DOCUMENTING THE CRITICAL COMPONENTS AND IMPLEMENTATION VARIATIONS OF THE MAKE-TO-LEARN INVENTION KITS

A Dissertation
Presented to
The Faculty of the Curry School of Education
University of Virginia

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

---

by
Eric David Yoder
August 2017

Executive Summary

Advisor: Dr. Stephanie Moore

The Make-to-Learn Invention Kits are a series of innovative, engineering-focused STEM learning modules that are currently being piloted, primarily in middle school settings. The series traces the progression of key inventions that transformed modern civilization between 1800 and 1960; inventions such as the electric motor, the telegraph, the telephone, and the radio. Open-source digital resource packages called Invention Kits contain virtual, 3D models from the Smithsonian collections, primary and secondary sources such as patent descriptions and inventors' notebooks, instructional guides, and other support materials for teachers and students. Using these resources, students reinterpret and reinvent the devices using either low-tech tools or advanced manufacturing technologies.

This study focused on the problem of supporting teachers who seek to provide engineering-focused STEM experiences to their students. This is especially important considering that the majority of K-12 teachers have little or no training or experience with engineering pedagogy. For these teachers, the Invention Kits represent an innovation. Educational change research suggests that educational innovations often fail to catch on because would-be adopters do not fully understand what the innovation will look like when implemented in the envisioned way. Innovation Configuration Mapping was developed as a strategy to address this problem. One goal of this study was to develop an Innovation Configuration Map for the Make-to-Learn Invention Kits. In doing so, the study addressed the following research questions: (1) What are the critical components of the Make-to-Learn Invention Kits from the perspectives of the developers and facilitators? (2) How do Invention Kit developers and facilitators describe their visions for how the components should be implemented? (3) In practice, how do teachers adapt the Invention Kits to their context? What components of the kits do teachers choose to implement or emphasize? Do the teachers add new components to the kits? If so, what are these additions?

The Innovation Configuration Mapping process consisted of document analysis, interviews with the Invention Kit developers, and interviews and classroom observations with teachers implementing the Invention Kits in five classrooms across three school districts. Findings related to (a) opportunities for students to fully participate in the process of reinventing the historical devices and develop high-tech and low-tech engineering competencies; (b) the strategies that teachers employed to facilitate knowledge construction of scientific principles; (c) activities through which students appropriated scientific knowledge and engineering skills and applied them to their own inventions; and (d) broader themes that were used to provide students with historical perspective and help them understand the process of invention. Findings detail what these and other components look like according to the visions of the developers and how they were adapted in different classroom contexts.

The results of this study underscore the complexity of the Invention Kits – and integrated STEM learning approaches, in general – which combine subject matter from

multiple content areas, engineering-design processes, project-based learning, and modern design and manufacturing technologies. Limitations included a small sample size – at the time of this study, the Invention Kits were being piloted at a small number of sites – and a relatively short study duration. Also, the unique characteristics of the Invention Kits, which utilize advanced manufacturing technologies such as 3D printing, may limit the transferability of the findings until such technologies and related approaches become more widespread in K-12 settings.

Instructional Technology
Curry School of Education
University of Virginia
Charlottesville, Virginia

APPROVAL OF THE DISSERTATION

This dissertation, "Documenting the Critical Components and Implementation Variations of the Make-To-Learn Invention Kits," has been approved by the Graduate Faculty of the Curry School of Education in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Stephanie Moore (co-chair)

Jennifer Chiu (co-chair)

Joe Garofalo

Larry Richards

Date

DEDICATION

To my children, Adelyn and Samuel,
For their enthusiasm and curiosity,

To my wife, Amy Frazier-Yoder,
For providing a model for academic success,

To my parents, John and Dorothy Yoder,
For their many sacrifices,

And to my grandfather, the late David R. Yoder,
For recognizing my greatest potential lay in using my head.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my committee co-chairs, Dr. Stephanie Moore and Dr. Jennie Chiu. Stephanie, thank you for helping me chart a path to completion and for providing critical guidance and encouragement at every stage of the journey. Jennie, thank you for your enthusiasm, your insightful feedback, and for lending me a small portion of your considerable expertise in STEM education.

