like this[1]	[1]*Adele rotates then folds pyramids together.*
7	Ava:	How 'bout like	
8	Adele:		*Adele folds pyramids back the other way.*
9	Ava:	Yeah like that?	
10	Adele:	This looks weird!	
11	Ava:	Yeah this looks awesome, 'cause we broke it right here.[1]	[1]*Ava reaches for a piece of spaghetti connected to the structure that has come loose.*
12	Adele:	Uh, right here, right here.[1]	[1]*Adele reaches for piece and reconnects it.*
13	Ava:	Wait, hold that right here.	
14	Adele:		*Adele does something not visible on camera.*
15	Ava:	Ok, now move it like that.[1]	[1]*Ava pulls down on one end, then releases it.*

16	Adele:		*Adele rotates structure.*
17	Ava:	Can we do that?[1] Ok, I got it. Ooh like that.	[1]*Ava points to structure*.
18	Adele:		*Adele folds and rotates structure.*

At the beginning of this episode, in response to Ava's question (line 1) of "Now what?" we saw Adele engaging in three different object manipulations (lines 4, 6, and 8) that functioned both as epistemic object manipulations (testing out the affordances of the materials and trying out a new design idea) and explanatory object manipulation (communicating her design ideas to Ava). Then, in lines 11 and 12, we saw Ava and Adele engaging in pragmatic object manipulation (reconnecting a piece of spaghetti that had broken free of the marshmallow connecting it to other pieces). Then, in lines 15 through 18, Ava and Adele switched back to trying out new design ideas, through objection manipulations that again served both epistemic and teaching and demonstrating functions.

We can distinguish between these epistemic and explanatory object manipulations by looking at how the object manipulations were responded to by other participants in the interaction. In the previous episode Ava responded directly to Adele's actions, as if they were turns of talk (e.g., line 9, "Yeah like that?", or line 17 "Can we do that? Ok, I got it."), indicating that they did serve to demonstrate or explain something to Ava. In contrast, if Adele had been manipulating the structure, while Ava's attention was elsewhere, we might infer that the function of that action was purely epistemic. Similarly, since, in many cases, students worked alone on all or part of challenges, in those instances, actions similar to the ones described in the previous episode would likely be interpreted as only epistemic (i.e., only for the individual learner's sensemaking), rather than serving dual epistemic and explanatory functions. For example, later in her work on this same challenge, after Adele, working alone, had built a cube-shaped spaghetti structure, I observed her holding the structure between two hands and wobbling it back and forth. This would have been counted as purely epistemic object manipulation, as there was no audience for the action but Adele.

In contrast, there were also instances when objection manipulation was done for an audience, but carried out in ways that made it clear that it was not epistemic but only explanatory. The following episode provides examples of such actions, carried out by one student, Travis, as he showed off his nearly complete dream home to two other students, Evan and Amadia (see Table 4.5).

Table 4.5

Travis Uses Object Manipulation to Show Evan His Dream Home

Line	Person	Talk	Actions
1	Travis:	Want to see my house?	
2	Evan:		*Evan stops while walking by.*
3	Travis:	Isn't this big?[1]	[1]*Travis rotates perspective on his house.*
4	Evan:	Whoa!	
5	Travis:	Ok, here's my son's room.[1]	[1]*Travis zooms in on one room.*
6	Amadia:	You have a son?	
7	Travis:	Yeah, he's in here[1] =somewhere. So, uh, I'm gonna put a wall there.	[1]*Travis points to room.*
8	Travis:	This is his, this is his bedroom, this is his bedroom, and then uh, the rest is ours. K, so, this is the uh bathroom, but I have to put a shower thingy and a toilet, and then here's the uh patio[1] just outside, back inside, and then here, here's the stairs to the, continuing, then here's my daughter's room, right here.	[1]*Travis continues to rotate around and zoom in and out to show off different parts of house.*
9	Amadia:	Dude!	
10	Travis:	No, no, for the future[1]	[1]*Travis makes gesture pushing hand forward.*
11	Amadia:	Neato	

12	Travis:	Thank you. This is the hallway, and then, and then uh, if I wanna uh go up here, I just have to uh jump.[1]	[1]*Travis points to top of stairs and then gestures moving figure up and onto second floor.*

In lines 3, 5, and 8 of this episode, Travis manipulated his dream home (digitally rather than physically). However, his object manipulations were preceded by rhetorical questions (e.g., line 3, “Isn’t this big?”) or statements directing attention to specific features of his dream home (e.g., line 5, “Ok, here's my son's room.”). This contrasts with Adele’s object manipulations, which stood alone or were accompanied by statements which connoted exploration (e.g., “Maybe like this”). Travis’s actions were also responded to differently than Adele’s. Whereas Ava’s responses to Adele’s actions were generally questions, which reinforced the interpretation that the girls were engaged in shared epistemic exploration (e.g., “Yeah like that?” or “Can we do that?”), Evan and Amadia’s responses to Travis either simply acknowledged what he was showing them (e.g., line 4, “Whoa!”) or asked for more information (e.g., line 6 “You have a son?”).

Gesture. A final aspect of distributed spatial sensemaking that the transcripts presented in this section highlight is the use of gesture to communicate or think through spatial ideas. In the dataset I analyzed, I identified 749 gestures representing or referencing spatial information. These gestures took three different forms: pointing or deictic gestures (85 percent), gestures representing dynamic spatial ideas (9 percent), and gestures representing static spatial ideas (7 percent). In the previous transcript (and in the other transcripts presented in this section) we saw examples of each of these different types of gestures. For example, in the previous transcript, in response to Amadia’s question, “You have a son?” Travis said, “Yeah, he's in here somewhere,” and pointed to a room in his dream home. Then later, when referencing the future when he would have the hypothetical children whose rooms he'd incorporated into his house, he said, "No, no, for the future" and accompanied this statement with a gesture (pushing his hand forward), which suggested that he was drawing on the spatial metaphor of the timeline to envision "future," as something ahead of now, and representing that static spatial information in his gesture. Finally, in the last line of the transcript, he accompanied his description of how to get from the hallway to the second floor of his house ("This is the hallway, and then, and then uh, if I wanna uh go up here, I just have to uh jump.") with a pointing gesture and a gesture representing the dynamic spatial process of jumping (points to top of stairs and then gestures moving figure up and onto second floor).

Sketching and Analogy. Finally, relative to the other sense making practices (gesture and object manipulation) that students used to make sense of spatial phenomena during the FUSE challenges, sketching and analogizing were less common. In the dataset, there were 55 instances of students spontaneously using analogy, and only one instance of students spontaneously sketching to solve a spatial problem. However, in the places where these practices were used, they played a productive role in advancing sensemaking and challenge work.

For example, students used spatial analogies as a resource for problem-solving across multiple challenges, and these analogies took two primary forms. One was a verbal comparison of a spatial structure they were working on with another spatial structure they'd experienced outside of the FUSE studio (37 total instances). This type of analogy was often used in the context of design-oriented challenges, where it served two primary functions. One was to advance design thinking. For example, during the Coaster Boss challenge, students compared their roller coaster designs to specific roller coasters that they'd experienced at a local amusement park. Similarly, while working on *Spaghetti Structures*, students compared the design of their structures to different types of buildings (e.g., teepee, pyramid) or iconic buildings (e.g., Eiffel tower). During *Dream Home*, students also made these sorts of comparisons, with one student comparing the design of his home to a temple and another comparing the design of her home to a spaceship. The second function these analogies served was an epistemic one (focused on understanding a tool or phenomenon). For example, during the Electric Apparel challenge, a student compared the LED lights to Christmas lights. Similarly, during the *Solar Roller* challenge, students compared the wires on their solar cars to what it looks like behind a TV and compared putting together all the small pieces of the solar car to putting together Legos.

In contrast, a second type of analogy involved comparisons between two or more structures or representations immediately available in the classroom environment (18 total instances). Because both structures or representations were immediately available, this form of analogy often involved not only mental alignment and structure mapping, but also physical alignment to aid in structure mapping. For example, while working on the *Solar Roller* challenge, students could seen physically aligning their solar car with a circuitry diagram on the website in order to add wires in the correct locations. During *Selfie Sticker*, students similarly held sheets of vinyl up to the designs on their screen that they planned to print on them, in order to insure they were the right size. Finally, during the Wind Commander challenge, students concerned with having all of their wind turbine blades be identical held blades found in the kit box up to each other and rotated them to the same orientation to make sure they were the same.

These findings are consistent with prior research demonstrating the importance of analogy in spatial thinking and STEM problem-solving. However, these findings also go beyond those of prior research by demonstrating how analogies are used spontaneously by students to advance design thinking and STEAM problem-solving and the role that both distally and locally available resources might by used to facilitate structure mapping.

Social, Material, and Task Constraints of Different Activities Promoted Different Forms of Distributed Spatial Sensemaking. The frequency data and transcripts of interactions presented in the previous section provided an overview of the types spatial skills and social and material resources students made use of during FUSE activities. However, there were also differences between activities in the way that these cognitive processes and sociomaterial resources were used. In other words, different activities, and the different sociomaterial resources and task constraints provided by them, afforded different forms of collaboration between people and objects and consequently different spatial processes and sensemaking practices.

Figure 4.2 summarizes the spatial skills used as part of each challenge as a percentage of total spatial idea units communicated through talk, gesture, or object manipulation during completion of that challenge. Intrinsic-static skills are represented in shades of blue, intrinsic-dynamic skills in shades of green, extrinsic-static skills in shades of yellow, and extrinsic-dynamic skills in shades of red.

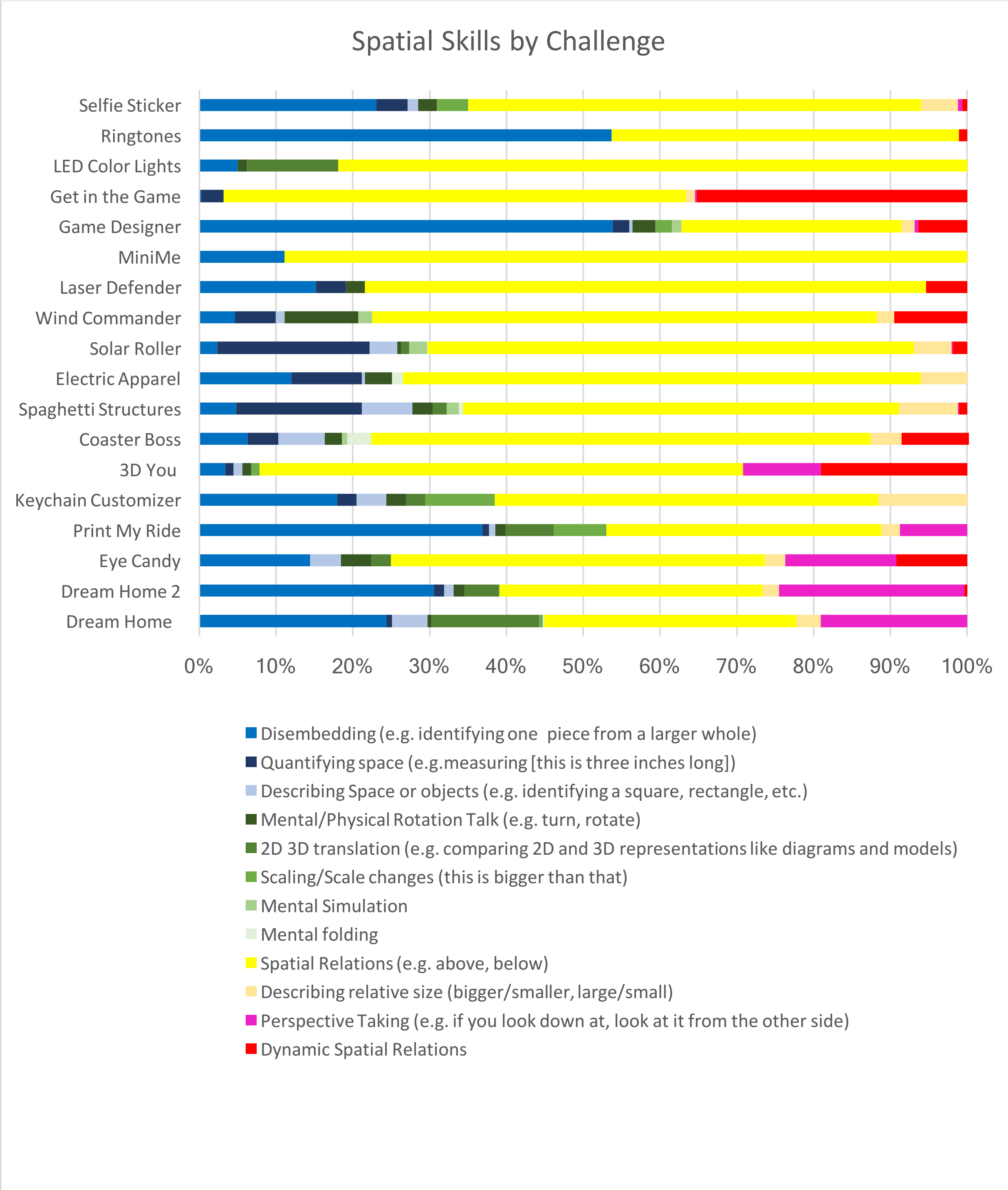
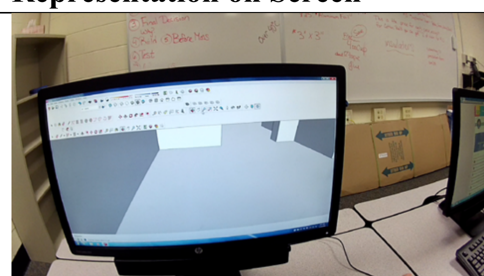
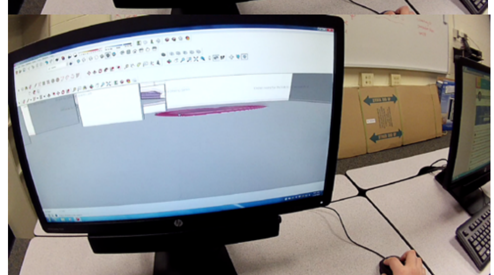
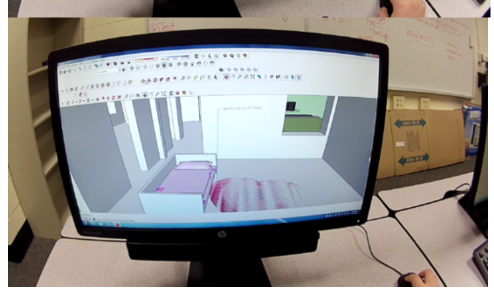


Figure 4.2. Spatial skills by challenge, as a percentage of total spatial idea units communicated through talk, gesture, or object manipulation during completion of that challenge.

There are at least three important things to notice in the relative frequencies of different spatial skills in the different challenges. The first is the relatively high frequency of both intrinsic-dynamic and extrinsic-dynamic skills in the CAD design challenges (*Dream Home, Dream Home 2, Eye Candy, Print my Ride, Keychain Customizer*). The second is the relatively high frequency of quantifying space (i.e., integrating spatial and mathematical thinking) in two of the kit-based challenges (*Solar Roller* and *Spaghetti Structures*). Finally, the third is the relatively high frequency of extrinsic-dynamic skills used in two challenges, *Get in the Game* and *3D You*, which both required the coordinated movement of multiple people, tools, and representations in order to complete at least part of the challenge. In the sections that follow, I will provide transcripts of interactions from each of these sets of challenges demonstrating how the particular goals and sociomaterial contexts of these different challenges may have led to these differences in spatial thinking.

Spatial Thinking with CAD Design Tools. The relative prevalence of both intrinsic-dynamic and extrinsic-dynamic spatial thinking during the CAD design challenges is interesting for at least two reasons. First, it highlights the spatial complexity of designing with these sorts of tools. Second, the way in which students used these types of spatial thinking, particularly perspective taking (extrinsic-dynamic) and mental rotation (intrinsic-dynamic), while designing in the CAD tool Sketchup highlights the importance of specific tools and representations in shaping students' spatial thinking and learning.

Although mental rotation and perspective taking were both used throughout the CAD challenges available in the FUSE studio, nowhere was the role of the tool and task constraints in shaping spatial thinking more apparent than in the *Dream Home* challenges (*Dream Home* and *Dream Home 2: Gut Rehab*). While working on *Dream Home*, students' design goals frequently required them to rotate or pan around their dream home in the software to see the home from different sides. Failure to do so often led to problems. We saw this in the case of Johanna, presented in Chapter 3, when she tried to add a wing to her dream home and inadvertently added it on a diagonal rather than flat on the ground, because she was looking at her dream home from above. Interestingly, in Johanna's later work on *Dream Home* 2, she encountered situations which similarly required her to look at her design from different angles to figure out where to place objects. However, as the illustrated transcript presented in Figure 4.3 demonstrates, when she encountered these situations in *Dream Home 2*, armed with the experience of having solved similar problems in *Dream Home*, she was better able to tackle them.

Line	Person	Talk	Actions	Representation on Screen
1	Johanna:	Victoria? Victoria, I forgot how to make them like go on the ground. Like it's always kind of[1]	[1]*Johanna zooms in on dream home floor.*	
2	Johanna:	Oh[1] Victoria, I actually put it on the ground the first time!	[1]*Johanna rotates view horizontally so rug is visible from side, gasps.*	
3	Johanna:	[1]Wow.[2]	[1]*Johanna rotates view up and down.* [2]*Johanna rotates view to look at rug from above. Rug is now in floor.*	

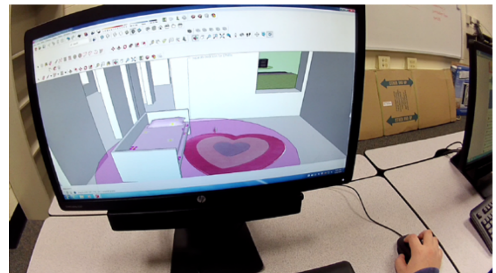
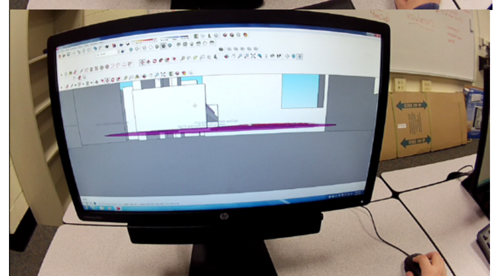
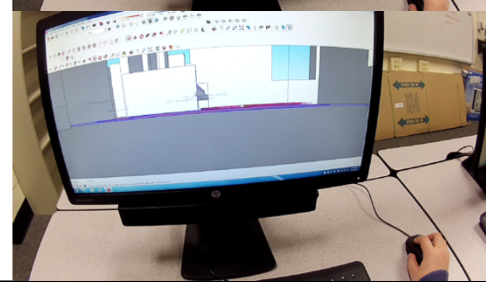
4	Johanna:	*Johanna pulls rug up.*	
5	Johanna:	*Johanna rotates to side view again. Now the rug is floating in midair.*	
6	Johanna:	*Johanna moves rug down until it's flat on the floor.*	

Figure 4.3. In order to place a rug on the floor on her dream home, Johanna rotates her perspective to view the rug from different angles.

Here, faced with the task of placing a rug and bed on the floor of her dream home (line 1), Johanna initially sought help from her friend Victoria. However, before Victoria came to her aid, Johanna switched to a side view of the rug and bed (line 2), in order to check whether they were on the floor, herself. Then by switching back and forth between top and side views and using the representational feedback she received from Sketchup, she was able to insure that the rug and bed were on the floor where she wanted them.

This episode demonstrates the importance of spatial thinking and understanding spatial representations for working in Sketchup. It also shows how continued work with Sketchup across the two *Dream Home* challenges helped Johanna improve her facility both with spatial problem-solving and with the tools available in Sketchup. However, it also raises an interesting question.

What type of spatial thinking was Johanna engaging in during this episode? Was it mental rotation (an intrinsic-static skill) or was it perspective taking (an extrinsic-static skill)? On the one hand Johanna is not moving; she is moving an object on her screen (her dream home), which would suggest that she is engaging in mental rotation. On the other hand, the primary tool she is using during this episode is the "pan" tool, which allows her to view her dream home from different perspectives. This is distinct from the "rotate" tool in Sketchup, which allows one to rotate individual objects in relation to the coordinate grid set up in the software.

The following transcript (see Table 4.6), which shows a conversation between Evan and Victoria, while Evan is trying to rotate furniture around inside of his dream home, highlights this contrast. At the start of this episode, Evan had imported a television and a couch from the 3D model warehouse in Sketchup, but the TV was perpendicular to the couch. So he was trying to figure out how to make it parallel to (directly across from) the couch. He also enlisted the help of Victoria, who was sitting next to him and also working on *Dream Home.*

Table 4.6
Victoria Helps Evan Rotate Furniture inside of His Dream Home

Line	**Person**	**Talk**	**Actions**
1	Evan:	How do you like rotate it like to be	
2	Victoria:	I don't know like	
3	Evan:	to for the couch or like the TV to be like,[1] I want the couch to be facing the TV	[1]*Evan zooms in and changes perspective on couch.* [2]*Evan holds hand up to screen making grabbing gesture, then moves hand forward from couch across screen to empty space that couch is facing (TV is currently perpendicular to couch).*
4	Victoria:	Hmm.	
5	Evan:	Or I would, no I want the TV on the wall.[1]	[1]*Evan makes another grabbing gesture and moves hand across screen toward wall again.*
6	Victoria:	Maybe, try this.[1]	[1]*Victoria points to rotate tool icon on toolbar.*
7	Evan:		*Evan smiles.*
8	Victoria:	Maybe, I don't know.	

9	Evan:	[1]Woah! Wha?! What?![2] I'm scared.	[1]*Evan selects rotate tool and rotates TV but rotates it in a vertical circle rather than a horizontal one.* [2]*Evan rotates TV back to where it was initially.*
10	Victoria:		*Victoria laughs.*
11	Evan:	How do I do that?	
12	Victoria:	Yeah. Oh those things!	
13	Evan:		*Evan moves TV forward.*
14	Victoria:	Ah:::a. What about, do you know the arrow thing?	
15	Evan:	Yeah[1]	[1]*Evan rotates TV again, this time around a vertical circle perpendicular to the first one.*
16	Victoria:	Nope.	
17	Evan:	[Ah! Help!	
18	Victoria:	[Nope, nope, nope.	
19	Evan:	Uh, Yeah. Ah![1]	[1]*Evan rotates TV again along same axis.*
20	Victoria:	Scroll	
21	Evan:		*Evan turns his attention to another student who has just come over.*

In this episode, the language that Evan used (line 1) was consistent with mental rotation rather than perspective taking ("How do you like rotate it like to be..."). Victoria then pointed Evan to the rotate tool (line 6) to change the position of his TV relative to his couch and the rest of his dream home, as opposed to pointing him to the pan tool (which he had already used in line 3) to change perspectives on the room where he was moving this furniture around. This suggests that even though, relative to Evan's position in the real physical space of the classroom, the processes of panning (to rotate the view of the house) and rotating (to change the position of the furniture relative to the house) were the same, in the virtual space of Sketchup they were different, and the tools in the software were designed to highlight that difference.