Thanks also to committee members, Dr. Joe Garofalo and Dr. Larry Richards. Joe, thank you for providing a practical perspective and a wealth of teacher-focused experience that contributed immeasurably to the potential usefulness of this work. Larry, thank you for contributing an outside perspective informed by your extensive experience in engineering education and hands-on learning.

I am also grateful to Dr. Glen Bull for introducing me to the Invention Kits and for modelling a dogged pursuit of innovation in education.

I also owe a debt of gratitude to Bill and Sally Frazier, who, along with my wife Amy, provided much behind-the-scenes support and encouragement, without which, this dissertation would not have been possible.

Finally, I would like to acknowledge educators who provided invaluable support and encouragement at various stages of my academic career. These include Ms. Martha Swigart and Mr. Michael Long at Huntingdon Area High School, Dr. Rachana Sachdev and Dr. Jeffrey Whitman at Susquehanna University, and Dr. Mable Kinzie at the University of Virginia. Thank you for nurturing my passions, exposing me to new ideas, and helping me build confidence in my abilities.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

FIGURE Page

CHAPTER 1

Introduction

Over the last decade, Science, Technology, Engineering, and Math (STEM) education has emerged as a high priority in K-12 education. In 2009, President Obama challenged the education community to recruit and educate 100,000 new STEM teachers before 2019 as part of his Educate to Innovate initiative, which has since garnered more than $1 billion to support STEM education programs (The White House, 2016). STEM was also a top priority in his $4.3 billion Race to the Top initiative (U.S. Department of Education, 2015). Countless other efforts are spearheaded by state and local governments, foundations, and businesses throughout the country (National Research Council, 2010). Advocates argue that investing in STEM education is crucial for the U.S. to maintain its competitive edge in the global economy, preserve national security, and foster a higher quality of life for its citizens (National Research Council, 2010; Committee on K-12 Engineering Education, 2009). Despite its importance, many argue that the current state of STEM education is unsatisfactory (Committee on K-12 Engineering Education, 2009; Moore et al., 2014; National Academy of Engineering & National Research Council, 2014; National Research Council, 2010, 2012). They criticize the lack of connections among the disciplines and decry the uneven treatment of the subjects in many schools (National Academy of Engineering & National Research Council, 2014). For example, science and mathematics have long been part of the standard curriculum, but they have been taught in isolation, their natural connections largely ignored. Technology education also has a relatively long history in the nation's schools as an off-shoot of the industrial arts, but it is often regarded as a second-tier subject, which students take as an elective. When offered, technology classes are typically taught in isolation, disconnected from other subjects (Committee on K-12 Engineering Education, 2009).

Meanwhile, the "E" in STEM – engineering – has historically received even less attention. Some refer to it as the "missing letter in STEM" (Brophy, Klein, Portsmore, & Rogers, 2008; Committee on K-12 Engineering Education, 2009). While the data are limited, the Committee on K-12 Engineering Education (2009) projected that, since the early 1990s, "fewer than 6 million students have had some kind of formal engineering education. By comparison, the estimated enrollment for grades pre-K–12 for U.S. public and private schools in 2008 was nearly 56 million" (p.6).

Recently, however, engineering is attracting attention, not only as subject in its own right, but as a strategy to break down the artificial divisions among of the four disciplines. "Because engineering requires the application of mathematics and science through the development of technologies, it can provide a way to integrate the STEM disciplines meaningfully" (Moore et al., 2014, p. 2). Through engineering, students practice combining math, science, and technology skills in ways that replicate how professionals apply those skills to address real-world problems. Students learn that, in beyond-school settings, the disciplines are rarely isolated (Committee on K-12 Engineering Education, 2009). Meanwhile, because the targets of engineering design are often socially, environmentally, or economically relevant, students respond with added engagement and motivation (Brophy et al., 2008; Roehrig, Moore, Wang, & Park, 2012). The National Engineering Association provides examples of these targets on their list of "14 Grand Challenges for Engineering in the 21st Century," including advancing personalized learning, making solar energy economical, improving urban infrastructure, and providing access to clean water (National Academy of Engineering, 2016). Finally, engineering provides students with opportunities to practice soft skills such as problem-solving, teamwork, and communication (Roehrig et al., 2012).

Recognizing this potential, more districts, schools, and teachers are seeking STEM curricula that incorporate a hands-on, engineering-centered approach (Moore et al., 2014). They are finding a limited, but increasing, number of partners to support them in this arena, including well-known non-profit organizations like Project Lead the Way and the International Technology and Engineering Educators Association (ITEEA), as well as universities, museums, and after-school programs.

Make-to-Learn Invention Kits

The Laboratory School for Advanced Manufacturing (Lab School) at the University of Virginia is one such entity that is developing engineering-focused activities that can be used to integrate STEM disciplines. Established as a joint venture between the University of Virginia's Curry School of Education and the School of Engineering and Applied Science, the Lab School collaborates with two Central Virginia school districts to explore advanced manufacturing technologies such as 3-D printing in K-12 schools. Its mission is to "pilot and validate instructional resources and activities that can be shared with other schools" (Bull, Haj-Hariri, Atkins, & Moran, 2015).

Currently, the Lab School is collaborating with the Smithsonian National Museum of American History and Princeton University to develop a series of lessons and activities that engage students in STEM through historical innovations. Entitled Make-to-Learn Invention Kits, the series traces the progression of key inventions that transformed modern civilization between 1800 and 1960; inventions such as the electric motor, the telegraph, the telephone, and the radio. The Invention Kits are open-source digital resource packages consisting of virtual, 3D models from the Smithsonian collections, primary and secondary sources such as patent descriptions and inventors' notebooks, instructional guides, and other support materials for teachers and students. Using these resources, students reinterpret and reinvent the devices using either low-tech tools or advanced manufacturing technologies.

One example of the Invention Kits focuses on the Linear Generator – or Magneto – a device developed shortly after Michael Faraday discovered in 1832 that the movement of a magnet through a coil of wire could generate an electrical current. Using replicas of this historical device which they build themselves, students explore scientific concepts relating to electricity and electromagnetism, including alternating current and voltage; apply mathematics as they calculate Hertz and chart voltage over time, and develop technological skills as they utilize instruments and tools such as oscilloscopes, laser cutters, 3D printers, and various software. After exploring their linear motor replicas, they reapply the content and skills gained during the lab activities to design and construct an invention of their own. Throughout these experiences, STEM content and skills are integrated and applied in a meaningful context. Meanwhile, students are invited to extend their thinking into other content areas, such as social studies and language arts, as they consider the historical and social implications of the innovation. According to the Invention Kit website, “The ultimate objective [of the series] is to inspire and inform a new generation of designers, and to underscore the power of new ideas rooted in fundamental principles of science and engineering” (FabNet Invention System, 2016).

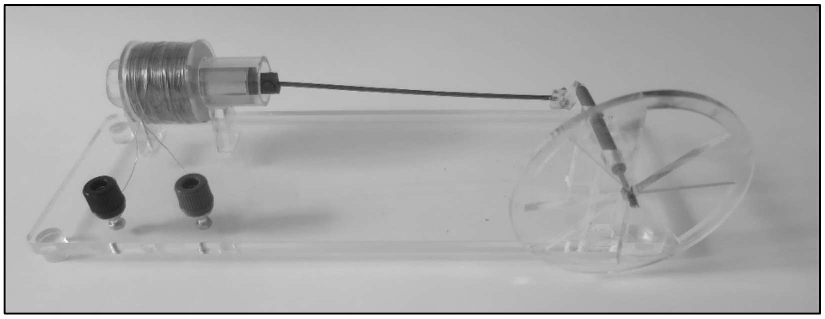


Figure 1. Replica of a linear generator constructed using a laser cutter and 3D printer