This distinction is made even clearer in the *Dream Home* challenge (relative to the other CAD challenges), because the object that students are designing is a house (an "object" which we would normally inhabit and walk around, rather than one that we would manually manipulate or rotate). The following transcript (see Table 4.7) demonstrates how the language students used around perspective taking actions in Sketchup, while working on the *Dream Home* challenge, drew on the analogy between the virtual model home and a real home. In this episode, Johanna, Victoria, and Andrea were trying to see inside of their respective dream homes, so that they could add furniture and interior decor. However, they didn't talk about *seeing* inside the home like it was an object, they talked about *being* inside the home like it was a real home.

Table 4.7
Johanna, Victoria, and Andrea Talk about Being Inside Their Dream Homes

Line	Person	Talk	Actions
1	Johanna:	[1]Andrea, I have no clue where I am right now.	[1]*Johanna zooms in and scrolls forward to explore inside her house*.
2	Andrea:	How do you do that?	
3	Johanna:	I went through the wall.	
4	Victoria:	I'm stuck inside my house.	
5	Johanna:	You're stuck inside your house?[1] I'm okay.	[1]*Johanna laughs*.
6	Victoria:	I'm suffocating.	
7	Johanna:	I would think there'd be air in your house. I don't think you're suffocating.	

In lines 4 through 7 of the transcript, Victoria and Johanna take the notion of being inside their dream homes so far as to discuss being "stuck inside" the home and "suffocating" (or not suffocating) because of the absence (or presence) of air.

The differences between these three episodes in the ways that students were acting on their dream homes and talking about their actions is suggestive of differences in underlying cognitive processes, mental rotation in one case and perspective taking in the others. Further, the different tools and tasks accompanying these different cognitive processes are indicative of the software tools (pan versus rotate) and the task constraints (created a model home rather than a model of a manipulable object) shaping students' spatial thinking. This sort of understanding of the ways in which particular tools and representations (particularly tools and representations like CAD software that are used by STEM professionals) might shape spatial thinking is one important relative advantage of looking at spatial thinking in the context of real-world thinking and learning activities, rather than trying to isolate spatial skills through psychometric assessments.

Learning from Spatial Thinking with CAD Design Tools. Another advantage to looking at spatial thinking in the context of these sorts of real-world thinking and learning activities is that it allows us to provide a process account of learning. And all three of the episodes presented in this section provide insight into the spatial learning processes occurring while students were working with CAD design tools. First, we saw Johanna progressing from not considering what objects would look like from different three-dimensional views, and consequently placing them on the wrong planes, to using the pan tool in Sketchup adeptly to make sure she was placing objects on the right plane. Then we saw both Evan and Victoria and Johanna, Victoria, and Andrea, at earlier stages in the learning process and saw the struggles they encountered in early forays into rotation and perspective taking with the software. For example, it took Evan multiple tries (lines 9, 15, and 19) to find the right axis to rotate the TV around to get it into the position he wanted. In the episode presented above, he never actually did get there. However, later in the class period, through trial and error, he eventually figured it out. Similarly, we saw from lines 1 and 2 of Johanna, Victoria, and Andrea's episode that the problem of navigating inside their dream homes was not a straightforward one but rather was something that the girls had to learn how to do through a combination of spatial thinking and learning the affordances of the software tools. These student cases demonstrate that, although working with CAD software involves complex spatial thinking and problem-solving, students' ability to engage in spatial thinking and problem-solving with these tools improves with experience.

Integrating Spatial and Mathematical Thinking During Challenges. The second notable difference in spatial thinking between challenges was in the relatively high frequency of students engaging in quantifying space (or integrating spatial thinking and mathematical thinking) that occurred during two specific kit-based (as opposed to software-based) challenges, *Spaghetti Structures* and *Solar Roller*. Looking at how students engaged in quantifying space during these challenges sheds light on how the particular material and task constraints of these challenges led to this particular type of spatial thinking.

For example, the goal of the *Spaghetti Structures* challenge is to build the tallest possible structure with a finite set of materials within a finite amount of time. Therefore, one of the requirements to complete each challenge level is for students measure the height of their structure. One might not think of this as a challenging problem, but for fifth graders just learning about mathematical concepts like 3D geometry, area, and volume, and not yet familiar with other geometric concepts like the Pythagorean Theorem, this appears not to be so straightforward. In the transcript below (see Table 4.8), we can see how one student, Adele, and some of her classmates coordinated spatial and mathematical thinking as they struggled to figure out how best to measure the height of Adele's spaghetti structure.

Table 4.8
Adele Coordinates Spatial and Mathematical Thinking to Measure her Spaghetti Structure

Line	Person	Talk	Actions
1	Facilitator:	That's really cool. So we ought to get that tape measure and take a picture of this, so when we finally get your account, we'll be able to	

2	Carmen:	[1]It is...	*[1]Carmen holds measuring tape up to structure and measures height on a diagonal along side of pyramid structure.*
3	Facilitator:	That's really cool.	
4	Adele:	I know!	
5	Carmen:	[1]2 inches. It's 2 inches.	*[1]Carmen looks at wrong end of measuring tape.*
6	Adele:	Let me see it[1] = Ten[2] = ten = ten	*[1]Adele reaches for tape measure, holds it up to structure, putting 0 end at top and measuring down, again on a diagonal. Instead of measuring whole height, she measures segments of spaghetti. [2]Adele holds measuring tape up to different parts of structure, measuring pieces of spaghetti.*
7	Adele:		*A piece of the structure comes loose. Adele reconnects it.*
8	Adele:	[1]Ok, 10, 10, 10 10 10.	*[1]Adele resumes measuring different parts of structure.*
9	Adele:	[1]Hmm.[2] Miss Rameys, what do I do now?	*[1]Adele begins measuring pieces in centimeters, then stands back and looks at structure. [2]Adele looks around, then walks over to researcher.*
10	Researcher:	Well, did you measure to see how tall it is?[1]	*[1]Researcher walks over to spaghetti structure with Adele.*
11	Adele:	Yes.	
12	Researcher:	How tall is it?	
13	Adele:	10 inches, then I got 4, then I kept getting 26's and 25's.	
14	Researcher:	So how 'bout the height? What would be the height of this?	
15	Adele:	10.	
16	Researcher:	So what would we measure on here to find the height?	
17	Adele:	The triangles?	
18	Researcher:	[1]So how would we find the total distance between the table[2] and this top part?[3]	*[1]Researcher laughs. [2]Researcher puts hand flat on table. [3]Researcher raises other hand up to top of structure.*
19	Adele:	U:::m.	
20	Researcher:	Is there a place where we could put that measuring tape to find that?	
21	Adele:	Right here?[1] Right there?	*[1]Adele points to outside of base of pyramid structure.*

22	Researcher:	M:::m, so we just want like from the table[1] to the top[2] right? So, what would that…	[1]*Researcher puts hand on table.* [2]*Researcher moves hand up to top of structure.*
23	Adele:	So from right here[1]	[1]Adele *points to base again.*
24	Researcher:	So what would that look like, if you measured from there?	
25	Adele:	So[1]	[1]*Adele holds measuring tape up to pyramid along diagonal side.*
26	Researcher:	Ok, so, yeah but look at, so see how you're also kind of measuring out this way too.[1] I wonder if there's a way we can prevent that?	[1]*Researcher waves finger horizontally.*
27			*Anna comes over. Adele turns to her.*
28	Researcher:	I wonder if she has an idea.[1] How would she measure the height of this, to figure out how tall her marshmallow is?	[1]*Turns to Anna.*
29	Anna:	It's probably this side, or maybe this side[1]	[1]*Anna holds hands up to same diagonal where Adele had just proposed measuring.*
30	Adele:	A::h!	
31			*Arya and Dante come over.*
32	Arya:	Nice Job!	
33	Adele:	Thank you! Thank you very much!	
34	Anna:	Maybe start like right here[1] through here,[2] if that works, because the spaghetti, that's the straightest part.	[1]*Anna points to spot on table on other side of pyramid.* [2]*Anna raises hand up to marshmallow at top.*
35	Adele:	[1]19 inches, on this side[2] and on that side.[3]	[1]*Adele takes measuring tape and measures where Anna showed her, still on an angle.* [2]*Adele points to side she just measured.* [3]*Adele points to other side.*
36	Researcher:	Yeah? 19 inches, you agree with that?	
37	Anna:	Yeah.	

In this episode, Carmen began by holding up the measuring tape on a diagonal, rather than straight up and down and looking at the wrong end of the measuring tape (lines 2 and 5), so that she measured the structure as “2 inches” tall. Adele rejected Carmen’s measurement of “2 inches” by saying “let me see it” (line 6) and tried a measurement of her own. However, when she initially measured she both did it on an angle and only measured one piece of spaghetti at a time, yielding multiple measurements of 10 inches, rather than one measurement of the height of the structure (lines 6 and 8). She then began measuring individual pieces of spaghetti in centimeters. Then she sought help from me, the researcher (line 9), and when I asked her how tall the structure was (line 12) reported the measurements of individual pieces of spaghetti that she had gotten in both inches and centimeters, although she didn’t say that was what they were, when she reported the numbers, 10, 4, 25, and 26 (line 13). Then, when I asked her which one was the height, she said “10” (line 15), which wasn’t the height of her structure, but made sense when I asked her, “So what would we measure on here to find the height?” (line 16) and she replied “The triangles?” (line 17), because 10 would, in fact, have been the length of one side of one the triangles (or triangular pyramids) making up her structure. However, when I asked her in a few different ways (lines 18, 20, 22, and 24) how she might measure the total distance from the bottom to the top of her structure (accompanied by some admittedly leading gestures), and she moved away from the triangle measuring method, she still fell victim to one of the same problems Carmen had had, measuring on a diagonal, rather than straight up and down.

Then, in line 29, Anna joined the interaction and introduced the idea that they could measure the structure on the other side, citing the reason (line 34) that “that's the straightest part.” Adele did that, but still measured on an angle up the side of the triangular structure, rather than straight up from the center, bottom of the structure (line 35) and got a measurement of 19 inches, which Anna agreed was correct (line 37). Neither girl seemed to understand yet why this measurement was problematic.

Learning from Integrating Spatial and Mathematical Thinking. In a later class period, however, Adele had again completed a structure, this time working together with Anna. This time, when they went to measure their structure, things unfolded somewhat differently (see Table 4.9).

Table 4.9
Adele and Anna Coordinate Spatial and Mathematical Thinking to Measure Their Spaghetti Structure

Line	**Person**	**Talk**	**Actions**
1	Adele:		*Adele begins measuring but again does it on an angle up the diagonal side of the structure.*
2	Anna:	Ok, so how long is it?	
3	Adele:		*Adele measures only one leg of the tower, not the whole height.*
4	Anna:	No, measure it from this side. This is our tallest side.[1]	[1]*Anna points to top of tower on other side*.
5	Adele:	[1]7 inches.	[1]Adele measures from top of tower, measuring full height but still at a diagonal alongside of structure.
6	Anna:	What? No[1]	[1]*Anna holds and looks at bottom of measuring tape on table*.
7	Facilitator:	[1]So what you want to measure though is just from the marshmallow[2] to the ground, straight down.[3]	[1]*Facilitator* comes over. [2]*Facilitator points to large marshmallow on top*. [3]*Facilitator makes line with hand down to table.*
8	Adele:	Ok.	
9	Anna:		*Anna holds tape measure now, still along outside of tower, but on other side*.
10	Facilitator:	So, you want zero to start at the top of the marshmallow and then go straight to the ground, right?	
11	Adele:	So, 10.	
12	Anna:	10.	
13	Facilitator:	About 10 inches. Why do we not measure on the angle?[1]	[1]*Facilitator points to side of tower*.
14	Anna:	Because then you get a bigger measurement.	
15	Facilitator:	Which would be great, right? But is it accurate?	

16	Anna:	But it's unfair.
17	Adele:	No, no, no.
18	Facilitator:	Exactly. So are you going to try another one right now? See if you can try to build it higher? You still have about 15 minutes.

In this episode Adele began measuring in the same way she had been at the beginning of the previous episode, on a diagonal up the side of the structure (line 1) and only measuring part of the structure, not the whole thing (line 3). Anna corrected her (line 4) by proposing an idea that she had had in the previous episode, that there was a "tallest side" of the structure and suggesting that Adele measure that instead (line 4) . This prompted a measurement of 7 inches from Adele in line 5, which was questioned by Anna in line 6.

Then in line 7, the facilitator entered the interaction and corrected them, explaining, through talk and gesture, that they should measure straight down, rather than on an angle (lines 7 and 10). The girls measured the structure the way that he had instructed and got a measurement of 10 inches (lines 11 and 12). Then, when he asked them "Why do we not measure on the angle?" (line 13), Anna correctly answered, "Because then you get a bigger measurement" (line 14), and in response to his question in line 15 about whether this would be accurate, Adele said no (line 17) and Anna said it wouldn't be fair (line 16).

In these episodes, we can see how the particular constraints of a challenge like *Spaghetti Structures* (trying to make and then document that you've made the tallest tower) promoted the integration of spatial and mathematical thinking in order to complete the challenge. In fact, in the context of the activities in FUSE, when mathematical concepts were invoked, they were almost always used to quantify space. The one exception to this is when they were used to quantify time or a combination of space and time (i.e., speed). In all cases the way in which math was invoked was framed by the particular social, material, and task constraints of the challenges at hand, and math was used authentically to solve challenge-related problems, rather than forced on learners in abstract, decontextualized ways, as is too often the case in school math classes. We can also see from these two episodes that the integration of spatial and mathematical thinking wasn't always easy for students, but that through feedback from other students and facilitators, these activities allowed them to improve their spatial understandings of mathematical concepts, like the hypotenuse being longer than the legs of a triangle or how to accurately measure the height of a structure.

Spatial Thinking in Challenges Requiring Coordinated Movement of People, Tools, and Representations. Finally, a third important thing to notice in the relative frequencies of different types of spatial thinking in the different challenges was the relatively high frequency of extrinsic-dynamic skills used in *Get in the Game* and *3D You*. I asserted that this was because both of these challenges required the coordinated movement of people, tools, and representations in order to complete at least part of each of the challenges. The following transcript (Table 4.10) and accompanying figure (Figure 4.4) demonstrate how the particular sociomaterial and task constraints of the *3D You* challenge led to a need to coordinate spatial representations (extrinsic-dynamic and otherwise) across representational media in the distributed spatial sensemaking system doing the challenge.

In this episode, two students worked with their teacher, the FUSE facilitator, on the last level of *3D You.* The goal of this challenge level was to use a Kinect to scan a 3D image of one student's head (in this case James' head) into a software program, so that the student could 3D print a bust of himself. At the opening of the interaction, Kumar was holding the Kinect, while

James, seated in a spinning desk chair revolved slowly in a circle. However, James' head had fallen out of alignment with the guides on the computer screen, prompting an error message. The facilitator joined the interaction and tried to help guide their coordinated activity, by referencing the representation of James' head on the computer screen, which during this interaction, only she could see (see Figure 4.4).

Table 4.10
A Distributed Cognitive System Does the Last Level of the 3D You Challenge

Line	**Person**	**Talk**	**Actions**
1	Facilitator:	Ok so, lets change this up here. Do you think you, why don't…	
2	Kumar:		*((moves Kinect down slightly))*
3	Facilitator:	Oop almost. So why don't you move to your left. James, move this way[1].	[1]*((spins hand in a counterclockwise circle))*
4	James:		*((spins slightly in a counterclockwise direction))*
5	Kumar:		*((mimics facilitator's gesture, while looking at her))*
6	Facilitator:	James, move your body[1].	[1]*((gestures to her right, James's left))*
7	James:		*((scoots the desk chair to his left))*
8	Facilitator:	Yep, yep, little more.	
9	James:		*((scoots the desk chair to his left))*
10	Facilitator:	Ok, like, ok go back a little more.	
11	James:		*((scoots his chair back))*
12	Facilitator:	Alright, now, you have to somehow come up[1], Kumar, because the face is like at the bottom.	[1]*((gestures up))*
13	Kumar:		*((raises Kinect up, but James's face still isn't aligning with guide on screen))*
14	Facilitator:	No.	
15	Kumar:		*((raises Kinect up more, but face still isn't aligning with guide on screen))*
16	Facilitator:	Here let me grab it.	*((reaches over computer, grabs Kinect, and raises it up more))*

17	Facilitator:	Oh wait, I got it. Yeah, now who's going to do it.	
18	James:		*((starts turning slowly so Kinect can scan his head))*
19	Facilitator:	Kumar, what do I do?	
20	James:	You need to like show underneath my chin slowly[1].	[1]*((puts hands to neck))*
21	Kumar:		*((comes around table to where facilitator is standing in front of computer))*

Figure 4.4. James, Kumar, and the facilitator coordinate multiple spatial representations through the representational media of talk, gesture, and movement, in order to scan a James' head for the last level of the *3D You* challenge.

In this excerpt, we can see that the need to coordinate spatial representations between the different human and non-human participants in this distributed interaction (Kumar, Jackson, the facilitator, the Kinect, and the computer) required the coordination of those spatial representations across different representational media in the system (gesture, talk, body position, and the display on the computer screen). In order for the activity to proceed successfully, communication and coordination of spatial ideas across these different representational media was necessary. Because of this, the human participants in the interaction were required both to think spatially, engaging in disembedding (lines 1, 8, 14, and 17), mental rotation (lines 3-5) perspective taking (lines 3, 6, 8, 10, 12, and 20), and thinking about both static spatial relations (lines 1-20) and dynamic spatial relations (lines 16, 18, and 20).

They also had to find ways to communicate those spatial ideas to each other and to the non-human participants in the interaction. For example, as the only one in the interaction who could see the computer screen, we could see the facilitator interpreting those spatial representations communicated by the computer via its display and communicating those spatial ideas via talk and gesture to both James and Kumar (lines 1, 3, 6, 8, 10, and 12). We could also see Kumar communicating spatial ideas to James, the facilitator, and the computer via gesture and movement of the Kinect (lines 2, 5, 13, and 15), and we could see James communicating spatial ideas to Kumar, the computer, and the facilitator via talk and body movement (lines 4, 7, 9, 11, 18, and 20). We could also see moments of interaction where there were breakdowns in the communication of spatial information. For example, in lines 3-7, based on the representations on the computer screen, James needed to move to the left, but the facilitator conveyed through her gesture (line 3) spin left or counterclockwise instead. Kumar and James interpreted her words and gesture as spin left and acted accordingly (lines 4-5). So then in line 6, she had to correct her earlier instruction by saying “James, move your body,” which then produced the correct movement from James (line 7). This contrasts with the other parts of this interaction where spatial representations moved more successfully across the representational media in the system, and consequently, challenge work moved ahead effectively.

In one of the groups I observed doing the *Get in the Game* challenge, distributed spatial sensemaking unfolded similarly, as a group of four students used the Makey Makey to jointly control a player in a video game. They did so by connecting four pieces of conductive fabric to the Makey Makey terminal with alligator clips (which was in turn connected to their computer), so that each could be used as separate buttons for the game. They then put one person in charge of each button, so that in order to play the game they had to coordinate activity between the four of them, using the representational feedback given to them by the game (via the onscreen display) and each other (via spatial talk and gesture) about the player's movement on the screen and the movements required by each person to move the player forward in the game.

In both cases, the communication of spatial representation across representational media in the distributed cognitive system was essential to productive advancement through and completion of the challenge. In particular, in both cases, the dynamic coordination of multiple tools, representations, and people required extrinsic-dynamic spatial thinking and communication. In contrast to prior design work on improving spatial thinking through instruction, where where a non-spatial concept might be communicated more spatially, or a spatial concept might be better conveyed through a better spatial representation or by training students to use particular actions or representations to think about that concept, these two challenges emphasize how an activity itself can be designed so as to necessitate the use of particular spatial skills. This approach to teaching spatial skills might not work in a regular classroom, where students aren't necessarily interested or invested in what they're doing and where grades and time constraints would create pressure to get the spatial thinking right the first time. However, it does seem to work in a choice-based, ungraded learning environment like FUSE, where students are: (1) motivated to complete challenges; (2) have the time and space to tackle complex spatial problems over and over again until them get them right; and (3) have a diverse array of resources to draw on to do so.

Distributed Spatial Sensemaking leads to STEAM Problem-solving and Learning. In the episodes presented in the previous sections, we saw examples of challenge engagement leading to improvements in spatial thinking (e.g., Johanna improving her understanding of perspective taking in Sketchup), as well as examples of spatial thinking leading to other STEAM insights (e.g., Adele and Anna improving their spatial understanding of geometric principals during *Spaghetti Structures*). We also saw in the previously presented examples how small moments of distributed spatial sensemaking advanced challenge work (e.g., James, Kumar, and the facilitator doing *3D You*). However, one thing we have not yet seen is how, over the longer term, these small moments of distributed spatial sensemaking led to problem-solving insights which advanced STEAM thinking and learning and allowed for successful challenge completion.

The two cases that I believe best illustrate how spatial thinking led to problem-solving insights, advanced challenge work, and advanced STEAM thinking and learning are the case of Adele working on *Spaghetti Structures* (accompanied at different points by an assortments of her classmates) and the case of Erin, Ajay, and Aiden working on *Solar Roller*. In both cases, students engaged in challenge work during multiple consecutive class periods and worked systematically through challenges levels. During challenge work, each group of students engaged in multiple rounds of troubleshooting and design iteration, which in many cases hinged on spatial insights.

For example, as Adele worked through the *Spaghetti Structures* challenge, she did level one multiple times, each time trying to improve upon her structure, making it taller and sturdier (see Figure 4.5). As she engaged in this iterative process of troubleshooting and design iteration, she was assisted by feedback from other students, the FUSE facilitator, the written challenge instructions, sketches, and perhaps most of all, the challenge materials themselves. She and her classmates applied a wide range of different types of spatial thinking, including disembedding, categorizing space, quantifying space, 2D to 3D translation, mental rotation, mental folding, mental simulation, perspective taking, spatial relations between objects or self and objects, describing relative size, dynamic spatial relations, and spatial analogies. They also engaged in a wide range of spatial sensemaking practices, including both epistemic and explanatory object manipulation, pointing gestures, gestures representing static spatial concepts, and sketching.

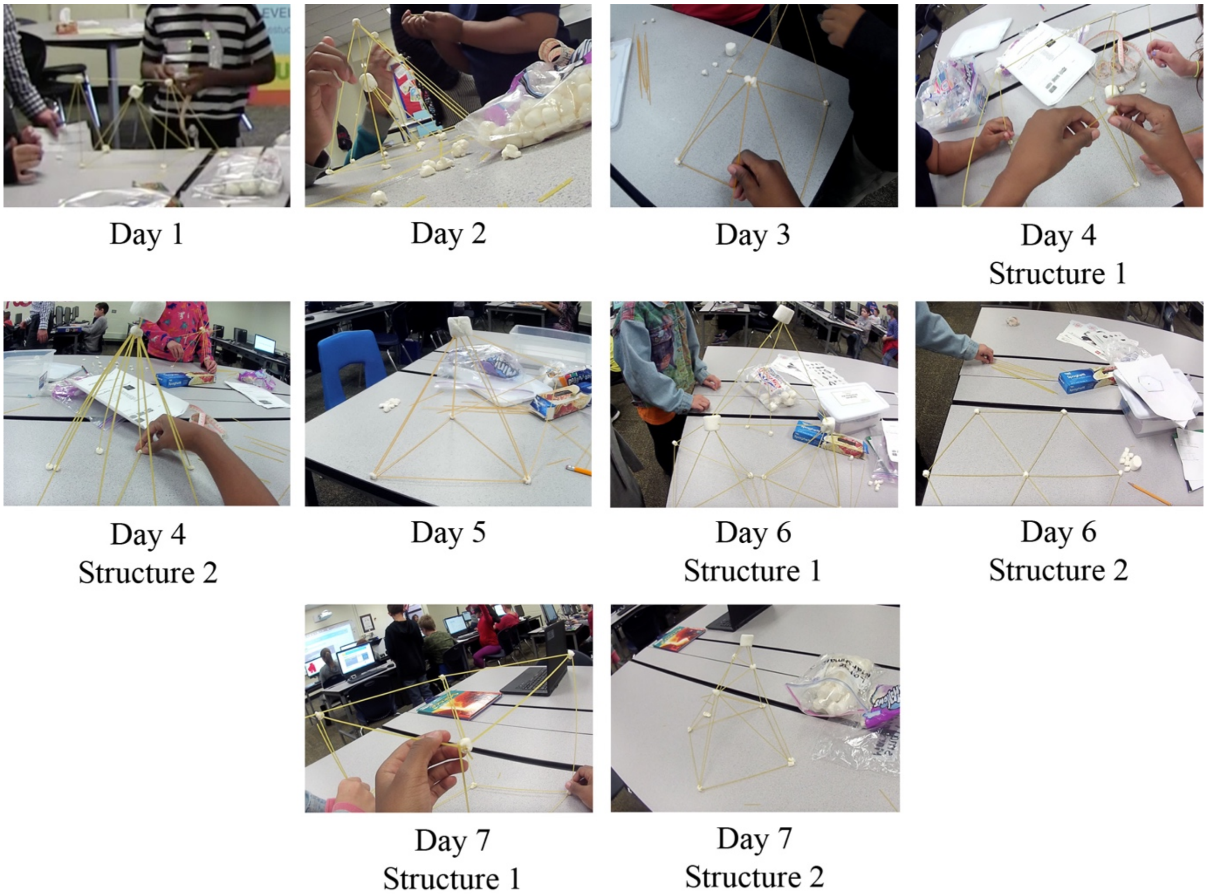


Figure 4.5. Spatial insights aid Adele and her classmates in iterating on their designs for Level One of *Spaghetti Structures*.

As Figure 4.5 shows, the primary difference between each iteration of Adele's structure is that each involved different spatial configurations of spaghetti and marshmallows. Each of these design iterations was born out of different distributed spatial sensemaking processes. For example, the structure from Day 4 was designed, in part, by drawing an analogy to the structure of a teepee. The structure from Day 5 was created by combining two pyramids through a process of rotating and folding the two pyramids (epistemic action, mental rotation, mental folding) to see how they might attach to one another. Similarly, Structure 1 from Day 6, was created by combining the structure from Day 5 with another identical copy of itself then tinkering with ways that additional pieces could be added to the top of that structure to make it taller (spatial relations, tinkering or exploring materials). Structure 2 from Day 6 was born out of a sketch (pictured in upper right corner of image) created by Ava and then built through coordinated action between her and Adele (sketching, drawing on other students as resources). Finally, Structure 1 from Day 7 was Adele's attempt at a different spatial arrangement of pieces (a cube rather than a pyramid), but was scrapped, after a wobble test (epistemic object manipulation) demonstrated that it wasn't sturdy enough to serve as a base for her structure. As a result of these different distributed spatial sensemaking processes, we can see that there was a progression in the height and complexity of Adele's structure over time, with the height peaking with Structure 1 on Day 6 and then some divergent design thinking occurring over the remainder of that class period and the class period on Day 7.

Erin, Ajay, and Aiden went through a similar progression of troubleshooting and iteration, facilitated by distributed spatial sensemaking, during their work on the *Solar Roller* challenge. As they worked systematically through the all three levels of *Solar Roller*, they encountered a number of problems that they needed to solve, and in many cases spatial insights, facilitated by material resources, helped them solve those problems. For example, as Figure 4.6 shows, while working on Level 1 of the challenge (on Day 2), the students used pieces of tape placed next to their measuring tape track to keep track of how far their car had gone on multiple iterative trials. Then, when they began Level 2 of the challenge (which requires that students create a 50-inch-long tunnel for their car to drive through), they searched for objects in the classroom that were already shaped like or could be arranged in the shape of a tunnel. On their first attempt at this (on Day 3), they used chairs, as Erin noticed that they resembled a tunnel (spatial analogy) and could be combined and arranged to provide 50 inches of cover for their track (spatial relations and quantifying space). Then later (on Day 5), when they switched from working on the floor to working on a counter and could no longer use the chairs, Erin had the idea first to tape pieces of printer paper together to form the tunnel (Day 7) then later to use box tops the students found in the classroom (Day 6).

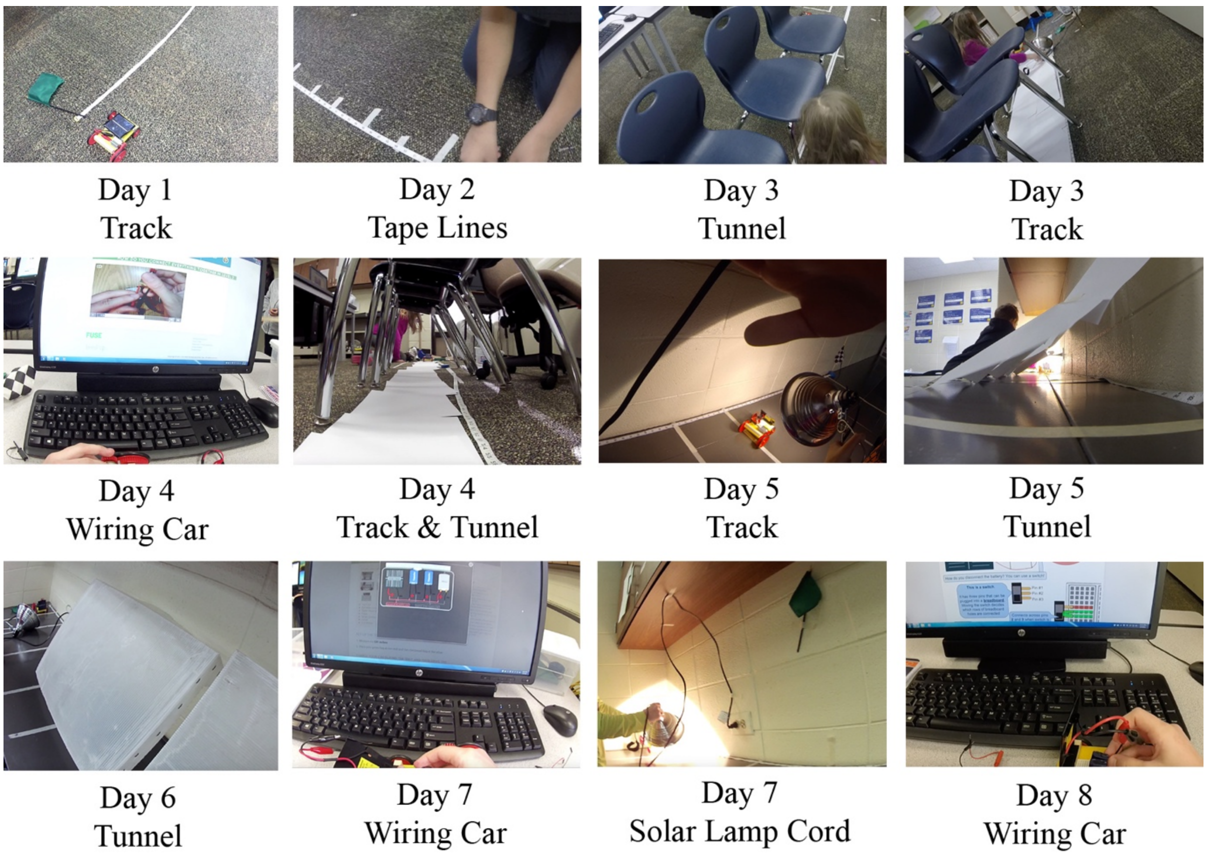


Figure 4.6. Spatial insights help Erin, Ajay, and Aiden progress through the levels of *Solar Roller*.

Another important insight, which relied, in part, on spatial thinking and spatial sensemaking practices was the insight to move from the floor to the counter in the first place. Noticing that the wheels of their solar car were spinning faster when they held it under the light in midair than when it was sitting on the carpet, the students hypothesized that the car would go further or faster if it were on a smoother surface. To solve this problem, Erin first suggested that Aiden put pieces of printer paper down on the floor (Day 3). Then, when that didn't work much better, they all went in search of a new surface on which to test their solar car. They found the counter and asked their teacher if they could remove the supplies normally kept there, in order to use it as a racetrack. She agreed, and only after the students' initial spatial observations (i.e., wheels spinning faster, distance the car was traveling, texture of different surfaces) did she provide the vocabulary word and accompanying scientific concept of friction to describe what they had noticed through observation. Noticing that their car did travel further and faster on the smooth counter than on the floor, the students continued testing there for the rest of their work on the challenge.

However, the placement of the outlet, in the middle of their racetrack, presented a new spatial problem — how to plug the lamp in but keep the cord out of the way during test runs. At first, on Day 5, Aiden solved this problem by holding the cord in the air while also holding the lamp over the car (Erin was in charge of holding, reseting, and retrieving the car itself). However, later, on Day 7, Aiden had the insight that a nonhuman could do this job for him and taped the cord to the wall and upper cabinet (spatial relations).

Finally, in addition to solving problems with their racetrack setup, the students also engaged in multiple rounds of troubleshooting and iteration with the solar car itself. Some of this was guided by challenge constraints, which required students to rewire and add additional items like capacitors to their cars to complete Levels 2 and 3 of the challenge. As we see from the images of challenge work from Day 4 and Day 8, in these instances, the students used help videos and diagrammatic instructions from the FUSE website to figure out how to correctly reconfigure their car (2D to 3D translation, spatial relations, physical alignment and structure mapping). In other instances, when wires came loose or gears fell out of alignment during testing, the students made adjustments to the arrangement of parts (spatial relations) through a combination of observations and tinkering.

In other words, throughout their work on the *Solar Roller* challenge, spatial observations, spatial thinking, and spatial insights were critical to helping Erin, Ajay, and Aiden advance through the levels of the challenge. However, it wasn't cognitive spatial processes alone that led to moments of insight and problem-solving, but the coordination of internal spatial representations with external tools and representations and between the three students working on the challenge, truly distributed spatial sensemaking.

Discussion

The findings presented in this chapter build on the work of Ramey & Uttal (2017) by applying their concept of distributed spatial sensemaking and their analytic techniques, to shed light on how learners made sense of spatial problems during FUSE making activities. The findings presented here also expand upon our analytic techniques, for endogenously examining spatial thinking in the context of STEAM learning activities, by integrating qualitative coding with interaction analysis. I also expand here, upon our previous work by examining differences in the character and content of distributed spatial sensemaking between specific making activities and tracking distributed spatial sensemaking over time to see how it led to improvements in spatial thinking, problem-solving insights, and STEAM thinking and learning.

Unlike previous research on spatial thinking in STEM, the data and analyses presented here examined spatial thinking and learning endogenously, in the context of actual problem-solving, rather than exogenously through psychometric assessments. These data and analyses also looked at spatial thinking and learning situated in the context of real-world learning activities, rather than in the artificial context of the laboratory. Finally, rather than focus on how didactic instruction might be modified to convey greater spatial understanding or train students to use particular spatial skills and strategies to solve specific, narrow problems in STEM, this investigation examined the ways in which students spontaneously made use of a variety of spatial skills and social and material resources in a makerspace environment to make sense of spatial concepts and solve STEAM problems.

The findings presented here demonstrate the important insights that can be gained from such a situated, endogenous account of spatial thinking. These insights extend both to understanding how spatial thinking unfolds in real-world problem-solving and learning contexts and specifically to how middle school students engage in spatial thinking and learning in a makerspace environment like FUSE.

First, spatial thinking was frequent and diverse in this makerspace environment and was well integrated with STEAM thinking, problem-solving, and learning. This provides an important contrast with regular school learning, where research on STEM thinking and learning suggests that verbal (e.g., reading, writing, and oral communication) and analytic approaches (e.g., mathematical formulas and calculations) have traditionally been privileged over spatial approaches to sensemaking (e.g., working with and communicating over shared spatial representations, tinkering with physical and digital materials, and designing physical and digital objects).

Second, although students engaged the types of intrinsic-static spatial thinking previously shown, in correlational studies using psychometric assessments, to be important for later success in STEM disciplines, these types of spatial thinking represented only one small sliver of the diverse array of spatial thinking that occurred in this context. This suggests that by using only these exogenous methods of assessing spatial thinking and learning, we are missing a lot of the richness of what students are actually doing.

Third, in making sense of the spatial aspects of the various FUSE activities, students used a variety of both social and material resources, often in coordination with one another. When allowed to arrange their own learning, as students were in FUSE, the primary resources they drew upon were other students and material resources, such as the physical or digital materials specific to each challenge. FUSE facilitators were used as learning resources much less frequently, indicating a sharp contrast between this learning environment and a traditional school learning environment. However, certain representations used by STEAM professionals, such as sketches, were also used infrequently, suggesting a contrast between how middle school students approach STEAM problem-solving and how professional might approach it. This indicates that by assessing spatial thinking in laboratory or testing contexts, where students are denied access to social and material problem-solving resources, we are likely missing large portions of what they would be capable of doing in more resource-rich contexts. It also indicates a need to shift the focus of research on ways to improve students' spatial skills away from ways in which didactic instruction can be modified to convey spatial information or ways in which students can be trained to approach specific problems more spatially and toward designing activities that provide students with the right task constraints to encourage particular types of spatial thinking and the right array of resources to draw upon to do so productively.

This last conclusion is also supported by my fourth finding, that the different sociomaterial contexts and task constraints of different of activities facilitated different types of distributed spatial sensemaking. For example, challenges involving CAD design involved more intrinsic- and extrinsic-dynamic forms of spatial thinking than did challenges which relied on other physical or digital tools. Particular tools available in the CAD design program Sketchup also had an impact on the specific way in which learners differently engaged in mental rotation versus perspective taking in that software environment. Similarly, challenges that included various forms of measurement in task goals or constraints (e.g., build the tallest spaghetti structure or build a solar roller car than can travel a certain distance in a certain amount of time) encouraged students to integrate spatial and mathematical thinking in ways that challenges without these mathematical constraints did not. Challenges which required learners to coordinate the movement of multiple objects and representations simultaneously to complete challenge goals encouraged distributed spatial sensemaking that involved complex coordination of extrinsic-dynamic spatial representations across human and non-human representational media. Meanwhile, open-ended, design-oriented challenges elicited the use of spatial analogies between structures students were working on and other spatial structures they'd experienced outside of the FUSE studio, while challenges which required mapping between different spatial representations or between objects and representations elicited more immediate analogical comparison, often accompanied by physical alignment of materials with other materials or with diagrammatic representations.

Further, the small moments of distributed spatial sensemaking, which occurred during all of the FUSE challenges served to advance both spatial thinking and also STEAM problem-solving and learning in ways that were pivotal to successful challenge completion. This suggests that the relative dearth of research on spatial thinking and problem-solving in makerspaces such as FUSE means that we have been missing out on valuable insights into how STEAM learning and problem-solving unfold in these contexts. It also means that the incorporation of making activities into the school day, and the spatial thinking and learning that they facilitate, may serve as a powerful antidote to the "hegemony of the printing press" (Uttal, 2017, np) or the dominance of texts as the objects of learning in traditional school classrooms (e.g., Dewey, 1898; Dewey & Childs, 1933; Miettinen, 1999; Engeström, 1987; Roth & Barton, 2004; Rajala, 2016; Whitehead, 1929).

Finally, the findings presented here have design implications, both for future FUSE challenges and for the design of other making or STEAM learning activities. First, specific spatial practices used by STEAM professionals, such as sketching, were notably absent from the distributed spatial sensemaking that occurred during FUSE challenges. If one believes sketching is a valuable practice for students to learn, to prepare them for success in STEAM disciplines, this suggests the need to design new challenges or redesign current challenges in ways that incorporate physical or digital sketching as a necessary part of challenge activity. Similarly, certain spatial skills identified in prior literature on spatial thinking in STEM learning, such as cross-sectioning or penetrative thinking (e.g., Cohen & Hegarty, 2007; Cohen & Hegarty, 2008; Kali & Orion, 1996) and locating an object or self with respect to a frame of reference or aligning different ways of location coding (e.g., Newcombe & Shipley, 2015) were notably absent in these activities, suggesting the potential for challenge development around these additional spatial skills. We can also take design implications from the spatial skills and practices that were present. Specifically, the fact that particular types of challenges promoted particular types of distributed spatial sensemaking provides insight into how one could design or redesign challenges to incorporate more of these specific types of spatial sensemaking. For example, designing additional challenges or activities which require the coordination of multiple people, objects, and representations simultaneously, as was the case in *3D You* and *Get in the Game*, would further promote the learning of extrinsic-static and extrinsic-dynamic spatial thinking as well as spatial communication via talk, gesture, and object manipulation. Adding more challenges, like *Spaghetti Structures* or *Solar Roller*, that require measurement or quantification of space, would further encourage students to integrate spatial and mathematical thinking during challenge work. Adding CAD challenges, particularly challenges like *Dream Home* that encourage learners to think of their CAD models both as objects and as navigable spaces, could further engage students in both extrinsic-static and extrinsic-dynamic spatial thinking, and adding more diagrammatic instructions, such as the ones found in *Solar Roller*, to challenges could help students learn to work from and better understand diagrammatic spatial representations. Finally, our findings regarding the diverse array of resources students drew on to make sense of spatial problems during challenge activity, suggest that teachers, both in FUSE and elsewhere, should seed learning environments with a diverse array of material resources, including spatial representations and physical and digital objects and encourage students to seek out and work in a collaborative and distributed manner with these varied resources to solve problems, rather than always conveying important information, a priori, via lectures or texts.

Chapter 5. Designing for Permeability: Supports and Barriers to STEAM Learning Across Contexts

In Chapters 3 and 4 of this dissertation, I presented evidence that the FUSE activity system facilitated both STEAM interest development and the learning of meta-disciplinary skills, such as 21st century skills and spatial skills. In other words, I have presented evidence that FUSE has the potential to not only motivate students to engage in future learning in other contexts, but also to provide them with a toolkit of knowledge and practices to use in future STEAM learning endeavors. However, I have also shown how the specific sociomaterial context (e.g., Orkilowski, 2007) of the FUSE studio and of specific FUSE activities facilitates STEAM interest development and learning, demonstrating that context matters, in determining what skills and practices are learned and applied and how interest develops. Therefore, to understand whether or how students might take things learned and interests developed in FUSE and apply them in other STEAM learning contexts, we must follow them as they travel across contextual boundaries, attending to the role that both students and their sociomaterial contexts play in determining what makes the crossing. The data and analyses I present in this chapter do exactly that, examining what happens as students move across contextual boundaries between FUSE and other in-school and after-school contexts. In following students across these contextual boundaries, I examine: (1) what interests and practices students are taking across these boundaries; (2) how they are using practices carried across contextual boundaries; and (3) how the sociomaterial contexts of both FUSE and the other STEAM learning activities and environments, in which students participate, influence how and what interests and practices make the crossing.

Prior Approaches to Studying Cross-Context Learning

Many researchers have argued for the importance of a cross-contextual approach to studying interest (e.g., Barron, 2006) and learning (e.g., Bell, et al., 2013; Lave, 1988; Keifert, 2015; McDermott, 1993; Rajala et al., 2013; Stevens, Wineburg, Herrenkohl, & Bell, 2005; for a recent review see Rajala et al., 2016). According to these researchers, the point of such an investigation is twofold. First, interest development and learning are no good to anyone if they never leave their context or problem of origin. In other words, true interest development and learning are only accomplished across settings (e.g., Barron, 2006; Bell et al., 2013). Second, examining what makes it across contextual boundaries and how sociomaterial contexts help or hinder students in the boundary crossing process can help us to better understand both cross-context learning and how to design for it.

In framing this analysis of cross-context learning, I draw on prior sociocultural conceptions of cross-context learning and boundary crossing. From this prior work, I draw three important framing principles. First, the communities in which we live shape the ways we observe, think, and talk about the world (Cole, 2007; Rogoff, 2003), and these settings are connected (Engeström, 1999; Leander, Phillips, & Taylor, 2010; Stevens et al., 2005). Therefore, understanding what influences the development of interests and learning requires that we move towards a connected analysis of how interests, skills, and practices are shaped by movement within and across settings. Second, in order for students to take knowledge, skills, and practices across contextual boundaries and apply them to new activities and contexts, they must both see the connections between contexts (e.g., Lobato, 2012) and be motivated to use the relevant knowledge, skills, and practices from one context in another. Third, the new context to which prior knowledge, skills, and practices are to be applied must be sociomaterially configured to allow for their application (e.g., Bell, et al., 2013; Tuomi-Gröhn & Engeström, 2003). For example, Bell et al. (2013) wrote that in examining cross-context learning, "The focus is on the modes of participation, which are afforded or constrained as persons attempt to coordinate and accomplish what they take to be personally consequential progress" (p. 272).

This approach to conceptualizing and promoting cross-context learning is distinct from psychological approaches, which would refer to processes like these as "transfer" (e.g., Gick & Holyoak, 1983) and which propose that learning is something that takes place within and is owned by an individual. Some cognitive approaches to transfer, such as structure mapping theory (e.g., Gentner, 1980; Gentner & Markman, 1997), acknowledge the importance of students seeing connections between tasks, problems, activities, or contexts. However, such approaches generally fail to acknowledge the importance of sociomaterial context in (1) allowing students to see these connections; and (2) making room for students to apply interests and practices learned in one context effectively in another. This is one likely reason that so many laboratory, or even classroom studies, aimed at training cognitive skills or imparting knowledge, fail to produce transfer. In attempting to be a-contextual, they instead produce learning that is too specific to the unique, and generally inauthentic, context in which the training occurs (Bransford & Schwartz, 1999) – and by context here I mean everything from the task to the tools and people available as resources to the literal physical space in which task occurs.