Project-based learning (PBL) provides the pedagogical framework for the Invention Kits. PBL is a systematic teaching method that engages students in learning knowledge and skills through extended investigations of complex questions, problems, or challenges (Buck Institute for Education, 2016). The complex, authentic problems embedded in the Invention Kits challenge students to pose questions, think critically, find resources, and apply information, both individually and collaboratively. Throughout the process, teachers ask students to reflect on their learning, the effectiveness of their strategies, and the obstacles they face. PBL generally culminates with the completion of a tangible product that can be shared (J. S. Krajcik, Blumenfeld, Marx, & Soloway, 1994). In this case, students first construct working models of a key invention then apply the underlying principles to design and build something new.

A small number of schools are currently piloting Invention Kits. Feedback from these implementations guides revisions to existing material. Meanwhile, the developers are creating additional Invention Kits. To date, beta versions of three kits have been developed and tested. Ultimately, the Invention Kits will be available nationally on the Smithsonian X 3D website.

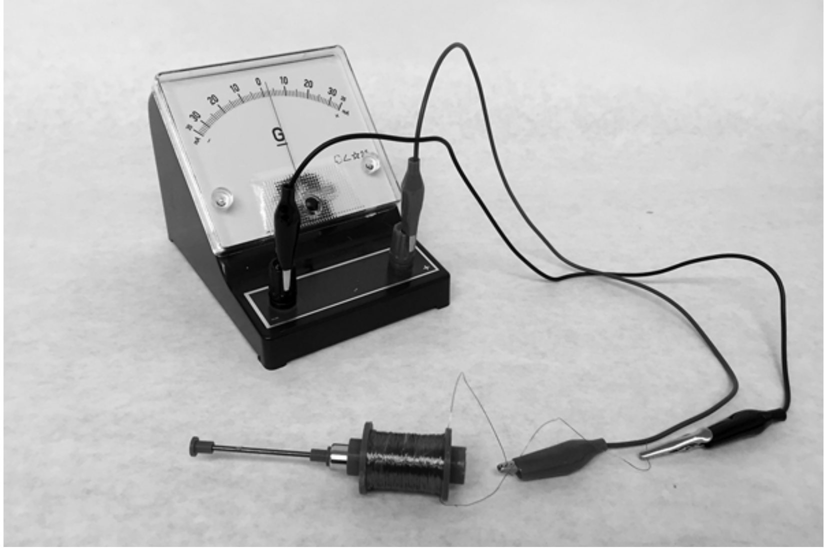


Figure 2. A 3D-printed solenoid with armature connected to an ammeter, a device used for measuring electrical current

Statement of the Problem

Using engineering to integrate STEM disciplines is an innovative approach with significant potential to capture the holistic spirit of STEM in K-12 settings. Nonetheless, there are barriers to its widespread adoption and efficacy. Few teachers have any kind of formal preparation in engineering education (Committee on K-12 Engineering Education, 2009). Also, engineering in K-12 settings lacks established learning standards, assessments, curriculum models, and documentation of effective teaching practices (Brophy et al., 2008; Committee on K-12 Engineering Education, 2009; Moore et al., 2014; Roehrig et al., 2012). Despite having little experience or support, teachers attempting to implement engineering projects will need to make significant changes or adjustments in their classrooms. However, decades of research on educational change and innovation underscore that teachers are notoriously resistant to change (Ellsworth, 2000). Teachers tend to stay within their comfort zones, sometimes despite their best intentions. For instance, Roehrig, et al. (2012) found that technology teachers implementing an integrated STEM curriculum developed by Project Lead the Way tended to gloss over science and math content and focused primarily on technology.