Within sociocultural research, researchers have also taken different approaches to comparing and analyzing interest development and learning across contexts. Some have compared learning in related activity systems involving different people (e.g., middle-school students designing and professionals designing; Stevens, 1999; Stevens, 2000, Stevens & Hall, 1998). Others have involved following the same people across contexts (e.g., Keifert, 2015;

McDermott, 1993; Stevens, et al., 2005) and using interaction analysis techniques to highlight differences in the interactional arrangements available for knowledge display (e.g., McDermott, 1993) or inquiry (e.g., Keifert, 2015; Mehus, Stevens, & Grigholm, 2013) in different contexts. A third approach to examining interest development and learning across contexts has involved asking students from one context about their activities in other contexts through interviews (e.g., Barron, 2006) or surveys (e.g., Maul et al., 2016). In this investigation, I draw on a combination of the second and third approaches. I followed the same students across contextual boundaries and used interaction analysis to demonstrate how different contexts afforded different opportunities for interest development and learning. However, I also drew on self-report data from interviews and surveys on ways in which students had pursued interests and learning from FUSE in other contexts, both in and out of school.

Another distinction between different prior approaches to studying cross-context interest development and learning is in the specific contexts that they compare. Most prior studies have compared in-school to out-of-school contexts (e.g., Keifert, 2015; Mehus, Stevens, & Grigholm, 2013) or examined the role of specific learning interventions in expanding the context of learning beyond the classroom (e.g., Rajala et al., 2013). One notable exception to this was the analysis conducted by McDermott (1993), which compared learning during classroom lessons and testing sessions not only to learning in everyday life, but also to learning in the intermediate space of a cooking class. In comparing interest development and learning in FUSE to interest development and learning in other contexts, I draw more on this third model, as FUSE itself is both in-school but is not school as usual. So, the meaningful comparisons are not just between in-school and out-of-school but also between FUSE and other, more traditional, school learning contexts. However, this investigation is also different from McDermott's, as his focus was specifically on how different contexts made learning disabilities more or less visible because of the way interactions were arranged within them. In contrast, here, I focus on ways in which different contexts facilitate interest development and learning.

Three Factors in Learning Across Contexts

In this investigation, I draw on work from Engström (2001) and focus particularly on tensions or contradictions between interacting activity systems. In this comparison, I focus specifically on three factors, drawn from prior literature, which I believe distinguish FUSE from many other STEAM learning activity systems, particularly in schools. The first of these is relative openness of the context. The second, related factor, is the amount of agency that the activity system affords, and the third factor is the object of learning in different activity systems.

Open versus Closed Contexts. Gresalfi et al. (2009) also focused on the relative openness or closed-ness of different contexts for learning, comparing social interactions in two middle school mathematics classrooms. In the more conventionally organized classroom, the tasks were relatively closed. Tasks emphasized the accurate use of procedures, and students were accountable for providing a correct answer to the teacher. In contrast, in the other classroom, tasks were more open-ended. The tasks involved creating and collectively discussing mathematical symbols, and students were accountable for convincing not only their teacher but also their peers. I assert that this second context, both in its openness and in students' accountability to their peers, rather than teachers, closely resembles FUSE, whereas other STEAM learning contexts in which students participate, particularly in school, more closely resemble the first context.

Agency. A second, related, factor distinguishing different STEAM learning contexts is the relative agency afforded to students in these different contexts. By agency here, I do not mean agency in the psychological sense (e.g., Bandura, 2001; Deci & Ryan, 1995), as a property of an individual, as these accounts of agency do not provide adequate tools for investigating the role that sociomaterial context plays in enabling and constraining agency. Instead, I draw on prior sociocultural conceptions of agency (e.g., Engeström, 2006; Holland et al., 1998; Rajala et al., 2013; Wertsch et al., 1993), defining agency as "the realized capacity of people to act upon and transform their activities and social circumstances," which is "constituted in relation to other people and objects of activity" and "mediated by discursive and practical tools" (Rajala et al., 2013, p. 31). In particular, Rajala et al. (2013) identified three different types of agency that an activity system for learning might afford: relational, conceptual, and transformative agency.

The first of these, relational agency, was described by Edwards and Mackenzie (2005) as involving "a capacity to offer support and to ask for support from others…one's capacity to engage with the world is enhanced by doing so alongside others" (p.29). Edwards & D'Arcy (2004) wrote that relational agency also involves "a capacity to engage with the dispositions of others in order to interpret and act on the object of our actions in enhanced ways" (p. 47). This capacity is constituted in relation to other people and objects of activity (Edwards, 2005; Holland et al., 1998), as well as mediated by discursive and practical tools (Wertsch et al., 1993). In other words, altering student agency requires altering its constituent social relations (Ratner, 2000). Thus, the way in which instructional activity is organized and what resources are made available for students mediates the students' possibilities to achieve agency; different pedagogical approaches and practices position students with varying degrees and forms of agency (McFarland, 2001; Lipponen & Kumpulainen, 2011; Gresalfi et al., 2009). In other words, this form of agency refers to how much control students have over their own collaborative arrangements or the ways and extent to which they use other people as resources for learning.

A second type of agency, conceptual agency, entails actions which depend upon "students' choices of the types of material or conceptual resources to be appropriated, adapted or modified for a specific purpose in the learning activity, as evidenced in students' transfer of knowledge and skills across contexts" (Rajala et al., 2013 p. 118; see also Engle, 2006; Greeno, 2006; Engle, Nguyen, & Mendelson, 2011; Kumpulainen & Lipponen, 2013). In other words, this form of agency refers to how much control students have over the content of their learning and the resources they draw on for learning.

The third form of agency Rajala et al. (2013) describe is transformative agency. They observed this form of agency in their intervention, in students breaking away from traditional 'taken-for-granted' practices (Engeström, 2008; Rainio, 2008) by: (1) taking initiative to influence local cycling conditions; and (2) contributing to a public political debate about cycling issues (Engeström, 2008; Lipponen & Kumpulainen, 2011). In other words, this form of agency refers to the extent to which students (or instructors) are able to shape their own or others' practices and contexts, either for learning or for other types of activity.

To some degree, all three of these forms of agency are granted to students in FUSE. Work by Penney (2016) and Stevens et al. (2016) on the variety of learning arrangements found in FUSE suggests that relational agency is prevalent in FUSE. Analyses presented in Chapters 3 and 4 of this dissertation also suggest that conceptual agency is strongly present in FUSE. And although there are fewer opportunities in FUSE for students to engage in transformative agency by directly influencing or transforming their environment through social outreach projects, like the one studied by Rajala et al. (2013), there are certainly opportunities for students and teachers to break away from traditional taken-for-granted classroom practices, indicating some space for transformative agency as well. However, it remains an open question to what extent students experience these forms of agency in other STEAM learning contexts or what impact having these sorts of agency in FUSE might have on students' learning in other contexts.

Differences in the Object of Learning. A final factor distinguishing different STEAM learning contexts is the object of learning. The most important element of any activity is its object; the object gives an activity meaning and is what distinguishes one activity from another (Leont'ev, 1978, 1981). For example, if the object of instructional activity is for students to acquire routine knowledge and procedural skills to perform well on tests, the scope of their appropriate actions is more limited than for students for whom the object of activity is the generative use of concepts and principles (Greeno & Engeström, 2014). Traditionally, the object of instructional activity has been written texts or verbal instruction from a teacher, rather than everyday problems and phenomena from students' lives or the wider society (Leander, 2002; Engeström, 1994). In contrast, in FUSE, the object of learning in shifted from traditional school texts to solving real problems of interest to students, using the tools of STEAM professionals.

Prior Pedagogical Approaches to Facilitating Cross-context Learning

Prior work comparing learning across contexts has also provided us with guidelines for the types of pedagogical approaches likely to facilitate cross-context learning. These are important both in shaping our conceptual understanding of what factors help or hinder cross-context learning and also to lay the theoretical groundwork on top of which I hope to build in this analysis of FUSE as context that may facilitate boundary crossing.

One prior approach to facilitating cross-context learning is the expansive learning approach (Engeström, 1987; Engle, 2006; Rajala et al., 2013). In expansive framing, students are positioned as actively contributing to larger conversations that extend across time, place, and people (Engle 2006; Engle et al., 2011; Engle, Lam, Meyer, & Nix, 2012). Engle (2006) showed that an expansive framing of classroom interactions could support students in connecting their learning across the diverse settings and activities of their lives. One classroom intervention, which took expansive learning as its framing principle, was the Bicycles on the Move! project, studied by Rajala et al. (2013). This project took as its goal expanding learning beyond the classroom by engaging teachers and students in an open-ended project on improving local cycling conditions. Through this project, students were invited to go out into the community and explore it through cycling and also to make recommendations to the community about ways to improve cycling conditions. Thus, rather than bringing outside practices into the classroom or classroom practices out into the world, Rajala et al. (2013) address the issue of designing for boundary-crossing by expanding the chronotope of the classroom — the time and space in which learning is able to occur — or in other words, by essentially eliminating some of boundaries between in-school and out-of-school altogether.

A second approach is the funds of knowledge approach (e.g., Hogg, 2011; Moll, et al., 1992; Vélez-Ibáñez & Greenberg, 1992). The concept of funds-of-knowledge stems from research carried out in Latino/a communities, aimed at combatting deficit framings of minority students' classroom performance (Moll et al., 1992; Vélez-Ibáñez & Greenberg, 1992). By demonstrating the wide range of expertise developed by students and their families at home and encouraging them to share these varied forms of expertise at school, the researchers demonstrated: (1) the ways in which a more nuanced, less stereotypical view of culture could help educators design for diverse groups of students; and (2) the ways in which household knowledge, skills, and practices could be brought into the classroom to support or augment existing classroom practices and learning.

In this line of research, Keifert (2015) used interaction analysis to demonstrate ways in which children's home inquiry practices were deployed at school and either taken up or not by teachers and peers in that context. From this analysis she proposed one specific way in which teachers might draw on something like students funds-of-knowledge, or really their funds-of-practice, in a classroom environment, by engaging in *reflective* and *directed weaving*. She wrote that "*reflective weaving* requires recognition of the abundance of practices upon which children are already able to draw whether those practices influence how children play (Heath, 1983), the ways they argue and engage in word play (Hudicourt-Barnes, 2003), or the way they engage in questioning and exploring" (p. 201-202). In contrast, *directed weaving* "requires teachers to collaboratively draw upon students' familiar practices, weaving those practices into the practices of the classroom" (p. 202). In other words,

> Teachers must both *observe* and *engage with* children as children attempt to draw upon family practices. By engaging in directed weaving teachers can purposefully inter-weave and transform students' practices together with students into a shared collection of ways of perceiving and knowing in the classroom so that family practices would not be "dead ends" in lines of experiences in the classroom where children are expected to "pick up" new lines. (p. 202)

Both of these approaches potentially grant agency to students that they might not have in a traditional school classroom. However, in larger part, they require agency on the part of the teacher (Edwards & D'Arcy, 2004; Lipponen & Kumpulainen, 2011; Rajala et al., 2013) to transform classroom practices. I propose that FUSE actually provides a third model of an activity system for learning that facilitates boundary crossing or extending learning across contexts. Although this model also requires some agency on the part of the teacher, it shifts more of the agency to students for pursuing their own interests and shaping their own learning.

Learning Contexts with Permeable Membranes

I argue that as an open context, which grants relatively high levels of agency, and has as its object of learning STEAM exploration and design challenges of students' choosing, FUSE is designed in a way that allows learners to bring in and incorporate interests and practices from other areas of their lives. As a result, that permeable membrane may also be more likely to flow the other direction, allowing learners to take interests and practices cultivated in FUSE and develop them further in other spaces. The model depicted in Figure 5.1 represents how I see the flow of ideas, interests, and practices moving both into and out of FUSE and evolving because of experiences and connections made during FUSE activities.

As the model shows, FUSE allows learners to bring in and incorporate interests and practices from other areas of their lives. As a result, those interests become paired with and changed by learners' experiences in FUSE. Further, the same permeable membrane that allows learners' interests into FUSE, makes it easier for learners' to extend the interests developed in FUSE out into other contexts, where they further develop and become paired with new interests. In contrast, other contexts, which are not as open to the import of interests and practices may also not be as open to their export.

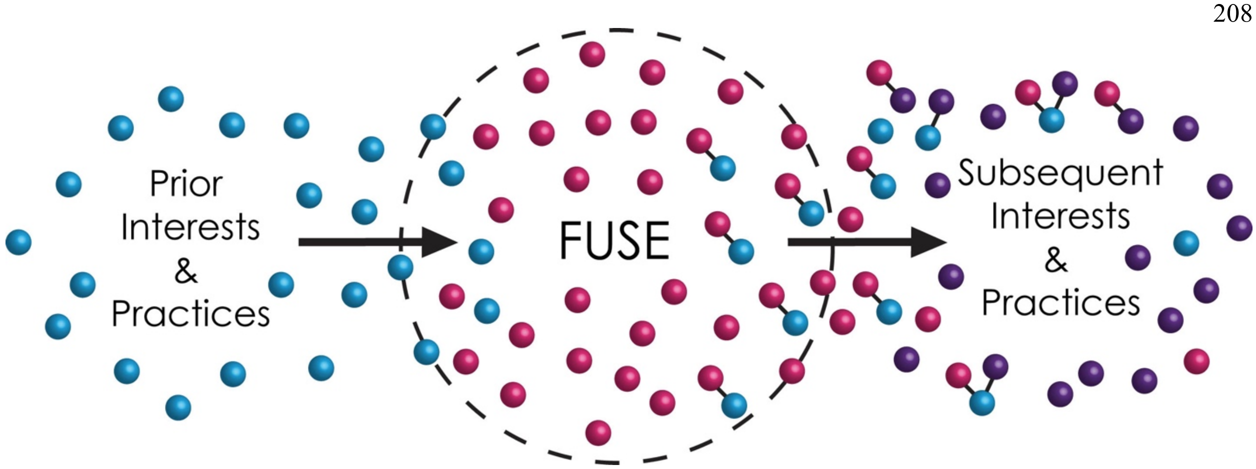


Figure 5.1. FUSE's permeable membrane allows students' interests to be both brought into and extended out of FUSE, while also developing, as a result of experiences and connections made during FUSE activities.

The findings presented in this chapter will demonstrate how FUSE serves as a permeable activity system for interest development and learning. I will also show how other learning contexts, particularly in school, may or may not have that same permeability, based on specific features of their respective activity systems. In this investigation, I will specifically focus on the following questions:

1. What interests and practices do students move across boundaries between FUSE and other contexts?
2. How do they use practices carried across contextual boundaries similarly or differently in different contexts?
3. How do the sociomaterial contexts of both FUSE and the other STEAM learning activities and environments in which students participate influence how and which interests and practices make the crossing and which do not?

Data Analysis

To answer these questions, in addition to the five classes of fifth and sixth grade students that I observed over two school years, during FUSE (90 minutes per week), I also followed those same FUSE students as they participated in select in-school and after-school STEAM learning activities, identified by teachers or students as related to FUSE. The first of these was a math-class tetrahedron-kite-making activity, that one class of fifth grade students participated in at the end of the 2014-15 school year (one hour a day for four days), after both teacher and students had participated in a full year of FUSE. The second was a Project Lead the Way (PLTW; Project Lead the Way, 2015) wind turbine engineering activity, in which I observed two classes (one sixth and one mixed fifth-sixth) participating at different points during the 2015-16 school year. The mixed fifth-sixth grade class did this activity in the fall, while the sixth-grade class did it in the winter. I also observed FUSE students at one school as they participated in after-school FUSE club and a school-wide science fair and students at another school as they participated in a school-sponsored STEM night for students and their families. Finally, in addition to direct observations of FUSE students engaging in STEAM activities both inside and outside of FUSE, I drew on data from a connected learning survey (Maul et al., 2016), administered to all FUSE students, as well as interview data and students' spontaneous self-reports regarding participation in FUSE-related STEAM activities in other contexts.

Analytic Methods. To analyze activity in and out of FUSE, I drew on a combination of cognitive ethnography (Hutchins, 1995a; Hollan et al., 2000) and interaction analysis techniques (e.g., Goodwin, 2000; Hall & Stevens, 2015; Jordan & Henderson, 1995; McDermott, et al., 1978; Mehan, 1982; Schegloff, 1992) as well as qualitative categorical coding of survey and interview data. I chose to employ interaction analysis specifically because of its history of use in cross-context examinations of learning. In particular, as Jordan and Henderson (1995) wrote, Interaction Analysis allows us to consider "to what extent the spatial layout of the setting is fixed or allows choices; that is to say, to what extent physical configurations and spatial arrangements are imposed and to what extent they are under the immediate control of participants" (p. 75). Jordan and Henderson (1995) also argue that interaction analysis affords an examination of *participation frameworks* — "fluid structures of mutual engagement and disengagement characterized by bodily alignment (usually face-to-face), patterned eye-contact, situation-appropriate tone of voice, and other resources the situation may afford." (p. 68). They argue that,

> The analysis of participation structures is also essential to understanding interaction in formal school settings. To what extent do teacher and students sustain different kinds of participation structures in group work or in lecture format? How do computers, workbooks, table arrangements, and other kinds of artifacts support or destroy such structures? (Jordan and Henderson 2002, p. 69).

The fact that interaction analysis allows for such an analysis, makes it an apt method for comparing contexts in terms of their differing sociomaterial contexts and the relative agency and specific types of practices and interactions that these contexts afford.

Analytic Process. In analyzing students' interaction data, I first developed content logs (Erickson & Schultz, 1997; Jordan & Henderson, 1995; Pomerantz & Fehr, 1997). Then I identified moments of interest, collaboration, and learning or problem-solving within the FUSE data and identified routine ways in which students engaged in FUSE. Then I identified instances in which students engaged in similar practices related to interest, collaboration, and learning or problem-solving in the other STEAM learning activities in which they participated. Then I created multimodal transcripts and engaged in turn-by-turn analysis from transcripts to understand what participants were accountably doing together in these different contexts, and how interactions in the different contexts looked similar or different.

Findings

In the sections that follow, I present the findings from two separate analyses, demonstrating the ways in which the boundary between FUSE and other STEAM learning activities and contexts served as a permeable membrane. First, I present students' self-report data from connected learning surveys, interviews, and observations on the places to which they extended FUSE interests and practices and which interests and practices they extended. Through this analysis, I demonstrate ways in which FUSE helped students to both bring outside interests and practices in and extend interests and practices out to in-school and out-of-school contexts. Then I present analysis of FUSE students participating in two in-school STEAM learning activities. The first activity is a tetrahedron kite-making activity that one class of fifth grade students engaged in, at the end of the school year. I present this case to demonstrate the ways in which practices from FUSE were productively applied in other STEAM learning contexts, when students and teachers had the agency to shape those activities. The second activity is a PLTW wind turbine activity, which I observed two classes of students participating in at different points in the school year. Here, I present analysis of one of these two classes doing the PLTW wind turbine activity, as a case demonstrating how, in contrast to FUSE, other in-school STEAM learning activities often resist permeability by closing off options, denying students agency, and focusing on different objects of learning.

Connections Between FUSE and Other Parts of Students' Lives. The students in my sample reported participating in FUSE activities or FUSE-related activities in a number of different contexts outside the FUSE studio. These included all of the locations explicitly asked about on the connected learning survey, which 78 of the students in my sample took. Of the locations explicitly asked about on the survey, the most commonly reported location was at home or friend's house (40), followed by on the internet (38), at class during school (23), at an after-school program (18), at a library (18), at a park district program (14), at camp during vacation (9), at a youth organization in the community (8), at a church, synagogue, mosque or other religious place (5), and at a museum or cultural center (5). Through the open-ended "other" question on the survey, end-of-year interviews, and informal interviews and discussions during FUSE time, students also provided additional locations where they participated in FUSE activities or FUSE-related activities outside the FUSE studio, including: in the car, at a family member's house, dance class, sports practices or games, the hospital, and Canada. One important thing to notice here is the wide variety of places in which students reported participating in FUSE activities or FUSE-related activities (16 different locations). The second thing to notice is that many of the locations students reported, such as the hospital, dance class, or sports practices or games are places that we might not have expected to see students making connections to FUSE.

Across these different settings, students also reported engaging in a wide variety of different FUSE activities and FUSE-related activities. First, students reported working on a number of specific FUSE challenges outside the FUSE studio. These included Ringtones, Game Designer, Dream Home, Electric Apparel, and Keychain Customizer. Students also reported engaging in a number of non-FUSE activities that they saw as related to FUSE. These included both in-school and out-of-school activities, such as playing the piano, making things with a 3D printer pen, computer programming, Scratch programming, Minecraft, drawing Anime characters, making pixel art, making Youtube videos, Lego robotics, kite-making, math, and a Project Lead the Way wind turbine activity.

Interests and Practices Moving into and out of FUSE. In addition to students' self-reports of taking interests and practices out of FUSE into out-of-school activities, we also directly observed students both bringing outside interests and practices into FUSE and extending interests and practices out of FUSE. Three cases, in particular, exemplify the different forms this boundary crossing took.

The first example is Emil, one of the students whose case I detailed in Chapter 3 of this dissertation. Emil chose the game designer challenge because of a prior interest in video games. He became excited about the idea of designing his own characters for the game using a web app he found called Piskel. In addition to continuing his work with Piskel during FUSE for the remainder of the school year, Emil also continued this activity both at home and in after-school FUSE club. This cross-context work was enabled by the fact that Emil was able to save his files to an online Piskel account, where he could access them from school or from home. It was also enabled by his FUSE facilitator, Mr. Williams, who not only didn't shut down his activity in Piskel, as might have happened in a more closed school learning context, but he actually encouraged it and praised it in his end-of-year interview.

> Mr. Williams: Emil is really ... It's so refreshing when I see him really excited about something. He would tell Kay what he did at home. "At home I got this working," and he'd come here and try to do it here, or continue on what he was doing at home. He's kind of funny because he ... I've had Emil for two years, and when he's excited, he talks higher, the pitch of his voice gets higher, and it's kind of more exciting for him. He seems pretty into this. I don't know, last year he worked on some challenges. This year, I would say the majority of the time, he wasn't on a regular challenge that was written by Northwestern. He kind of went on the Piskel, and did kind of his own things, but he would get those figures to move. A lot of them, they end up coloring, or making a new one, same type of ... They'll look at one as a model, and then maybe they'll change the colors, maybe one pixel at a time, where he tries to go beyond a little bit, and that's how he is. He tries to go beyond in a lot of other things. He really seemed to be more, I don't

> want to overuse the word engaged, but he was a little bit more engaged into that than others.

At the end of the year, Emil reported that when he grows up, he wants to be a video-game designer, indicating that his pursuit of this interest within the FUSE context and its extension across contextual boundaries led to interest and identity development around this activity.

The second example of students bringing outside interests and practices into FUSE and extending them out from FUSE is related to CAD design and 3D printing. A number of FUSE challenges incorporate these tools and activities, and they are some of the most popular challenges. For many students, designing things with CAD software for the 3D printer proved to be an activity where they could bring in outside interests by, for example, designing objects related to those interests, such as characters from video games, favorite cars, or sports logos and equipment (See Figure 5.2).

As a result of students' interest in the 3D printer, I heard a number of stories from students and parents, about students asking for 3D printers, or more affordable 3D printer pens, to use at home. For example, on fifth grade student, Annabelle asked for, and received a 3D printer pen for Christmas. Afterward, she asked permission to bring it in to FUSE, so that her FUSE facilitator, Mr. Lewis, and other students could share it with her and help her figure out how to use it. Because of the openness of the FUSE studio and the agency granted to students in FUSE – both by the design of the activity system and by the facilitator – Annabelle was able to bring the 3D printer pen in and experiment with it, with her classmates. This began with a few days of online research and experimentation, during which she and her classmates figured out how to load filament into the pen. Then, after they'd figured out how to use it, Annabelle and her classmates used the pen to create designs, such as a Batman face (see Figure 5.2), which drew on outside interests in similar ways as those created with the 3D printer. At this point, the FUSE facilitator also encouraged Annabelle to design a challenge around the 3D Printer Pen, further indicating his acceptance of this activity. It wasn't until Annabelle had created and completed that challenge that she took the pen home, where she reported continuing to use it.

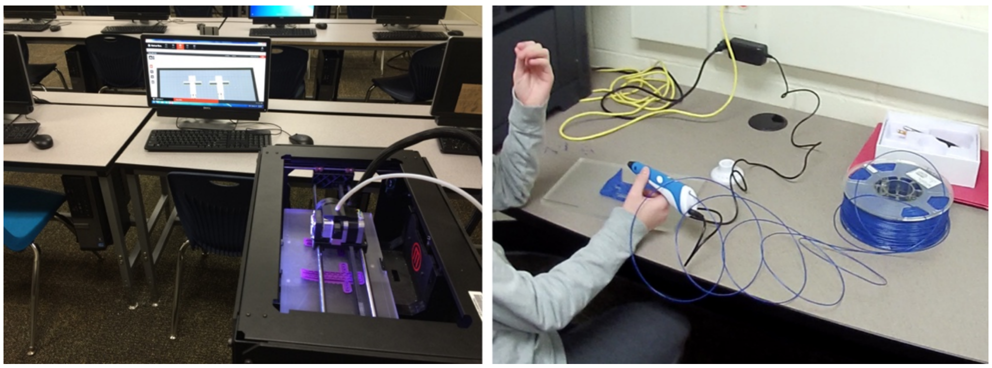


Figure 5.2. Students created objects of interest to them, such as favorite characters, with the 3D printer (left) and also with a 3D printer pen that one student brought into the FUSE studio (right).

A third case of a student bringing interests and practices into the FUSE and then also extending them out from the FUSE studio, came from a fifth-grade student, Erin, mentioned in the Solar Roller case presented in Chapter 4. In addition to reporting working on FUSE challenges at home, Erin saw a connection between the FUSE activities and Scratch programming that she had learned to do as part of a girls-in-engineering program. So she started doing scratch during FUSE. Notably, rather than shutting this activity down, as a teacher might in another classroom, her FUSE facilitator, Ms. Vonn, not only allowed her to continue, but also encouraged her to show the class how Scratch worked. Then, later, through a conversation with a member of our research team, her facilitator became aware of the similarities between Scratch programming and the programming in the FUSE Game Designer challenge. So, she opened the challenge (which was previously only available to sixth graders at that particular school) and suggested to Erin and her classmates that if they liked Scratch, they might also like Game Designer. Erin and a number of her classmates did try Game Designer, and as the transcript below shows, in her end-of-year interview, Erin talked about her Game Designer project as one of the things she was proudest of from her time in FUSE and discussed the connections she saw between Scratch and Game designer (see Table 5.1).

Table 5.1
Erin Talks About Her Game Designer Project in Her End-of-year Interview

Line	Person	Talk
1	Researcher:	Can you show me something that you're proud of from FUSE, and tell me about it?
2	Erin:	Well, I'm pretty proud of my Game Designer, because for the coding, it's pretty difficult to see the coding and stuff like that and to make Mario jump and to make the flag work again and to add some more ground for him to walk on, something like that. Yeah, the coding blocks are pretty difficult to do, but I have some experience using Scratch, and I've been on Scratch for over, for seven months or eight months so far. So, yeah.
3	Researcher:	How did being on Scratch help you with Game Designing?
4	Erin:	Scratch has lots of coding in it, like you can make projects with coding in it, and then there are blocks for coding in Game Designer that are very similar to Scratch but with different properties and stuff like that, to make Mario jump and stuff. They also have sprites and ways to control the sprites and do some stuff there.

As the transcript shows, not only did Erin see a connection between Scratch and Game Designer (line 2), but making that connection: (1) allowed her to make a project she was proud of (line 2); and (2) helped her make progress on that project in Game Designer by applying things she'd learned from doing Scratch (line 4). Later in the same end-of-year interview, Erin also talked about how when she grows up, she wants to be an astrophysicist, chemist, or programmer (See Table 5.2).

Table 5.2

Erin Talks About Her Career Aspirations to Be an Astrophysicist, Chemist, or Programmer

Line	Person	Talk
1	Researcher:	Have you thought about what you want to do when you grow up?
2	Erin:	Yeah, I want to, since I really like space and stuff like that, I would like to be an astrophysicist or chemist, even though an astrophysicist is a mix of physics and chemistry. I would like to also be a programmer or stuff like that.
3	Researcher:	Did you want to be those things before you started doing FUSE?
4	Erin:	Yeah, I was into science a long time ago, and I still am.

The reader will note from the transcript that although Erin cites her interest in science as predating her time in FUSE (line 4), indicating that her career interest in astrophysics or chemistry (line 2) may not have been the result of FUSE, she does not make the same claim for her interest in programming, suggesting that this particular interest may, in fact have been sparked or at least cultivated by her work on Scratch and Game Designer.

Emil, Annabelle, and Erin's cases demonstrate how the FUSE activity system's permeability allowed students to bring in outside interests and practices. They also show how the openness and agency granted by FUSE allowed students to cultivate those interests and practices and make important connections between related activities or objects of learning in ways that furthered problem-solving, learning, interest development, and identity development.

Moving Practices Across Contexts: A Math Class Tetrahedron Kite-making Activity. So far, the three cases I've presented, show how students carried STEAM interests and practices back and forth between FUSE and out-of-school spaces. The next example shows how practices from FUSE got used in subsequent in-school STEAM learning, specifically in a tetrahedron kite-making activity that a group of fifth grade students did in their math class.

The kite activity was a four-day activity that occurred at the end of the school year, after both the students and the teacher, had participated in FUSE for a full year. On the first day of the activity, the classroom looked pretty much like it would during a typical math class (See Figure 5.3). The teacher introduced the activity via powerpoint. Students sat mostly at their desks and worked mostly individually, following diagrammatic instructions.

Figure 5.3. On day one of the kite activity, the activity system looked like a typical math class.

However, over the course of the four-day activity, both teacher and students made specific moves that transitioned the activity system from a traditional math class activity system, into something that looked more like FUSE. First, when students had questions, the teacher referred them to the diagrammatic instructions rather than directly answering their questions. She talked about this as being more like what she did during FUSE than during regular math class, and we can see from the transcripts below, the first from FUSE (Table 5.3) and the second from the kite activity (Table 5.4), that her self-report accurately reflected what we observed in her interactions.

Table 5.3

Ms. Ross Refers Students to the Directions During FUSE, Rather Than Answer Their Questions Directly

Line	Person	Talk	Actions
1	Aarav:	Here, here, here, Drew, Drew,[1] actually, you know what we could do?	[1]*Aarav puts solar car on table in front of Drew.*
2	Drew:	What?	
3	Aarav:	First lets, wait, are we allowed to do it along here?[1]	[1]*Aarav points to the table and moves hand back and forth along length of table.*
4	Drew:	Huh?[1]	[1]*Drew looks at Aarav.*
5	Aarav:	Are we allowed[1] to use the solar roller?	[1]*Aarav points to solar car.*
6	Marigold:	Can we use that after you guys?	
7	Aarav:	[1]Sure.[2]	[1]*Aarav looks at group of girls.* [2]*Aarav looks back at Drew.*
8	Ms. Ross:	Uh, guys, you have to take turns with the light.	
9	Drew:	[1]No we don't have to[2]	[1]*Drew looks at the directions on the computer screen.* [2]*Drew looks at the facilitator.*
10	Aarav:	Wait, we don't have to do it on the carpet, do you?	
11	Drew:	[1]No.[2]	[1]*Drew looks at Aarav.* [2]*Drew looks at Ms. Ross.*
12	Aarav:	Let's do it on here, cause you could actually go faster.	
13	Ms. Ross:	[Let's, you have to share the light	
14	Aarav:	[Yeah wait, are we allowed to	
15	Ms. Ross	These are the	
16	Aarav	Are we allowed to use, um are we allowed to race [along here	
17	Ms. Ross	[[1]What does the directions say?	[1]*Ms. Ross points to the computer screen.*
18	Aarav and Drew:		*Aarav and Drew look at directions on the computer screen.*
19	Ms. Ross:	[You gotta read it.	
20	Drew:	[Yeah it doesn't say.	
21	Ms. Ross:	[Is it on the carpet?	
22	Aarav:	[Ok[1]	[1]*Aarav goes to get measuring tape and flags from floor and brings them over to the table.*

From the transcript in Table 5.3, we can see that after Aarav had the idea to test his and Drew's solar car on the table, rather than on the carpet (line 3), he first consulted Drew (lines 3-5). Then when Ms. Ross entered the interaction to enforce sharing of the solar lamp with Marigold's group (line 8), Aarav asked her as well (lines 14 and 16). However, instead of answering his question directly, Ms. Ross referred him to the directions, by asking "What does the directions say?" and pointing to the computer screen, where the boys had the challenge directions visible (line 17). Aarav and Drew then looked at the directions (line 18), and Drew concluded that the directions didn't say one way or the other (line 20). So Aarav said "Ok" (line 22) and went to get the measuring tape and flags from the floor and bring them over to the table.

We can compare this with a similar episode from the kite activity, shown in Table 5.4.

Table 5.4

Ms. Ross Refers Students to the Directions During the Kite Activity, Rather Than Answer Their Questions Directly

Line	Person	Talk	Actions
1	Liam:	[1]Is this a good triangle?	[1]*Liam turns toward Dimitri and holds up the triangle he has made.*
2	Dimitri:	This is awesome![1] How did you do that?	[1]*Dimitri reaches out and grabs one leg of triangle, looks at it, then releases it.*
3	Liam:	[1]I have no idea.	[1]*Liam looks at Dimitri.*
4	Dimitri:	Can you help me?	
5	Liam:	I don't know how I did it.	
6	Dimitri:		*Dimitri walks away.*
7	Liam:	[1]Dale, I don't know how I did this.[2]	[1]*Liam turns toward Dale.* [2]*Liam holds up the triangle he has made.*
8	Dale:	[1]That's pretty cool. I have Under Armour.	[1]*Dale walks over.*
9	Marigold:	[1]Wait, you're supposed to tie it on each end? Wait, can I see? [Liam! Liam, can I see it?	[1]*Marigold looks at Liam.*
10	Dimitri:		[*Dimitri walks back over.*
11	Liam:	[[1]I need some Under Armour.	[1]*Liam looks at Dimitri.*
12	Dimitri:	I got some.[1]	[1]*Dimitri points to his shorts.*
13	Liam:	I need some better armor.	

14	Marigold:	[Liam, can I see that? Liam!	
15	Dale:	[[1]I want to help you guys.	[1]*Dale looks at Dimitri.*
16	Liam:		*Liam looks at Dimitri.*
17	Dimitri:	[I gave you a good one.[1]	[1]*Dimitri walks away again.*
18	Marigold:	[You're supposed to tie them here?[1] Oh.	[1]*Marigold looks at and points to the directions.*
19	Ms. Ross:	Ok, everybody needs to do a floor check right now, after you're done cutting.	
20	Marigold:	Wait, are there supposed to be two strings hanging here.	
21	Ms. Ross:	[1]Did you measure your string out before you did this? Is this one meter?	[1]*Ms. Ross picks up triangle.*
22	Marigold:	Yeah, it's one meter.	
23	Ms. Ross:	Ok, read your directions.[1]	[1]*Ms. Ross points to the directions.*
24	Marigold:	And it says make one longer and one shorter.[1]	[1]*Marigold points to the directions.*
25	Ms. Ross:	Ok, but where do you do it?	
26	Marigold:	Oh.[1]	[1]*Marigold begins reading the directions out loud, while pointing to the words.*

In this episode, after seeing Liam hold up the triangle he had made out of string and straws (lines 1 and 7), Marigold asked him for advice on constructing her own triangles, saying, "Wait, you're supposed to tie it on each end? Wait, can I see? Liam! Liam, can I see it?" (Line 9). However, Liam, who was having a conversation with Dale and Dimitri (lines 1-8, 10-13, and 15-17), didn't respond to Marigold's original question or her second bid for his attention (line 14). So then, when Ms. Ross entered the interaction, to remind the students to clean up the floor around their table, after they finished cutting (line 19), Marigold asked her question of Ms. Ross instead (line 20). Marigold's bid for help from Ms. Ross, following a failure to get her question answered by another student and following Ms. Ross' entrance into the interaction for another purpose, closely resembled Aarav's bid for her help in the episode from FUSE presented in Table 5.3.

Ms. Ross' subsequent response to Marigold's question, referring her to the directions (line 23), also closely resembled Ms. Ross' response to the similar bid for help from Aarav in FUSE. Like Aarav and Drew, Marigold followed Ms. Ross' suggestion to look at the directions, and with her "Oh" (line 26) seemed to indicate that she had found the answer to her question there.

In addition to encouraging students to consult the directions, rather than directly answering their questions, Ms. Ross also made other moves that helped transition the activity system of the kite activity into a more open, agentic system, with objects of learning more like those in FUSE. These moves included encouraging students to help each other and to do independent research. For example, before showing a student how to measure and cut three meters of string, she said, "I'll show you how to do it, and then you'll show the next group." Similarly, after giving a student a tail for his kite, she said, "You're going to have to figure out how to connect it. I'm not telling you anything. There you go, go get a computer and do research."

The material context of the kite activity system also played an important role in its transition to an activity system that more closely resembled FUSE. Specifically, because of scarcity of certain materials, like string and yard sticks, by day two of the activity, some students had done some aspects of material prep, like measuring and cutting string, while other students had done others, like tracing and cutting tissue paper. This then helped create some relative expertise within the classroom, a typical feature of the FUSE activity system identified in prior research (Penney, 2016; Stevens et al., 2016). As a result of this, instead of sitting in their desks and raising their hands to ask the teacher for help, students began to help each other, and could be seen up and about, orienting toward both material and human resources in the classroom environment, and doing self-directed research and experimentation, regarding optimal string and tail placement for their kites.

Nowhere was this helping and self-directed experimentation clearer than on the last day of the activity, when students took their kites outside to fly them. When they went outside, the class also brought with them a laundry basket of tools and extra supplies. So once the students got outside and started test flying their kites, they quickly began alternating between test flights and repairs and modifications to their designs at the laundry basket maintenance station. As they did this, the teacher shared her thoughts with me on connections she saw between the students' behavior and FUSE (see Table 5.5).

Table 5.5
Ms. Ross Describes Differences She Observed in Students' Actions During the Kite Activity That She Attributed to FUSE

Line	Person	Talk	Actions
1	Researcher:	Yeah, so does it feel like it's going better, worse, about the same as it's gone in past years?	
2	Ms. Ross:	I think they're much more independent.	
3	Researcher:	Yeah.	
4	Ms. Ross:	It would be=	
5	Researcher:	Yeah.	
6	Ms. Ross:	I think independence is the biggest change.	
7	Researcher:	Yeah.	
8	Ms. Ross:	As you see.[1] Before they were like.	[1]*Ms. Ross points to students working on kites at repair station.* [2]*Ms. Ross makes crying face and gestures toward her face.*
9	Researcher:	Oh.[1]	[1]*Researcher laughs.*
10	Ms. Ross:	And now[1]	[1]*Ms. Ross points to students working on kites at repair station.*
11	Researcher:	Right they're like, 'I can fix it.'	
12	Ms. Ross:	And they're helping, and they're much more collaborative I think.	
13	Researcher:	Ok, yeah.	

14	Ms. Ross:	Helping each other and problem solving, and they're not giving up as easy.	
15	Researcher:	Sure.	
16	Marigold:	[inaudible]	*Marigold runs toward Ms. Ross and researcher flying kite.*
17	Researcher:		*Research laughs.*
18	Ms. Ross:	She's so cute, but she was one of mine who would give up all the time.	
19	Researcher:	Yeah, aww.	
20	Ms. Ross:	So we just really worked on that.	
21	Researcher:	Yeah.	
22	Ms. Ross:	Marigold, I was just telling Miss Ramey how you used to go 'I can't do that. I can't do it.' And now what do you do?	
23	Marigold:	I can do it![1]	[1]*Marigold raises kite in the air above her head.*
24	Researcher:	Yay![1]	[1]*Researcher laughs.*

As the transcript in Table 5.5 shows, in response to me asking whether the kite activity was going better, worse, or about the same as it has gone in past years, when the students hadn't had FUSE (line 1), Ms. Ross noted a number of differences she observed between these students and those that she'd had in previous years, who hadn't had FUSE. She noted that her students were more independent (line 2), were helping each other and were more collaborative (line 12 and 14), and were problem-solving and "not giving up as easy" (line 14). Then, as if to prove her point, one of her students, Marigold, ran over with her successfully flying kite (line 16), and at Ms. Ross' prompting (line 22) demonstrated the very "can-do" attitude (line 23) that Ms. Ross had just argued she didn't have before (line 22).

Students also made both implicit and explicit connections between FUSE and the Kite Activity. For example, one student, Aarav, made both implicit and explicit connections between the kite activity and a specific FUSE challenge he had spent a lot of time on, the Dream Home Challenge (see Table 5.6).

Table 5.6
Aarav Talks About Connections Between the Kite Activity and the Dream Home Challenge in FUSE

Line	Person	Talk
1	Researcher:	So making these triangles, does this remind you guys of anything you do in STEM class? *(STEM is what they call FUSE)*
2	Aarav:	U::m
3	Kimmie:	No, not really no.
4	Aarav:	In Dream Home it's kind of.
5	Kimmie:	Well you read the directions.
6	Researcher:	In Dream Home? What about Dream Home?
7	Aarav:	Well, you can make triangular houses.
8	Johnny:	What?!
9	Kimmie:	What?!
10	Aarav:	You actually can make triangular houses.
11	Johnny:	Yeah but it's easier, because it's on the computer.
12	Kimmie:	Yeah!
13	Aarav:	Yeah
14	Johnny:	Here you've got a string and 50 million materials.
15	Researcher:	Yeah, yeah.

In the transcript shown in Table 5.6, when I asked a group of students (line 1) if making triangles (or really 3D pyramids) for their kites reminded them of anything they did in STEM class (which is what they call FUSE), Aarav made an explicit connection between making triangles for his kite and making triangular houses in a CAD program (Sketchup) as part of the Dream Home challenge (line 4, 7, and 10). In contrast, Kimmie, who hadn't spent as much time doing the Dream Home challenge in FUSE, initially didn't report seeing any connections between making triangles for her kites and her work in FUSE (line 3). Then, in line 5, she reported seeing a different connection between the two contexts, the one Ms. Ross had emphasized, reading the directions. Kimmie and Johnny also expressed surprise or disbelief (lines 8-9) when Arrav mentioned that one could make triangular houses in Dream Home (line 7). This interaction indicates that Aarav's greater experience with the Dream Home challenge may have set him up to make connections between this specific aspect of the kite activity and FUSE, in a way Kimmie and Johnny did not.

Aarav further demonstrated that he had made connections between the kite activity and his work on the Dream Home challenge in FUSE by engaging in two problem-solving practices during both activities. The first was the collaboration and helping that both he and a number of his classmates engaged in during both FUSE and the kite activity. The second was an embodied, spatial practice of digitally or manually rotating objects in order to understand and improve their design, or a version of what Kirsch & Maglio (1994) refer to as epistemic action. While working on Dream Home, Aarav frequently used the rotate tool in Sketchup to turn his house and view it from different angles, in order to decide what to do next to improve it. Later, on multiple occasions during the kite activity, he engaged in the same practice, manually rotating his kite, looking at it from different angles, to decide where to attach his string and tail.

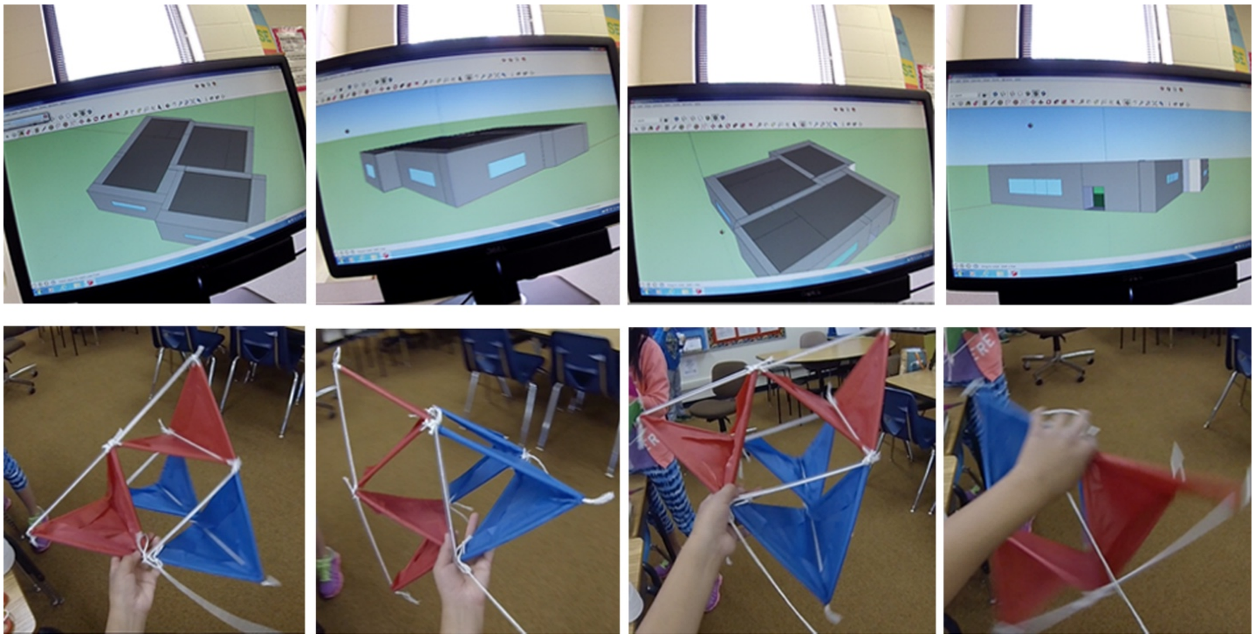


Figure 5.4. Aarav engages in digital rotation of his Dream Home (top) and manual rotation of his kite (bottom).

Aarav and his classmates provide examples that, through participation in FUSE, students learned STEM problem-solving practices in flexible ways that allowed for their productive use in other contexts. However, as in any case of transfer or boundary crossing, certain things need to be true for learners to move practices between contexts. First, there must be similarities in the sociomaterial conditions of the two activity systems (e.g., opportunities for collaboration or scarcity of materials leading to relative expertise). Second, there must be similarities in the object of learning (e.g., not a powerpoint or textbook, but the design and testing of an object or idea). Third, learners must recognize the connections between the two activities (e.g., Aarav seeing connections between Dream Home and the kite activity). Finally, the activity system must be open enough and allow for enough student agency that students are able to bring in practices from other contexts (e.g., the teacher allowing or even encouraging students to draw on a variety of sociomaterial resources in the classroom instead of giving them the answers through direct instruction).