Gene Hall and Shirley Hord (2013) state that educational innovation and change often occurs modestly (or not at all) because "the implementers, facilitators, and policymakers do not fully understand what the change is or what it will look like when it is implemented in the envisioned way" (p. 56). Because the desired change is not clearly communicated, teachers enact their own interpretations of the innovation or reject it altogether. This risk is magnified when the innovation is complex – and many innovations are more complex than they initially appear (Rogers, 2003). A number of factors make integrating STEM through engineering complex, including specialized teaching and assessment strategies, classroom workflows, student groupings, and technological tools. Meanwhile, many would-be adopters must also contend with factors that are external to the innovation itself but nonetheless impact classroom implementations, such as limited budgets or scheduling constraints. For an implementation of curricula rooted in engineering to be successful, especially when implemented by teachers who have little experience with engineering themselves, it will be crucial for teachers to understand its critical components and be able to visualize what application might look like in their own classrooms (Hall & Hord, 2013).

Purpose of the Study

This study focused on a particular innovation - a series of engineering-focused STEM learning modules called Make-to-Learn Invention Kits, which are currently under development by a team from the University of Virginia, the Smithsonian National Museum of American History, and Princeton University. This series traces the progression of key inventions that transformed modern civilization between 1800 and 1960, such as the electric motor, the telegraph, the telephone, and the radio, which students reinterpret and reinvent using either low-tech tools or advanced manufacturing technologies (Smithsonian Institution, 2015). The primary task of the study was to identify the essential elements of the Invention Kit series and describe those elements in operational terms that can help would-be adopters visualize the various ways these elements might be applied in diverse settings. While pilot implementations are underway, the essential characteristics of the Invention Kits and a vision for their implementation had not yet been precisely documented. To do so, I used a process called Innovation Configuration Mapping developed by Hall and Hord (2013). Rooted in educational change and innovation research, and relying upon qualitative methodology, Innovation Configuration Mapping is a highly iterative process that involves breaking down an innovation into its essential elements. Various implementation adaptations for each element that are observed in the field are then mapped along a continuum from high, medium, and low fidelities to the original intentions of the Invention Kit developers. It is important to note that such maps are not intended to pass judgments on adaptations. In fact, adaptations to the Invention Kits are anticipated and even encouraged. Rather, IC Maps are used to expressly acknowledge that adaptations are inevitable and that tools are needed to chart such changes (Hall & Hord, 2013, p. 57).

This study was intended to serve a number of purposes at a theoretical level, a practical level, and a personal level.

Theoretical Level:

At the theoretical level, this study was intended to help situate the Make-to-Learn Invention Kits in the context of a larger movement to integrate STEM and establish engineering practices and pedagogies in K-12 settings. In doing so, I attempted to identify philosophical and epistemological influences of the Invention Kits, including constructionism and project-based learning, and describe how they shape classroom practices and culture. Some teachers are new to these approaches and are not sure what they look like in practice. This study acknowledged this newness and applied principles and practices of educational change and innovation to help address the challenges faced by those setting out to implement integrated STEM and engineering design with K-12 students.

Practical Level:

At the practical level, this study was intended to document and communicate the Make-to-Learn Invention Kits as an educational innovation. Specifically, I asked the developers to articulate detailed visions of the Invention Kits and their applications in the classroom. These conversations helped produce rich descriptions that may be effectively communicated to potential adopters, advocates of STEM education, and other stakeholders. Classroom observations and interviews with a variety of teachers implementing the Invention Kits were used to document the various ways that the kits were modified in diverse settings and at different stages of implementation. Word pictures were developed and mapped to capture the range of observable elements, practices, and behaviors associated with the Invention Kits implementations. These maps may allow adopters to compare their own implementations of the Invention Kits to the intentions of the developers and to other implementations in different settings. Changes and modifications are inevitable and occasionally desirable – the purpose of this study was not to advocate a "right" way of implementing the Invention Kits. However, descriptions of the vision of the developers and common implementation variations may help teachers, facilitators, and administrators evaluate their progress and identify areas for improvement.