These insights further our understanding of the impact of FUSE on students' STEM learning in other contexts and provide guidelines for educators hoping to aid students in bringing knowledge and practices from FUSE or other informal making and design contexts into STEM classrooms. The next case I will present emphasizes the importance of these guidelines in designing for cross-context learning by demonstrating what happens when these aspects of context are not present.

Permeable and Non-permeable Contexts: A PLTW Wind Turbine Activity. The following case comes from a two-week Project Lead the Way, wind turbine activity that many of our focal FUSE students participated in during the 2015-16 school year. Here, I focus on one class of students, a mixed fifth and sixth grade class, who did this doing this activity during the Fall. This class did the activity with a teacher who wasn't their FUSE facilitator or regular classroom teacher, but who had facilitated FUSE with her own class.

In presenting this case, my primary aim is to highlight the differences between the Project Lead the Way activity system and the activity systems of both FUSE and the kite activity. However, as with the kite activity, I will also discuss important shifts that happened within this activity that changed the nature of the activity system for better or worse. Specifically, I examine differences within and between activity systems in openness, agency, the object of learning, and arrangements of social and material resources and demonstrate how differences in these factors led to different types of interactions and had consequences for student interest and learning.

Early Signs of Permeability. The wind turbine activity began similarly to the kite activity, and many other conventional school lessons, with the teacher presenting a Powerpoint, on renewable energy sources. At first, what followed also seemed like it might also resemble the kite activity. The teacher instructed students to do independent research on computers and use it to come up with blade designs for their wind turbines. As they did so, students freely collaborated with their friends or other students sitting near them. For example, as we can see from the transcripts presented in Tables 5.7 and 5.8, Johanna and Victoria, two of the girls discussed in Chapter 3, who frequently helped each other in FUSE, also offered or sought help from each other as they did research on wind turbine blades.

Table 5.7
Victoria Offers Advice to Johanna, While They Research Their Blade Designs

Line	Person	Talk	Actions
1	Victoria:	Johanna.	
2	Johanna:	Yeah?	
3	Victoria:	You don't really need a picture. All you need to do is go like blegh.[1]	[1]*Victoria gestures curved horizontal line.*
4	Johanna:	Blegh? What's Blegh?	
5	Victoria:	Go like that, but with a bump[1]	[1]*Victoria draws curve on table with hand.*
6	Johanna:	Ha, like a curve, [basically?	
7	Victoria:	[Yeah	
8	Johanna:	But you know, I just want to go, you know find a picture to go off of.	
9	Victoria:	Yeah, I got one. Search ‘a blade of a wind turbine.’	
10	Johanna:	Ok[1]	[1]*Johanna scrolls back up to search bar and begins typing.*
11	Victoria:	See look at the one me and Andy.	
12	Johanna:	Ok.[1]	[1]*Johanna finishes typing in ‘blade of wind turbine’ and hits enter. Images appear.*
13	Victoria:	See that one?	
14	Johanna:	Oh.[1]	[1]*Johanna selects an image.*
15	Victoria:	Yeah, wait, this one.[1]	[1]*Victoria points to Andy's screen.*

16	Johanna:	Wait, oh found it. Yeah! I'm going to do the other one that I found before. Where did it go?[1]	[1]*Johanna continues scrolling through images.*

In the transcript presented in Table 5.7, we can see Victoria making a bid for Johanna's attention (line 1) in order to share an insight she'd had about sketching her turbine blade design (lines 3 and 5). She told (and showed) Johanna that all she needed to do was draw a curve. Then, in response to Johanna's expressed desire to have an image to draw from (line 8), Victoria shared the search phrase she had used to find images of turbine blades (line 9). Johanna tried that phrase in her search bar, and as she scrolled through the images, Victoria directed her to a specific image that she and Andy had used as a guide (lines 10-15). After finding it, Johanna ultimately decided to use the one she had been looking at before instead (line 16). However, just the fact that the advice was given and gave her additional resources to draw on in thinking about her design is consequential, as this pattern of interaction resembled the pattern of helping the girls demonstrated in FUSE, with help frequently being offered or requested, but advice not always being taken.

As in the Kite Activity, students also made explicit connections between the wind turbine activity and FUSE. For example, in the episode presented in Table 5.8, Emil discovered an image of a wind turbine, which he recognized as being created in Sketchup (line 1), a tool that he had previously used during FUSE. He shared this discovery with me, the researcher (lines 1, 3, and 7). Then when I asked if he thought he could find wind turbines in the model library in Sketchup (line 10), he said maybe, but stated and reiterated that it would be hard (line 11).

Table 5.8
Emil Finds an Image of a Wind Turbine Created in Sketchup

Line	Person	Talk	Actions
1	Emil:	Hey someone used[1] someone used Sketchup here.	[1]*Emil looks at Researcher.*
2	Researcher:		*Researcher comes over.*
3	Emil:		*Points to image on screen.*
4	Researcher:	Oh, they made their wind turbine model in Sketchup?	
5	Emil:	ER: Yeah!	
6	Researcher:	O::h, that's cool.	
7	Emil:	This looks like Sketchup, I guess.	
8	Researcher:	Yeah, it does look like Sketchup. Huh.	
9	Emil:	How did he do that?	
10	Researcher:	[1]I wonder if you could find example wind turbines in the model library in sketchup? You think that would be something that would be in there?	[1]*Researcher laughs.*
11	Emil:	That is, that is hard. Maybe. That's hard though.	

However, in contrast to his statement that finding wind turbine designs in the model library in Sketchup would be hard, in a separate conversation (see Table 5.9), Emil argued that it would be easier to design a three-dimensional wind turbine in Sketchup than to draw it in two dimensions on paper.

Table 5.9
Emil Discusses Differences Between Creating 2D, Pencil and Paper Sketches and a 3D Sketchup Model of his Wind Turbine Design

Line	Person	Talk	Actions
1	Emil:	[1]Yes![2] Did you see what this is? Does this look anything like that? Don't say yes.	[1]*Emil finishes drawing a sketch of a wind turbine blade design.* [2]*Emil turns to Jasmine.*
2	Jasmine:	No.	
3	Emil:	Thank you.	
4	Emil:	Cameron.	
5	Cameron:	Yeah?	
6	Emil:	Turns computer monitor. Does this,[1] does this look anything like that?	[1]*Emil holds up notebook with sketch.*

7	Researcher:		*Researcher, walking by, laughs.*
8	Cameron:	Um	
9	Emil:		*Emil labels drawing.*
10	Researcher:	Yeah, I think it looks pretty good.	
11	Emil:		*Emil continues labelling drawing.*
12	Researcher:	Yeah it's hard to, it's kind of hard to draw something [3D on a 2D page, huh?	
13	Emil:	[3D, yeah. I mean it's	
14	Researcher:	Do you think it's, do you think you could model that[1] like in sketchup or tinkercad or something? Do think that would be easier [than trying to draw it on paper?	[1]*Researcher points to drawing.*
15	Emil:	[I think so.	
16	Researcher:	Or do you think it would be harder?	
17	Emil:	I think	
18	Jasmine:	I think that would be harder.	
19	Researcher:	Yeah, yeah.	
20	Emil:	I think it'd be easier, 'cause you could actually see multi[1] views of it, you know?[2]	[1]*Emil holds his hands up and moves them in a 3D cylinder resembling the shape and movement of the wind turbine pictured on the screen.* [2]*Emil moves hands back and forth, parallel to table.*
21	Researcher:	[Sure	
22	Emil:	[Instead of just one view,[1] trying to draw the shadows and stuff.	[1]*Emil holds hands up, parallel, slightly apart and makes single grabbing gesture.*

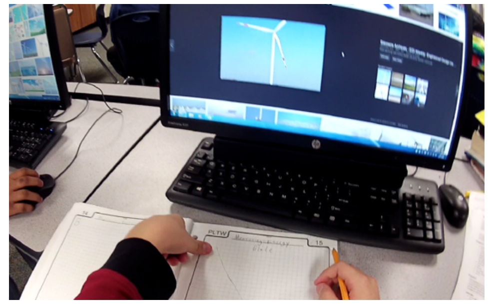
In the interaction presented in Table 5.9, Emil showed two of his classmates a sketch of a particularly complex 3D wind turbine design he'd drawn from a picture found online and invited them to critique it (lines 1 and 6). When I observed this, I told him that I thought it looked pretty good (line 12) and then started to comment on it being hard to create 2D dimensional drawings of 3D objects like the turbine (line 12). However, before I even got the whole sentence out (line 12 "Yeah, it's hard to, it's kind of hard to draw something…"), he filled in the rest of the sentence with “3D, yeah” (line 13), indicating that he had identified the same problem. Then when I asked him if he thought he could model it in Sketchup or Tinkercad (two of the CAD software programs used in FUSE) and whether that would be easier (line 14), he said “I think so” (line 15). He then went on to elaborate, saying, “I think it'd be easier, 'cause you could actually see multi views of it, you know?” (line 20) and finished by saying “Instead of just one view, trying to draw the shadows and stuff” (line 22).

In making this argument, he demonstrated that not only did he see the potential for using Sketchup or Tinkercad for this sort of modeling, but he both saw the specific affordances of the software and thought that modeling his turbine in Sketchup would be easier than drawing it with paper and pencil. This shows a form of representational competence (e.g., Kozma & Russell, 1997; Kozma, Chin, Russell, & Marx, 2000; Wu, Krajcik, & Soloway, 2001; Nathan, Stephens, Masarik, Alibali, & Koedinger, 2002) and metarepresentational competence (diSessa & Sherin, 2000) that Emil likely would not have been able to demonstrate without having had experience using Sketchup for the Dream Home challenge during FUSE.

Emil also brought in his own material practices that were conducive to him doing the blade design task and closely resembled practices he would later use in FUSE. As is shown in Figure 5.5, he used grid paper and counted squares to check the scale of his wind turbine blade sketch (episode 1, line 2). Later, in FUSE, he used a similar procedure to check the accuracy of pixelated characters he’d drawn in the software program Piskel (episode 2, lines 2 and 3).

Episode 1. Emil draws a sketch of a turbine blade from an image he found online, then counts squares in his graph paper notebook to check the scale of his drawing.

Line	Person	Talk	Actions	Image
1	Emil:		*Emil draws line on grid paper.*	

2	Emil:	Is this 6 inches?[1] One, two, three, four, five, six, seven, eight. Oh wait, what?[2] One, two, three, four, five, six. Yeah, way, too too big.	[1]*Emil uses thumbs to point to squares and counts.* [2]*Emil starts over using thumbs to point to squares again.*	
3	Emil:		*Emil erases line.*	

Episode 2. Emil draws a sketch of a turbine blade from an image he found online, then counts squares in his graph paper notebook to check the scale of his drawing.

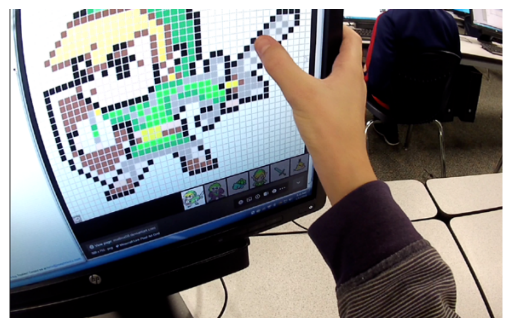
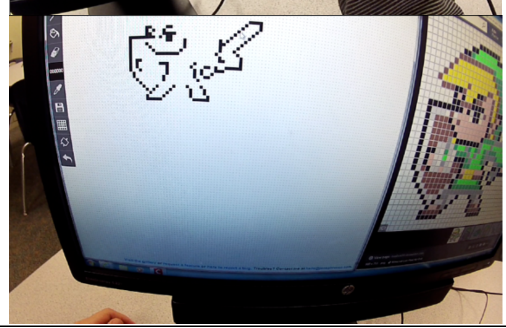
Line	**Person**	**Talk**	**Actions**	**Image**
1	Emil:	What? I messed up.[1]	[1]*Emil looks back and forth between his drawing and the original Link image.*	
2	Emil:	How did I mess up?[1] One, two, three, four, five, six.	[1]*Emil counts the black pixels on the sword in the original image, running his thumb over them.*	
3	Emil:	[1]One, two, three, four, five, six.	[1]*Emil counts the pixels on the sword part of his drawing, running his mouse over them.*	

Figure 5.5. Emil draws from a guide image and counts squares to check scale and accuracy in both Project Lead the Way and FUSE.

Finally, Emil also made explicit connections between the PLTW wind turbine activity and one specific FUSE challenge, Wind Commander, which has a similar object and uses similar materials (See Table 5.10).

Table 5.10
Emil Discusses Connections Between PLTW Wind Turbine Activity and FUSE Wind Commander Challenge

Line	Person	Talk	Actions
1	Researcher:	Do think that there's a connection between this and FUSE?	
2	Emil:	Um, yeah, because we have um a what's it called, a challenge like that	
3	Researcher:	Wind Commander	
4	Emil:	Yeah	
5	Researcher:	Have you tried that?	
6	Emil:	No.[1]	[1]*Emil shakes his head.*
7	Researcher:	Not yet?	
8	Emil:	Not yet.	
9	Researcher:	No.	
10	Emil:	No.	
11	Researcher:	Why not?	
12	Emil:	I don't think it, I mean we're already doing it here, so like	
13	Researcher:	Ah ha ha	
14	Emil:	So like the first couple levels are going to be boring.	
15	Researcher:	Ah ha, yeah.	
16	Emil:	Yeah, that's why.	

In the transcript in Table 5.10, we can see that when asked about connections between the wind turbine activity (“this”) and FUSE (line 1), Emil answered that he saw a connection to a particular challenge (line 2). In line 3, the member of our research team who was talking to him filled in the name of the challenge (“Wind commander”), and Emil agreed (line 4) that this was the challenge to which he was referring. The researcher then went on to ask him if he had tried that challenge (line 5), and Emil said he had not (line 6), citing as a reason, “we’re already doing it here” (line 12), “so like the first couple levels are going to be boring” (line 14).

From this interaction, we can take at least three important points. First, it was not essential for Emil to have done the FUSE wind commander challenge for him to see connections between that challenge and the PLTW wind turbine activity. Second, the fact that surface similarities existed between this one specific FUSE challenge and the PLTW activity seemed to have gotten in the way of him making deeper, more personally meaningful connections between FUSE and PLTW in response to this particular question. However, it is clear from the interactions presented in Table 5.8, Table 5.9, and Figure 5.5 that elsewhere he does make deeper, more useful connections between the two activity systems. This argues for the importance of examining cross-context learning using not just survey or interview data but also observations and video recordings of interactions. Finally, in the transcript in Table 5.10 (line 14), we saw the first glimmer that Emil may not have been as engaged in the wind turbine activity as he was in other activities (like Piskel) that we saw him engage in during FUSE, as he wasn’t interested in pursuing it further during FUSE, after completing the PLTW unit. Later in this analysis, I will present more evidence in support of this last point, as well as my assertions, based on the data, as to why this was the case.

Shifts in the Activity System: From Permeable to Impermeable. Both Emil’s case and Johanna and Victoria’s case demonstrate ways in which, during the independent research and design phase of the wind turbine activity, the activity system remained relatively open to students making implicit and explicit connections to practices and activities engaged in during FUSE. The connections they made during this part of the activity closely resembled those made by Aarav and his classmates during the kite activity (e.g., collaborative forms, material practices, and connections to designing in Sketchup and to other specific FUSE challenges). However, in contrast to the relative permeability of the wind turbine activity system during the independent research and design phase, on the fourth day of the wind turbine activity, the relative openness of the activity system and relative agency granted to students was quickly disrupted in at least three ways.

Shifts in and Constraints on Collaborative Forms. First, students were assigned to groups and assigned specific locations in the classroom where their groups were supposed to work. After this, if students were seen moving about the classroom, working somewhere other than their assigned spots, or collaborating with members of other groups, they were chastised. For example, when one group of girls tried to work at a counter rather than on the floor, Ms. Bell, the Project Lead the Way teacher, instructed them to move (see Table 5.11).

Table 5.11
Ms. Bell Instructs Group of Girls to Move to the Floor, Instead of Working at the Counter

Line	**Person**	**Talk**	**Actions**
1	Ms. Bell:	So you're deciding, can I have you guys sit in a group instead?	
2	Myra:	[Yeah	
3	Ms. Bell:	['Cause when you're along,[1] it's really good to have that communication back and forth, so everyone can kind of see what they're doing, instead of on the counter.	[1]*Ms. Bell points up and down length of counter.*
4	Myra:	Ok.	*Girls move to floor, and sit in a circle.*

The next day, when that same group of girls went over to one of the computers to do some additional research on turbine designs, Ms. Bell came over again with an implied critique of their group's physical location (See Table 5.12).

Table 5.12
Ms. Bell Checks on Girls Working at a Computer, Prompting Them to Move

Line	Person	Talk	Actions
1	Myra, Victoria, Brittany, and Destiny:		*Girls stand around computer while Myra does an internet search.*
2	Ms. Bell:	Are you guys[1] done with yours?	[1]Points in a circle to members of group.
3	Myra, Victoria, Brittany, and Destiny:		*Girls look at Ms. Bell, then walk silently back to spot on the floor where they'd been working before.*

Although Ms. Bell didn't explicitly tell the girls to go back to their spot on the floor (line 2), the fact that this was their response (line 3) to her question "Are you guys done with yours?" (line 2) indicates that they interpreted her question as an implied critique of their location.

Finally, in a later class period, when groups were testing their wind turbine designs, students began migrating away from their respective groups to talk to students in other groups. For example, Victoria went over to watch Johanna's group test. However, unlike in FUSE or early in the independent research phase of the wind turbine activity, when Johanna and Victoria were allowed to freely collaborate, at this point in the wind turbine activity, Ms. Bell chastised students for their movement about the classroom (see Table 5.13).

Table 5.13
Ms. Bell Chastises Students for Wandering Around the Classroom and Instructs Them on What They Should be Doing

Line	Person	Talk	Actions
1	Ms. Bell:		*Ms. Bell claps fives times to get class' attention.*
2	Students:		*Students clap five times in same rhythm as Ms. Bell and fall silent.*

3	Ms. Bell:	Nice job. A lot of excitement, so I'm hoping those are really good wows that it's working and not an error, because I'm being careless and unsafe. Alright? So keeping that in mind, I see a lot of wandering. And right now, we have five minutes left. So you are going to right now, there's been a lot of activity going on. So you need to turn to your engineering notebooks right now, and you need to do some writing, some observations. So what has happened. So right now, everybody, the last five minutes. We're going to start cleaing up in about one minute, but you're going to take the last three minutes out of what we have left to do some writing of your notes. Ok? So right now, we'll start cleaning up in a little bit, so writing in your notes. So we have about 6 minutes

Ms. Bell's structuring and restructuring of collaborative activity during the later parts of the wind turbine activity represent a limiting of students' relational agency. They also created an activity system that contrasted with the fluid, student-driven movement and collaboration allowed in FUSE, the free movement and helping allowed in the kite activity, and even the student-driven helping that occurred early in the wind turbine activity itself.

Shifts in and Constraints on the Object of Learning. The second way in which agency and openness were disrupted, and in which the object of learning shifted further away from something that resembled FUSE, was in the way the teacher instructed students to proceed with turbine design. First, rather than have students work together to create one turbine design for their group, Ms. Bell had all students create three designs of their own, then pick the best one to present to the group. Then the group had to decide which person's design was the best. As is shown in the transcripts presented in Tables 5.14, and 5.15, this led to students lobbying for their own designs, rather than focusing on which design was best, according to the variables they were supposed to consider. For example, in the transcript presented in Table 5.14, Marcus had been presenting his design to the group when Emil spontaneously started singing and dancing (line 1). Then, when Marcus asked him what he was bragging about (line 2), Emil said it was because his idea was better (line 3).

Table 5.14
Emil Brags that His Turbine Blade Design Is Better than Marcus'

Line	**Person**	**Talk**	**Actions**
1	Emil:		*Emil starts singing and dancing in his seat.*
2	Marcus:	What is you bragging about for?	
3	Emil:	I'm just saying my idea is better.	
4	Marcus:	But, nobody said that, but I'm still presenting it.	

Later on, Emil lobbied further for his idea, when the class was asked to choose the design they were going to use and draw it on the white board at the front of the classroom (See Table 5.15).

Table 5.15
Emil Lobbies for His Blade Design

Line	**Person**	**Talk**	**Actions**
1	Marcus:	Can we please put mine up there?	
2	Emil:	I mean mine's way better than all ya'll.	
3	Marcus:	Uh huh.[1]	[1]Marcus smiles at Emil.
4	Emil:	Just kidding.[1] Wait, for Marcus, what did I give him again?[2] I gave him a one.	[1]Emil turns toward other group members. [2]Emil looks at decision matrix worksheet.
5	Marcus:	You gave me a three.	
6	Emil:	[1]No I gave him a one.	[1]Emil turns toward Marcus.

7	Dixon:	You did?[1]	[1]Dixon smiles.
8	Emil:	Yeah.	
9	Dixon:	I gave Jasmine a 10.	
10	Emil:	Oh my god.	
11	Dixon:	Jasmine did really well. Hers was the best idea we had.	
12	Jasmine:	[1]Ha!	[1]*Jasmine raises her hand with paper in it in the air.*
13	Dixon:	Come on let's do Jasmine's idea. It's more cost effective and it's more, less time consuming.	

In the transcript, we see Marcus asking if they can put his design up on the white board (line 1) and Emil responding by arguing that his was better (line 2). Marcus' replied by saying uh huh, but smiling as he did, perhaps indicating that he didn't take Emil's response seriously (line 3). Emil's response of "Just kidding" (line 4) further supports this interpretation. However, his subsequent focus on what score he gave Marcus and his statement that he gave Marcus a one (line 4) indicates that regardless of how he was positioning his earlier statement for Marcus, he was serious about making a case for his being better. Emil and Marcus then argued over what Emil gave Marcus (lines 4-6), and it should be noted that throughout this discussion they talked as though the scores were being assigned to Marcus, the person, not Marcus' design (e.g., "I gave him", "You gave me"). Then, after Emil reiterated that he gave Marcus a one, Dixon expressed disbelief by smiling and asking "You did?" (line 7). This response and his follow up (line 9), when he claims to have given Jasmine a 10 (on a five point scale) seem to indicate that he suspects shenanigans from Emil and is countering with his own. Emil recognizes this in line 10 by saying "Oh my god," and only then does the conversation turn to Dixon making a serious case for Jasmine based on the merits of her design (lines 11 and 13). In the midst of this, however, Jasmine engages in the same sort of bragging behavior that Emil had engaged in during the episode presented in Table 5.14, raising her hand up in the air and laughing when Dixon praises her design (line 12).

This theme of lobbying for students' own designs, rather than discussing the true merits of the designs continued throughout this groups interactions, as well as the interactions of many other groups. For example, even after this group finally chose Emil's design, he maintained ownership of it, rather than allowing it to become the group's design. This could be seen when they went up to the board to draw the design and Marcus asked "Can I sketch it out?" and Emil responded, "No it's mine."

This problem also seemed to be exacerbated by a second move on the part of Ms. Bell, asking students, after they had done most of their research, to focus, in their decision-making, not on the spatial and material features of their model turbine blades, but on the materials, cost, and time it would take to build an actual wind turbine represented by their model. She enforced by handing out a "decision matrix" worksheet, with a table on it for them to fill in ratings of each student's turbine on each of those three variables (cost, materials, and time). As we can see in the transcript presented in Table 5.16, because students didn't initially attend to these factors when researching their designs, many just made them up as they were discussing their designs in their groups.

Table 5.16
Emil Presents His Wind Turbine Blade Design to His Group

Line	**Person**	**Talk**	**Actions**
1	Emil:	Ok, this is my design everybody.[1] It's going to start wide. It's going to start wide at the,[2] and then as you get here, it's gonna get straighter and thin.	[1]*Emil holds up notebook.* [2]*Emil points to drawing.*
2	Dixon:	So it's like closing in like a needle.[1]	[1]*Dixon brings hands together in triangular point.*
3	Emil:	But it's going to have a flat bottom.[1] I know.	[1]*Emil laughs.*

4	Jasmine:	A flat, oh, it looks like a needle.	
5	Emil:	And, it's going to have a twist.[1] Like it's going to start twisting.[2] And then, there are going to be three of these on the turbine. The cost, since I want it to be over 100 kilowatts, it will be one, I mean 50 thousand dollars to 80 thousand dollars or more.	[1]*Emil makes twisting gesture.* [2]*Emil makes twisting gesture again.*
6	Dixon:	Per blade?[1] Or for all of it?	[1]*Dixon looks at Emil, eyes wide.*
7	Emil:	[Per blade.	
8	Marcus:	[Alright my turn	
9	Dixon:	Are you serious?	
10	Emil:	I'm ki:dding, for the whole turbine.	
11	Dixon:	That's still a lot. [My blades are 90, 990 dollars each.	
12	Marcus:	[What is, what is your product made out of.	
13	Emil:	Oh, um, it is made out of stuff.	
14	Marcus:	No, no, no, no.[1] You have to give me specific details.	[1]*Marcus shakes his head.*
15	Emil:	Well, spoo-cific, I got the time it might take. I don't know, and the materials, I don't know. I haven't, I haven't gotten to it.	
16	Marcus:	I have to give you a, I have to give you a one on material if you don't give me your material.	
17	Emil:	I don't have it. I don't have it yet. It's probably just light weight. Oh ok, I know. Light weight carbon fiber, just like you know the material that cars are made out of?	
18	Marcus:	Uh huh, uh huh.	
19	Emil:	[And then	
20	Marcus:	[And then what possible risk do you think it's gonna have.	
21	Emil:	It might break [easily	
22	Marcus:	Mmhmm	
23	Emil:	But, to prevent that, I could put aluminum in there, like this.	
24	Marcus:	Good job, now the truth.[1] Time? What is the time?	[1]*Marcus writes something down in his notebook.*
25	Emil:	The time. I don't know the [time	
26	Marcus:	[How did it, how long would it take you?	
27	Emil:	I'm thinking = I'm = less than a day for one I think.	
28	Marcus:	One?	
29	Emil:	Yes.	
30	Marcus:	One of those whole ones?[1]	[1]*Marcus lifts arm up in air in vertical line.*

31	Jasmine:	Yeah, I think, that seems pretty reasonable.	
32	Marcus:	Ok, I got you.	
33	Emil:	Less than a day.	
34	Marcus:	Uh, how much it cost?	
35	Dixon:	It's real expensive.	
36	Emil:	Uh, for the whole turbine though,[1] for all the, for the stem of the turbine, for the	[1]*Emil makes vertical line with his arm.*
37	Dixon:	Who has a calculator here?	
38	Marcus:	How much, how much? Just check how much it is.	
39	Emil:	[1]That much, 50,000 to 80,000 or more, [but that's for the whole	[1]*Emil points to his own decision matrix paper.*
40	Marcus:	[O::h boy you got a whole bunch.[1]	[1]*Marcus writes something down in his own matrix.*
41	Emil:	That's for the whole turbine though. That's why.	

We can see from the transcript that in Emil's initial presentation of his blade design to his group, he emphasizes the spatial features of the design (lines 1, 3, and 5), and Dixon and Jasmine respond with a spatial analogy to a needle (lines 2 and 4). This is reflective of the fact that these were the features emphasized in Emil's research and in his sketch (as they were for many other students), not the features that Ms. Bell later told them they should use in decision-making. It isn't until line 5 that Emil begins to discuss features of his turbine covered in the decision matrix (specifically cost). This sparks a discussion about the cost of Emil's turbine, relative to the other students' designs (lines 5-11). Then in line 12, Marcus inquires about the next category in the decision matrix, materials. In line 15, Emil says he doesn't know the materials or the time it will take to build his turbine. Then after Marcus responds by saying, "I have to give you a one on material if you don't give me your material" in line 16, Emil changes his answer (line 17) repeating again that he doesn't know, but then seeming to make up a material on the spot ("It's probably just light weight. Oh ok, I know. Light weight carbon fiber, just like you know the material that cars are made out of?"). This makes it clear not only that he hadn't decided on materials prior to this moment but that the number he had just given for cost was likely meaningless, since materials would impact cost. In line 24, when Marcus next asked about time, a similar interaction unfolded, with Emil first saying he didn't know (line 25) then haltingly saying "I'm thinking = I'm = less than a day for one I think" (line 27).

The students spent the rest of the interaction debating whether the answers Emil had given for the categories on the matrix seemed realistic or reasonable (lines 28-41). This problematic from a learning perspective for two reasons. First, the numbers they are debating are apparently completely arbitrary, as Emil appears to have just made them up on the spot. Second, none of what is discussed from the end of line 5 to line 41 (the majority of the interaction around Emil's design) will have any impact on the success of the model wind turbine they will be building and testing over the next few days of the activity.

In other words, having students focus on abstract aspects of turbine design, such as cost, time, and materials of the turbine their model represented changed the object of learning from a concrete testable model to something more abstract and arguably less meaningful and useful for the purposes of this activity. Further, constraining the students' decision-making process both in terms of how students should choose a design and which variables they should consider in doing so limited students' conceptual and transformative agency during this part of the activity.

This constrained decision-making process contrasted with students' activity in FUSE in at least two important ways. First, in contrast to PLTW, where students were required to do their own designs first, then choose and present the best one, then chose one students' design to represent the whole group, in FUSE, students had more agency over collaborative arrangements and decision-making processes. In FUSE, students organizing their own collaboration and decision-making tended to result in two different collaborative forms, neither of which resembled the prescribed collaboration in PLTW. The first was students all making their own designs and just helping each other or offering advice as needed (e.g., Johanna, Victoria, and Andrea doing Dream Home). The second involved students working together from the beginning to come up with shared designs or engage in shared problem-solving (e.g., Anna and Adele doing Spaghetti Structures).

The second difference between the two activity systems was the object of learning. In PLTW, rather than having students focusing on the variables that would actually matter for successful turbine testing (blade shape, materials for model turbine, number of blades, and position), Ms. Bell encouraged students to focus on more abstract features of design (cost, time, and materials for actual turbine) that wouldn't matter for testing their models, only for building the real thing, which students would never do. This was different than how design and testing unfolded in FUSE, where students decided which factors to consider in designing and problem-solving and where considerations of spatial arrangements and materials were generally at the forefront of design-thinking and problem-solving.

These differences between activity systems had implications not only for design-thinking and problem-solving but also for interest and engagement. As noted earlier, in the analysis of the transcript, presented in Table 5.10, of Emil discussing connections between the PLTW wind turbine activity and the FUSE Wind Commander challenge, Emil gave signs that he wasn't particularly engaged in the PLTW activity, such as expressing a lack of interest in continuing the activity in FUSE, via the Wind Commander challenge. Emil gave multiple other signs to this effect, such as doing other things while the Ms. Bell was giving the class instructions, saying, "You know I'm bored," while doing research on his wind turbine design, and failing to do research that had been assigned as homework on the second day of the activity. This contrasted sharply with Emil's interest and engagement in FUSE, where, as we saw from the analysis presented in Chapter 3 of his work on Piskel, he not only worked diligently on challenges or challenge-related activities during FUSE but continued working on them at home, without being asked or required to do so.

I claim that these differences in Emil's interest and engagement were the result of a lack of agency, a lack of openness, and different objects of learning in PLTW than in FUSE. Unlike in FUSE, where students could choose which challenges they wanted to work on and how they would go about those challenges, in PLTW, and to a lesser extent in the kite activity, both the activity itself and how students were required to go about it were constrained by the teacher. These constraints made these other activity systems less permeable to outside interests and PLTW, in particular, less permeable to outside practices. As a result, students were both less interested and engaged in the activities themselves and less likely to pursue them across contextual boundaries. This parallels the model presented in Figure 5.1, which proposed that more permeability for students to bring outside interests and practices in would lead to greater permeability for taking interests and practices out, as it seems the opposite is also true; less permeability coming in, leads to less permeability going out.

Discussion

The data and analyses presented in this chapter demonstrate how features of activity systems, such as openness, agency, and different objects of learning can help or hinder students in engaging in interest development and learning than span contextual boundaries. They also demonstrate how differences in these factors distinguish FUSE from other in-school STEAM learning activity systems and the implications those differences had for interest development and learning in FUSE versus other contexts.

In answer to the first research question, “What interests and practices do students move across boundaries between FUSE and other contexts?” I presented analysis of survey, interview, observation, and interaction data. These analyses showed that students brought a variety of outside interests and practices into FUSE and pursued STEAM interests and practices from FUSE in a variety of in-school and out-of-school contexts.

In answer to the second research question “How do they use practices carried across contextual boundaries similarly or differently in different contexts?” I presented analyses of students’ interactions in FUSE and in related in-school STEAM learning activities (the kite activity and the PLTW wind turbine activity). These analyses demonstrated that when allowed to, students productively used collaboration and problem-solving practices from FUSE in other in-school STEAM learning contexts.

Finally, in answer to the third research question, “How do the sociomaterial contexts of both FUSE and the other STEAM learning activities and environments in which students participate influence how and which interests and practices make the crossing and which do not?” I presented observation data and interaction analyses demonstrating differences between three STEAM learning activity systems (FUSE, the kite activity, and the PLTW wind turbine activity) in which practices or interactions they permitted and which they did not.

From the analyses presented here, we can draw some important conclusions about how cross-context learning works and how to design for it. First, the agency and openness of FUSE make it more permeable than other, more conventional, school learning activity systems to the import of outside interests and practices. This, in turn, seems to make it easier for students to export interests and practices to other, related contexts. Importantly, the agency that distinguishes FUSE from other STEAM learning activity systems isn't just found in students having a choice of what challenges to work on, but also in students having control over how they go about those challenges. In contrast, other in-school STEAM learning activities, which limit agency, are consequently less permeable to outside interests and practices coming in. As a result, these other contexts also seem less apt to cultivate interests and engagement either within or beyond the immediate context. So, in designing activity systems for learning, researchers and educators should be conscious of designing for permeability, by attending to issues of agency and openness. In fact, the very instinct that many of us might have, to carefully design, control, and constrain activities, collaborative arrangements, and problem-solving approaches, to insure particular sorts of learning outcomes, though perhaps efficient in the short term, is likely to backfire when designing for interest-development and learning that span larger expanses of time and space.

Second, similarities and differences in the object of learning in different contexts matter for students seeing connections between and carrying practices between contexts. In both the kite activity and PLTW, when the object of learning more closely resembled FUSE (e.g., engaging in independent research, design, construction, and iteration on digital or tangible models) students were more likely to deploy collaboration and problem-solving practices that resembled those used in FUSE. In contrast, when the object of learning was quite different (e.g., listening to a Powerpoint presentation, completing a worksheet, making decisions based on abstract variables versus spatial features and functional variables), fewer relevant practices could be brought to bear on the activity. This argues for designing activity systems for learning in which the object of learning more closely resembles objects of learning students would experience in other parts of their lives (mostly outside of school). It also argues for carefully attending to the ways in which small pedagogical moves, such as Ms. Bell changing the decision criteria for comparing wind turbine designs, can have a large impact on both the object of learning and consequently which outside practices students are able to bring to bear on those activities.

A third, related, implication has to do with the role of the teacher in the activity system. Previous research has demonstrated that enacting novel curriculum and pedagogy that encourages cross-context learning requires agency on the part of the teachers, not just the students (Edwards & D'Arcy, 2004; Lipponen & Kumpulainen, 2011; Rajala et al., 2013). The analyses of teachers' interactions with students presented here further demonstrate this point. In FUSE, Mr. Williams, Ms. Ross, Mr. Lewis, and Ms. Vonn all either made moves (or refrained from making moves) that facilitated students bringing outside interests and practices into FUSE or taking them out into other contexts. During the kite activity, Ms. Ross also explicitly used moves she would typically make in FUSE, such as referring students to the directions instead of answering their questions or encouraging them to do independent research, testing, and iteration, and these moves helped create a more permeable activity system. Finally, in contrast, Ms. Bell made moves during the PLTW wind turbine activity that constrained student agency, and changed the object of learning in ways that made that activity system less permeable to outside interests and practices. Importantly, most of this was done within the confines of curricula (e.g., FUSE, PLTW) neither designed by nor chosen by the specific teachers implementing it within their classrooms, indicating that even in an education system where teachers appear to have relatively little agency, the decisions they make, in regards to classroom practices, can still have a substantial impact on student experiences.

Finally, the analyses presented here demonstrate how FUSE might serve as an alternative model for designing in-school learning environments that facilitate cross-context learning. Rather than encouraging teachers to design lessons that draw on students' and families' funds of knowledge (e.g., Hogg, 2011; Moll, et al., 1992; Vélez-Ibáñez & Greenberg, 1992) or designing expansive learning activities that extend the time and space of school learning (Engle, 2006, Rajala et al., 2013), the FUSE model emphasizes contextual permeability by granting students agency both in choosing activities and deciding how to approach those activities. The analyses presented here demonstrate that by designing for permeability we can encourage or make space for learners to move interests and practices across contextual boundaries. Better yet, we can do so by placing minimal additional burden on teachers. Rather than asking teachers to identify and design lessons around relevant funds of knowledge or find time and space to shift learning activities from school out into the community, designing for permeability requires only that teachers let things in — interests, practices, choice, agency — and then allow students the time, space, and other support, as needed, to make and cultivate the connections that naturally follow.

Chapter 6. Conclusions and Implications

The broad goal of this dissertation was to further our understanding of what is learned in makerspaces, how interest is related to that learning, and what features of makerspace activity systems facilitate learning, both within and across contexts. In service of that goal, I examined one set of in-school makerspaces, FUSE studios.

From that examination, I found that the choice-based nature of FUSE activities allowed student interests in and allowed interests to drive learning within the FUSE activity system. This impacted learning in FUSE in a number of important ways, including: (1) influencing students' choices of FUSE challenges; (2) influencing students approaches to challenges (i.e., sampling, completing, diving, off-roading); (3) increasing engagement; (4) helping students work through frustration to achieve goals; (5) shaping STEAM career interests and identity; and (6) motivating learners to find ways to pursue interests and learning across contextual boundaries. I also found that students in FUSE both used and learned a variety of meta-disciplinary skills and practices. Some of these skills, including twenty-first century skills, such as collaboration, communication, adaptive problem-solving, initiative, and self-direction, were learned regardless of the challenges students engaged in or the ways in which they engaged with the challenges. Others, such as spatial skills, were influenced more by the particular sociomaterial contexts of specific challenges. I also found that the permeable membrane around the FUSE activity system flowed outward, with FUSE activities motivating and enabling students to take practices learned and interests developed in FUSE out into other in-school and out-of-school contexts. I argued that this was because of the openness, agency, and particular objects of learning afforded by the FUSE activity system and showed how differences in these characteristics distinguished FUSE from other in-school STEAM learning activity systems.

I also proposed and tested qualitative methods for the endogenous (Hall & Stevens, 2015; Stevens, 2010) assessment of meta-disciplinary skill learning in FUSE. First, I demonstrated how a framework, which arranged learning on a continuum from proximal to distal learning outcomes, could be used both by researchers and facilitators to assess the learning of twenty-first century skills. Through the use of this framework, I demonstrated that students on different interest pathways learned many of the same things but demonstrated learning in different ways – ways that might have been missed by traditional assessments. Then I demonstrated how spatial thinking and learning within FUSE challenges could be analyzed endogenously, rather than exogenously (i.e., using psychometric tests) and the benefits that confers for: (1) understanding the role of sociomaterial context in shaping spatial thinking; and (2) understanding the relation between spatial thinking and other sorts of STEAM learning, in making activities.

These findings further our understanding of what and how learning occurs both within makerspaces and more generally, and they have a number of theoretical, methodological, and design implications. First, the research presented here lends empirical support to theoretical writing on the promise of making activities for learning. It also provides an account of mechanism, explaining not just which skills making activities facilitate but how and what features of particular making activity systems support the learning of these skills and practices. Additionally, it provides insight into ways in which making activities or makerspaces could move into the school day, using FUSE as a model for in-school making. The research presented here shows how FUSE balances choice and structure and the benefits this confers for supporting students in engaging with challenges in multiple different ways (sampling, completing, diving, off-roading). Unlike more constrained activity systems like Project Lead the Way, FUSE allowed students to bring in outside interests, and this had an impact on both engagement and learning. However, the rich array of resources available in FUSE (challenge instructions, help videos, diagrams, physical materials, other students, and facilitators) also provided structure, guidance, and support, when needed, so that students didn't get discouraged.

The identification of different interest pathways through FUSE (sampling, completing, diving, off-roading) is also, in itself, an important contribution to the literature, as it expands upon and provides an alternative to Ito et al.'s (2010) categories of engagement in media-rich learning environments (hanging out, messing around, and geeking out). Specifically, while "sampling" is analogous to "messing around", "completing", "diving", and "off-roading" provide three different characterizations of what it might mean to "geek out" in this sort of space. Further, it is important that none of the students I observed in FUSE had interest pathways characterized simply by "hanging out." I believe there are two reasons for this. The first is found in the difference between characterizing student activity on any given day versus characterizing a dominant mode of engagement in activity spanning an entire school year. In other words, although there may have been moments or even class periods, where some students were simply "hanging out" during FUSE, these were always outnumbered by moments or class periods where they were sampling, completing, diving, or off-roading. A second reason may be because FUSE studios I observed were all in schools, during the regular school day, and therefore, "hanging out" was not seen by students, their peers, or FUSE facilitators as an acceptable mode of engagement within the studio.

The research presented here also has broader implications for understanding and designing for STEM interest development, both within and across contexts. The findings presented here demonstrate that choice-based learning contexts like FUSE allow interests in and that allowing interests in may make it easier for students to both develop those interests and take new interests out into other contexts. The student cases presented here also demonstrated that interest motivated the learning of twenty-first century skills like initiative, self-direction, and persistence. This suggests that if we want learners to persist in STEM, or in problem-solving and learning more generally, rather than focusing design efforts on cultivating personal characteristics such as grit, we should be designing for choice, interest, and engagement.

I also demonstrated that FUSE provides an alternative model for designing for cross-context learning, a permeable membrane model. This model differs from the funds of knowledge approach (e.g., Hogg, 2011; Moll, et al., 1992; Vélez-Ibáñez & Greenberg, 1992), in that it places the burden (but also the agency) for bringing in outside interests on students rather than teachers, by providing a choice-based context that naturally allows for that. It also differs from the expansive learning approach (Engeström, 1987; Engle, 2006, Rajala et al., 2013), in that, rather than literally expanding the time and space of the classroom context, it simply makes the barrier between the classroom context and other out-of-school contexts easier to cross.

The findings presented here also suggest that designing learning contexts with the sort of permeable membrane found around FUSE may be particularly beneficial for promoting equity and supporting students who don't excel within the structure of conventional school learning. Amadia's case is one good example of how interest in FUSE led to deeper engagement with STEM learning for a student who was otherwise disinterested in school math and science. Amadia's case also demonstrates that equally important to allowing interests in, is: (1) providing choice and support for different ways of engaging with learning activities; and (2) having a framework for attending to and valuing the different ways in which learning might be demonstrated, along different interest pathways.

Further, the data and analyses related to spatial thinking and learning in FUSE not only contributes to our understanding of what is learned through making activities and how it is learned but also provides new insights into ways to support and assess spatial thinking and learning in schools. The analyses presented here demonstrate both the wide range of spatial skills used and learned during making activities and also how an endogenous, rather than exogenous, examination of spatial thinking can provide insight into ways to design or redesign making activities to cultivate particular spatial skills and practices. My analyses of spatial thinking and learning in FUSE also suggest that, in addition to their other benefits, making activities may be one way to incorporate more spatial thinking and problem-solving into a school day dominated by verbal and analytic reasoning. Using making to incorporate more spatial thinking into school learning also represents a new approach to designing for spatial thinking and learning. This approach would rely not on didactic instruction but on the design of activities that require spatial thinking and the seeding of an environment with spatial resources to draw on to solve problems encountered in those activities.

Finally, the findings presented here also open up new questions for further investigation. The first is what educators can add on top of the design of a choice-based makerspace environment like FUSE to further encourage both the exploration of student interests and cross-context learning, particularly for students from underrepresented groups. The second is whether the methods used here for understanding and assessing learning in FUSE can be adapted and scaled up for use by teachers, to evaluate learning in FUSE, in makerspaces more generally, or even in other school learning contexts. The third concerns the relation between the spatial skills and practices demonstrated by students endogenously in FUSE and those same students' performance on psychometric assessments. In other words, does a student's performance on a psychometric assessment of spatial skills actually correlate with what they are able to do in real-world STEAM problem-solving contexts, like FUSE or not? Finally, a last open question is what might be learned by applying the analytic techniques used in this dissertation to: (1) understand what other disciplinary or meta-disciplinary skills and practices are learned in FUSE; and (2) make additional cross-context comparisons, specifically between FUSE and other makerspaces or other informal learning contexts.

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Appendix A: Survey Questions

Survey administration plan:
In–school and afterschool studios participating in comprehensive survey will get Part 1 questions on their second day at FUSE. Then, they will get Part 2 questions after 10 hours, 20 hours, and after 50 hours (or end of school year).

Part 1 - FOR 2nd DAY AT FUSE:

Header: FUSE Survey #1

Welcome to FUSE! Please take a few minutes to answer this short survey. We would like to know what you think of FUSE so far. There are no right or wrong answers, but please be honest. The only correct responses are those that are true for you. Whenever possible, let the things that have happened to you help you make a choice. Your answers are very important and they will help us improve FUSE. Thank you!

Your answers to the survey will not be saved until you click the "Submit" button on the last page. To make sure you don't lose any of your answers, please do not close this survey or your browser window before then.