Personal Level:

As an instructional technologist, I have a deep interest in helping teachers innovate and incorporate technologies meaningfully into their curricula. This study allowed me to further explore strategies for communicating and facilitating K-12 engineering and integrated STEM curricula, a field of tremendous innovation. Meanwhile, this study helped me to better understand how different teachers, classrooms, and settings impact implementations of a common curriculum.

Rationale

Several characteristics made the Make-to-Learn Invention Kits a good choice for this kind of study. Foremost among these characteristics is their emphasis on addressing STEM content through engineering. The Invention Kits are also heavily influenced by project-based learning (PBL), a pedagogical approach that is common to many integrated STEM curricula and is well-suited to engineering activities. A final characteristic that made the Make-to-Learn Invention Kits attractive is that they can be adapted to both high-tech and low-tech environments. Some adopters of the Invention Kits were utilizing advanced manufacturing technologies, including 3D printing and laser cutting. As advanced manufacturing technologies become more common in K-12 schools, it is important to document effective strategies for implementing them with students. At the same time, schools lacking these technologies are able to implement the kits using low-tech strategies, which also should be documented. Taken as a whole, the Invention Kits materials were well-situated within the sphere of STEM education and K-12 engineering-integration efforts, which increases the possibility that an Innovation Configuration Map charting the Invention Kits' essential elements and implementation variations in diverse settings may contribute to a more general understanding of how engineering can facilitate STEM learning.

Research Questions

This study addressed the following research questions:

1. What are the critical components of the Make-to-Learn Invention Kits from the perspectives of the developers and facilitators?
2. How do Invention Kit developers and facilitators describe their visions for how the components should be implemented?
3. In practice, how do teachers adapt the Invention Kits to their context? What components of the kits do teachers choose to implement or emphasize? Do the teachers add new components to the kits? If so, what are these additions?

Significance of the Study

An examination of the essential components of engineering-focused learning modules like Make-to-Learn Invention Kits held a number of possible benefits. The Invention Kits are complex and includes multiple technological and pedagogical innovations. Examining how each of these innovations contribute to the kits was a first step toward operationalizing the Invention Kits' essential components, envisioning an ideal implementation of the kits, and communicating the various configurations one might see in diverse settings. This information may benefit current users and potential adopters as they consider how the Invention Kits might be adapted and utilized to match their own needs and settings. The findings of this study may also contribute to the ongoing development and evaluation efforts of the Invention Kit development team, especially as they prepare to disseminate the materials for use outside their core pilot sites. Meanwhile, because the Invention Kits are in many ways representative of an emerging genre of engineering-focused materials, clear descriptions of its salient features may be useful to other groups developing and implementing similar K-12 STEM curricula.

At a practical level, Innovation Configuration Map developed during this study may contribute to the effective implementation of the Make-to-Learn Invention Kits in the following ways:

Clarity

First, the IC Map may help clarify key components of the Invention Kits and their underlying innovations. The Invention Kit series is a complex innovation comprised of other innovations such as digital fabrication, engineering design, and project-based learning, among others. Some of the innovations are technological; others are pedagogical. Clear descriptions of the various parts of this complex curriculum may help developers and facilitators identify areas where instructional and conceptual supports will need to be built into the Invention Kits.