For each of the following statements, fill in the circle that matches how you feel. Even though some statements are very similar, please answer each statement.

Math has been my worst subject.

Strongly disagree Disagree Agree Strongly Agree

I would strongly consider a career that uses math.

Strongly disagree Disagree Agree Strongly Agree

Math is hard for me.

Strongly disagree Disagree Agree Strongly Agree

I am the type of student to do well in math.

Strongly disagree Disagree Agree Strongly Agree

I can handle most subjects well, but I cannot do a good job with math.

Strongly disagree Disagree Agree Strongly Agree

I am sure I could do advanced work in math.

Strongly disagree Disagree Agree Strongly Agree

I can get good grades in math.

Strongly disagree Disagree Agree Strongly Agree

I am good at math.

Strongly disagree Disagree Agree Strongly Agree

I am sure of myself when I do science.

Strongly disagree Disagree Agree Strongly Agree

I would strongly consider a career in science.

Strongly disagree Disagree Agree Strongly Agree

I expect to use science when I get out of school.

Strongly disagree Disagree Agree Strongly Agree

Knowing science will help me earn a living.

Strongly disagree Disagree Agree Strongly Agree

I will need science for my future work.

Strongly disagree Disagree Agree Strongly Agree

I know I can do well in science.

Strongly disagree Disagree Agree Strongly Agree

Science will be important to me in my life's work.

Strongly disagree Disagree Agree Strongly Agree

I can handle most subjects well, but I cannot do a good job with science.

Strongly disagree Disagree Agree Strongly Agree

I am sure I could do advanced work in science.

Strongly disagree Disagree Agree Strongly Agree

Please read this paragraph before you answer the following group of questions.

Engineers use math, science, and creativity to research and solve problems that improve everyone's life and to invent new products. There are many different types of engineering, such as chemical, electrical, computer, mechanical, civil, environmental, and biomedical. Engineers design and improve things like bridges, cars, fabrics, foods, and virtual reality amusement parks. Technologists put in place the designs that engineers develop; they build, test, and maintain products and processes.

I like to imagine creating new products.

Strongly disagree Disagree Agree Strongly Agree

If I learn engineering, then I can improve things that people use every day.

Strongly disagree Disagree Agree Strongly Agree

I am good at building and fixing things.

Strongly disagree Disagree Agree Strongly Agree

I am interested in what makes machines work.

Strongly disagree Disagree Agree Strongly Agree

Designing products or structures will be important for my future work.

Strongly disagree Disagree Agree Strongly Agree

I am curious about how electronics work.

Strongly disagree Disagree Agree Strongly Agree

I would like to use creativity and innovation in my future work.

Strongly disagree Disagree Agree Strongly Agree

Knowing how to use math and science together will allow me to invent useful things.

Strongly disagree Disagree Agree Strongly Agree

I believe I can be successful in a career in engineering.

Strongly disagree Disagree Agree Strongly Agree

When you're working together with others...

I am confident I can lead others to accomplish a goal.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can encourage others to do their best.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can respect the differences of my peers.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can help others my age.

Strongly disagree Disagree Agree Strongly Agree

When I make decisions, I think about what is good for other people.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can work will with students from different backgrounds.

Strongly disagree Disagree Agree Strongly Agree

And when you're working on your own...

I am confident I can produce high quality work.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can make changes when things do not go as planned.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can set my own learning goals.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can manage my time wisely when working on my own.

Strongly disagree Disagree Agree Strongly Agree

When I have many assignments, I can choose which ones need to be done first.

Strongly disagree Disagree Agree Strongly Agree

How much does doing FUSE challenges make you think about subject areas and careers?

Here are descriptions of subject areas that involve math, science, engineering and/or technology, and lists of jobs connected to each subject area. As you read the list below, you will know how interested you are in the subject and the jobs. Fill in the circle that relates to how interested you are.

There are no "right" or "wrong" answers. The only correct responses are those that are true for you.

Physics: is the study of basic laws of motion, energy, structure, and matter. This can include studying how the universe works. Some examples careers include: aviation engineer, research physicist, astronomer.

Not at all Interested Interested Very Interested

Environmental Work: involves working to protect or improve the environment. This includes finding and designing solutions to problems like pollution, reusing waste, and recycling. Some examples careers include: environmental scientist, soil scientist, environmental lawyer

Not at all Interested Interested Very Interested

Life Sciences Work: involves working with or studying living things (such as plants and animals). Some examples careers include: animal scientist, geneticist, zoologist

Not at all Interested Interested Very Interested

Veterinary Work: involves the science of preventing or treating disease in animals. Some examples careers include: veterinary assistant, veterarian, animal caretaker

Not at all Interested Interested Very Interested

Working with Numbers: Using math and statistics to solve problems or analyze data. Some examples careers include: accountant, economist, mathematician, financial analyst, market researcher, sports statistician

Not at all Interested Interested Very Interested

Design Work: Working with clients to create design solutions for their product or service. Some examples include: industrial designer, animator, filmmaker, graphic designer, interior designer, illustrator.

Not at all Interested Interested Very Interested

Architecture, Landscape & Urban Planning Work: Working with clients and local governments to create buildings and city plans. Some examples include: city planner, urban designer, landscape architect, architect.

Not at all Interested Interested Very Interested

Working as an Artist: Working individually or as part of a team or company to produce works of art. Some examples include: jewelry designer, painter, muralist, dancer, actor, sculptor, teaching artist, animator, filmmaker, sound artist, storyteller.

Not at all Interested Interested Very Interested

Health Care: working in a hospital or clinic to help patients stay healthy and treat disease. Some examples include: physician's assistant, nurse, doctor, nutritionist, emergency medical technician, physical therapist, dentist

Not at all Interested Interested Very Interested

Earth Science: is the study of the earth, including the air, land, and ocean. Some example careers include: geologist, weather forecaster, archaeologist, climate scientist

Not at all Interested Interested Very Interested

Computer Science: involves creating and testing computer systems and helping others to use computers. Some examples include: computer programmer, game designer, information technology specialist

Not at all Interested Interested Very Interested

Medical Research: involves researching human disease and working to find new solutions to human health problems. Some examples include: clinical lab technologist, medical scientist, pharmacologist (developing new medicines), epidemiologist (studying disease)

Not at all Interested Interested Very Interested

Chemistry: studying how chemicals work and how they can be combined to create new materials. Some examples include: chemical technician, chemist, chemical engineer

Not at all Interested Interested Very Interested

Energy: involves looking for ways to use energy more efficiently and exploring new ways of collecting and storing energy. Some examples include:

Engineering: involves designing, testing, and manufacturing new products (like machines, bridges, buildings, and electronics). Some examples include: civil, industrial, agriculture, or mechanical engineers; welder, auto mechanic

Not at all Interested Interested Very Interested

Please tell us a little bit about you:

In the future, do you plan to take advanced classes in:

Math?
Yes | No | Not sure

Science?
Yes | No | Not sure

Do you know any adults who use science at work?
Yes | No | Not sure

Do you know any adults who work as engineers?
Yes | No | Not sure

Do you know any adults who use math or statistics at work?
Yes | No | Not sure

Do you know any adults who work with technology?
Yes | No | Not sure

Click Submit, and then you're all done! Thank you very much.

In a few weeks, we will ask you these questions again, plus a few more. Please take a few minutes to complete that survey when you see it next.

Survey Part 2: AFTER 10, 20, 50 hours:

Header: FUSE Survey #2/3/4

Hello again! We hope you've been having a lot of fun at FUSE. Please take a few minutes to complete this survey. We would like to know your thoughts about FUSE now that you have had more of a chance to try it. There are no right or wrong answers, but please be honest. Your answers are very important and they will help us to improve the FUSE program.

Your answers to the survey will not be saved until you click the "Submit" button on the last page. To make sure you don't lose any of your answers, please do not close this survey or your browser window before then.

Thank you!

I can always find something fun to do when I come to the FUSE Studio.

Strongly disagree Disagree Agree Strongly Agree

I like to repeat FUSE challenges I've already tried.

Strongly disagree Disagree Agree Strongly Agree

The beginning levels of FUSE challenges aren't too easy and they're not too hard.

Strongly disagree Disagree Agree Strongly Agree

I come back to challenges that I didn't finish the first time.

Strongly disagree Disagree Agree Strongly Agree

I don't like the current FUSE challenges.

Strongly disagree Disagree Agree Strongly Agree

I like to work with other people when solving challenges.

Strongly disagree Disagree Agree Strongly Agree

There are some FUSE challenges that look so hard, I don't think I could ever try them.

Strongly disagree Disagree Agree Strongly Agree

I often have a hard time understanding what I need to do to complete a FUSE challenge.

Strongly disagree Disagree Agree Strongly Agree

I only try hard challenges with my friends.

Strongly disagree Disagree Agree Strongly Agree

For each of the statements below, fill in the circle that matches how you feel.

Trying FUSE challenges has helped me become more curious about things I wasn't interested in before.

Strongly disagree Disagree Agree Strongly Agree

By trying FUSE challenges I discovered an interest I didn't know I had.

Strongly disagree Disagree Agree Strongly Agree

The FUSE challenges I've tried are like things I might want to do for work in the future.

Strongly disagree Disagree Agree Strongly Agree

The FUSE challenges I've tried are like things I might want to study in school in the future.

Strongly disagree Disagree Agree Strongly Agree

I am comfortable trying to work with a friend to figure something out together for another class.

Strongly disagree Disagree Agree Strongly Agree

Having a chance to work with my friends at FUSE makes me feel more confident about helping people in other classes at school.

Strongly disagree Disagree Agree Strongly Agree

Since you first started coming to FUSE:

Have you gotten really excited about doing something at FUSE?

☐ Yes ☐ No

IF YES: What was the thing you were so excited about?

I was most excited about: ___________

Since coming to FUSE, what are all the <u>other</u> places besides FUSE where you do ACTIVITY: Fill in with student's answer]? (Check all that apply.)

☐ at home or at a friend's house
☐ at class during school
☐ at an afterschool program at my school
☐ at a park district program
☐ at a museum or cultural center
☐ at a library
☐ at a youth organization in the community
☐ at a church, synagogue, mosque, or other religious place
☐ on the Internet
☐ at a camp during vacation
☐ other (Name the place:)
☐ I only do this at FUSE

Who else did [ACTIVITY] with you?

☐ someone I met for the first time at FUSE
☐ someone in FUSE I wasn't friends with before
☐ a friend
☐ a brother or sister
☐ an adult relative
☐ Someone else (Who:)

I have bought or downloaded something I needed to continue working on [ACTIVITY].

☐ Yes

☐ No

I sometimes work on FUSE challenges with my friends on our own, outside of the program.

☐ Yes
☐ No

I've made up my own FUSE challenges for me and my friends.

☐ Yes
☐ No

When I'm working on a challenge at FUSE:

	Yes	No
There are people my age who can show me how to do something I want to learn.	☐	☐
There are people my age who are willing to answer if I have a question about something.	☐	☐
There are people my age who I can get ideas from.	☐	☐
There are people my age who I share my ideas about the challenge with.	☐	☐
There are people my age who I like to do the challenge with.	☐	☐
There are people my age who I can ask questions if I get stuck in the challenge.	☐	☐
There are people my age who I share my ideas on the challenge with.	☐	☐

Tell us a little bit more about how you work with other people at FUSE.

	Yes	No
People my age here who are also doing the challenge are unwilling to answer questions I have.	☐	☐
I mostly work on challenges by myself.	☐	☐
I usually keep to myself when at the FUSE Studio.	☐	☐

Choose "yes" or "no" for how you feel about each statement below.

	Yes	No

I signed up for a new class or club at school because of something I did at FUSE.	☐	☐
In FUSE, I have developed new skills that have helped me do better in school.	☐	☐
Since starting FUSE, I have made new friends who share my interests.	☐	☐
I have a better attitude about school since coming to FUSE.	☐	☐

Since coming to FUSE:	Yes	No
When I am asked to solve a problem in another class I am more likely to ask a friend for help before asking a teacher for help.	☐	☐
When I am asked to solve a problem in another class I am more likely to look it up myself before asking a teacher for help.	☐	☐
When I am working on a difficult homework assignment, I am more likely to look it up myself before asking an adult for help.	☐	☐
When I am working on a difficult homework assignment, I am more likely to ask a friend for help before asking an adult for help.		

For each of the following statements, fill in the circle that matches how you feel. Even though some statements are very similar, please answer each statement.

Math has been my worst subject.

Strongly disagree Disagree Agree Strongly Agree

I would strongly consider a career that uses math.

Strongly disagree Disagree Agree Strongly Agree

Math is hard for me.

Strongly disagree Disagree Agree Strongly Agree

I am the type of student to do well in math.

Strongly disagree Disagree Agree Strongly Agree

I can handle most subjects well, but I cannot do a good job with math.

Strongly disagree Disagree Agree Strongly Agree

I am sure I could do advanced work in math.

Strongly disagree Disagree Agree Strongly Agree

I can get good grades in math.

Strongly disagree Disagree Agree Strongly Agree

I am good at math.

Strongly disagree Disagree Agree Strongly Agree

I am sure of myself when I do science.

Strongly disagree Disagree Agree Strongly Agree

I would strongly consider a career in science.

Strongly disagree Disagree Agree Strongly Agree

I expect to use science when I get out of school.

Strongly disagree Disagree Agree Strongly Agree

Knowing science will help me earn a living.

Strongly disagree Disagree Agree Strongly Agree

I will need science for my future work.

Strongly disagree Disagree Agree Strongly Agree

I know I can do well in science.

Strongly disagree Disagree Agree Strongly Agree

Science will be important to me in my life's work.

Strongly disagree Disagree Agree Strongly Agree

I can handle most subjects well, but I cannot do a good job with science.

Strongly disagree Disagree Agree Strongly Agree

I am sure I could do advanced work in science.

Strongly disagree Disagree Agree Strongly Agree

Please read this paragraph before you answer the following group of questions.

Engineers use math, science, and creativity to research and solve problems that improve everyone's life and to invent new products. There are many different types of engineering,

such as chemical, electrical, computer, mechanical, civil, environmental, and biomedical. Engineers design and improve things like bridges, cars, fabrics, foods, and virtual reality amusement parks. Technologists put in place the designs that engineers develop; they build, test, and maintain products and processes.

I like to imagine creating new products.

Strongly disagree Disagree Agree Strongly Agree

If I learn engineering, then I can improve things that people use every day.

Strongly disagree Disagree Agree Strongly Agree

I am good at building and fixing things.

Strongly disagree Disagree Agree Strongly Agree

I am interested in what makes machines work.

Strongly disagree Disagree Agree Strongly Agree

Designing products or structures will be important for my future work.

Strongly disagree Disagree Agree Strongly Agree

I am curious about how electronics work.

Strongly disagree Disagree Agree Strongly Agree

I would like to use creativity and innovation in my future work.

Strongly disagree Disagree Agree Strongly Agree

Knowing how to use math and science together will allow me to invent useful things.

Strongly disagree Disagree Agree Strongly Agree

I believe I can be successful in a career in engineering.

Strongly disagree Disagree Agree Strongly Agree

When you're working together with others...

I am confident I can lead others to accomplish a goal.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can encourage others to do their best.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can respect the differences of my peers.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can help others my age.

Strongly disagree Disagree Agree Strongly Agree

When I make decisions, I think about what is good for other people.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can work will with students from different backgrounds.

Strongly disagree Disagree Agree Strongly Agree

And when you're working on your own...

I am confident I can produce high quality work.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can make changes when things do not go as planned.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can set my own learning goals.

Strongly disagree Disagree Agree Strongly Agree

I am confident I can manage my time wisely when working on my own.

Strongly disagree Disagree Agree Strongly Agree

When I have many assignments, I can choose which ones need to be done first.

Strongly disagree Disagree Agree Strongly Agree

How much does doing FUSE challenges make you think about subject areas and careers?

Here are descriptions of subject areas that involve math, science, engineering and/or technology, and lists of jobs connected to each subject area. As you read the list below, fill in the circle that relates to how interested you are.

There are no "right" or "wrong" answers. The only correct responses are those that are true for you.

Physics: is the study of basic laws of motion, energy, structure, and matter. This can include studying how the universe works. Some examples careers include: aviation engineer, research physicist, astronomer.

Not at all Interested Interested Very Interested

Environmental Work: involves working to protect or improve the environment. This includes finding and designing solutions to problems like pollution, reusing waste, and recycling. Some examples careers include: environmental scientist, soil scientist, environmental lawyer

Not at all Interested Interested Very Interested

Life Sciences Work: involves working with or studying living things (such as plants and animals). Some examples careers include: animal scientist, geneticist, zoologist

Not at all Interested Interested Very Interested

Veterinary Work: involves the science of preventing or treating disease in animals. Some examples careers include: veterinary assistant, veterarian, animal caretaker

Not at all Interested Interested Very Interested

Working with Numbers: Using math and statistics to solve problems or analyze data. Some examples careers include: accountant, economist, mathematician, financial analyst, market researcher, sports statistician

Not at all Interested Interested Very Interested

Design Work: Working with clients to create design solutions for their product or service. Some examples include: industrial designer, animator, filmmaker, graphic designer, interior designer, illustrator.

Not at all Interested Interested Very Interested

Architecture, Landscape & Urban Planning Work: Working with clients and local governments to create buildings and city plans. Some examples include: city planner, urban designer, landscape architect, architect.

Not at all Interested Interested Very Interested

Working as an Artist: Working individually or as part of a team or company to produce works of art. Some examples include: jewelry designer, painter, muralist, dancer, actor, sculptor, teaching artist, animator, filmmaker, sound artist, storyteller.

Not at all Interested Interested Very Interested

Health Care: working in a hospital or clinic to help patients stay healthy and treat disease. Some examples include: physician's assistant, nurse, doctor, nutritionist, emergency medical technician, physical therapist, dentist

Not at all Interested Interested Very Interested

Earth Science: is the study of the earth, including the air, land, and ocean. Some example careers include: geologist, weather forecaster, archaeologist, climate scientist

Not at all Interested Interested Very Interested

Computer Science: involves creating and testing computer systems and helping others to use computers. Some examples include: computer programmer, game designer, information technology specialist

Not at all Interested Interested Very Interested

Medical Research: involves researching human disease and working to find new solutions to human health problems. Some examples include: clinical lab technologist, medical scientist, pharmacologist (developing new medicines), epidemiologist (studying disease)

Not at all Interested Interested Very Interested

Chemistry: studying how chemicals work and how they can be combined to create new materials. Some examples include: chemical technician, chemist, chemical engineer

Not at all Interested Interested Very Interested

Energy: involves looking for ways to use energy more efficiently and exploring new ways of collecting and storing energy. Some examples include:

Engineering: involves designing, testing, and manufacturing new products (like machines, bridges, buildings, and electronics). Some examples include: civil, industrial, agriculture, or mechanical engineers; welder, auto mechanic

Not at all Interested Interested Very Interested

Please tell us a little bit about you:

In the future, do you plan to take advanced classes in:

Math?
Yes | No | Not sure

Science?
Yes | No | Not sure

Do you know any adults who use science at work?
Yes | No | Not sure

Do you know any adults who work as engineers?
Yes | No | Not sure

Do you know any adults who use math or statistics at work?
Yes | No | Not sure

Do you know any adults who work with technology?
Yes | No | Not sure

Click Submit, and then you're all done! Thank you very much.

[for 1st and 2nd administrations of Part 2] In a few weeks, we will ask you the same set of questions again. Please take a few minutes to complete that survey when you see it next.

Appendix B: End-of-year student interview questions

1. So, I'm pretty new to this and I don't know a whole lot about FUSE. Can you tell me about it?
2. What do <u>you</u> normally do in FUSE?
3. Thinking back over the whole year of FUSE, what do you remember most?
4. Can you show me something on your MyStuff page that you're proud of and tell me about it?
    a. [*Follow up* Why did you pick that?]
    b. [*Follw up* So, do you do this in teams, or on your own, or what?]
    c. [*Follow up* Tell me something hard you had to figure out about that.]
    d. [*Follow up* Can you remember *how* you figured it out? Did you figure it out by yourself?]
5. Do you plan to keep working on that or any other things you've done in FUSE? (Like, this summer, next year in 7th grade.)
6. Have you done FUSE outside of school? (Have you done anything *like* FUSE outside of school?)
7. What's it like to work in FUSE?
8. Let's say there was a fifth grader who was about to start FUSE, what would you tell him/her about what to expect?
9. Is FUSE different from [science math art music] class?
10. What do teachers normally do in science [science math art music] class?
11. What do <u>you</u> normally do in science [science math art music] class?
12. What do you think you've learned in FUSE this year?

13. How do you learn best?

14. Have you thought about what you want to do when you grow up?

    a. [*If no* Has FUSE given you any ideas about something that might be interesting?]

    b. [*If X* Is there anything you've done in FUSE that might relate to X?]

15. Do you have ideas about FUSE challenges that you'd like to see?

16. Is FUSE fun?

17. What does "fun" mean?

18. Last question … is there anything you would like to tell the people who designed FUSE?

Appendix C: End-of-year facilitator interview questions

1. If you were to describe a typical day in FUSE for you what do you do?
2. Can you tell me a story or two from FUSE this year that you think you will really remember?
    a. [follow up: Are there stories about specific kids this year in FUSE that you want to tell?]
    b. As you know we've been doing interviews with the kids. Can I ask you about some specific kids? [insert specific kids here - kids with standout interviews/stories]
3. What do you think your students have learned in FUSE?
4. Beyond what they've learned, are there other ways that FUSE has affected your students?
5. Thinking big picture, what are your goals for your students in FUSE?
6. Are there ways that you've adapted or added to FUSE to achieve these goals? What happened when you made these changes?
    a. [*follow up if only a success story,* were there any changes you made that did not work that well?]
    b. [*follow up if only a failure story,* were there any changes you made that worked well?]
7. [*For experienced teachers*] You did FUSE last year. Is there anything you did differently this year? [*Or for new teachers*] You were new to FUSE this year. Is there anything you do differently now than you did at the beginning of the year?
8. [*Follow up for all*] Are you doing FUSE next year? Are you planning on making any changes for next year? What kind of things have your students learned in FUSE?

9. You see these kids in the rest of the school day too. Do you notice any differences in the way they participate in FUSE and in other subjects?
10. How is your role different in FUSE and other subjects? [*possible follow up*: How do you feel about that?]
11. Has being part of FUSE affected how you teach in other parts of the day?
12. What do you think kids would say about FUSE?
13. In the interviews we have done with kids, a lot of them use the word fun to describe their experience in FUSE. What do you think about that?
14. In our interviews, we've also heard kids use the word "challenging" to describe FUSE. What do you think about that?
15. Is there anything you would like to tell the people who designed FUSE?
16. Let's say there is a teacher who is new to FUSE, what would you tell him/her to expect? What advice would you give him/her?
17. Have parents talked to you about FUSE? [follow up if answer is yes: Can you tell me some of the things you have heard from them?]
18. I have what might seem like a funny question, is there anything that ***you*** have learned from doing FUSE?
19. Finally, let me give you a what if...What do you think would happen if other parts of school were structured like FUSE?