Communication

Second, the IC Map may facilitate adoption by building consensus among stakeholders and establishing a common vocabulary. When stakeholders have different understandings of an innovation, they communicate mixed messages, which leads to confusion and frustration (Hall & Hord, 2013, p. 77). Specifically, the IC Map may:

1. Help developers build consensus about the nature of the project and communicate its vision to STEM advocates and other stakeholders.
2. Help STEM advocates understand the Invention Kits and effectively communicate them to educators around the county.
3. Help school administrators understand the Invention Kits and effectively communicate them to their teachers.
4. Help interested teachers understand the Invention Kits and effectively communicate them to their administrators, colleagues, and students.

Professional Development

Leading up to the implementation of the Make-to-Learn Invention Kits, the IC Map may help facilitators target skills for professional development. After teachers begin using the Invention Kits, the IC map may be used again as a diagnostic tool to guide additional professional development or coaching. Because IC Maps break the innovations into components and plot implementation variations along continua, they can help schools and their facilitators identify areas of strength or weakness so that they can more efficiently allot time and resources to aid improvement.

Teacher Self-Reflection

In the future, it is likely that some teachers will use the Invention Kits in isolation, without support from the developers and without colleagues for "comparing notes." Used as a self-assessment tool, the IC Map may help those teachers focus on the salient components of the Invention Kits and aid self-reflection by providing them with known adaptations of the Invention Kits with which they can compare their own efforts.

Assessment and Program Evaluation

As tools to evaluate the progress and effectiveness of implementations of curricula or innovations, IC Maps can inform decision-making at the classroom and building levels, as well as at the level of development. Pilot implementations of the Invention Kits are currently underway around the country. Common pre-and post-assessments have been developed for each Invention Kit to assess student outcomes related to curricular content knowledge. Without a formal means of documenting the extent and nature of each implementation, it may be difficult to rely on the pre- and post-test data to draw inferences about the effectiveness of the Invention Kits. Observations and interviews with pilot teachers revealed that, even in the pilot phase, there was a tremendous amount of variation in the ways the kits were being implemented. Ultimately, charts of these variations may prove useful to researchers seeking to reveal what specific practices correlate with higher outcomes. Developers could leverage these insights to refine and improve the Invention Kits prior to nationwide dissemination.

An example of an Innovation Configuration Map is depicted in Table 1. This map was derived from Hord et al. (2006) to illustrate how the implementation of a Primary Science Program could be mapped. The innovation (the Primary Science Program) is broken into critical components. Underneath each component, observable variations are plotted. “Variation a” represents the behavior that is closest to the intentions of the developers. Additional variations are plotted to the right of Column “a” to signify increasing levels of dissimilarity to the original intentions. The variations listed in the columns farthest to the right generally represent what the adopter is doing instead of the targeted component.

Overview

In this chapter, I outlined the context and purpose of this study. I stated that, while there is growing interest in providing K-12 students with engineering experiences, many teachers charged with this responsibility have little or no training in engineering education. I also claimed that implementing engineering-focused curricula requires significant changes and innovations in instructional practices that many teachers are not prepared for. Next, I presented the Make-to-Learn Invention Kits as an example of an innovative engineering-focused curricula. I pointed to the assertion by Hall and Hord (2013) that change often occurs modestly or not at all because the implementers do not fully understand the nature of the change and what it looks like in practice. I briefly described Innovation Configuration Mapping, which is presented as a strategy for helping implementers understand and visualize the essential components of an innovation. Finally, I described how developing an Innovation Configuration Map for the Make-to-Learn Invention Kits may benefit stakeholders and potential adopters of the kits in a variety of ways. In the next chapter, I review literature that formed the basis of this study.

Table 1
Innovation Configuration Map for the Implementation of a Primary Science Program

Component 1: Uses PSP [Primary Science Program] materials (PSP texts, PSP supplemental materials, teacher created materials, other materials)					
Variation a	Variation b	Variation c	Variation d	Variation e	
Uses PSP texts and PSP supplemental materials in the classroom and laboratory	Uses PSP texts only in the classroom and the laboratory; does not use PSP supplemental materials at all	Uses PSP texts and materials he or she created in the laboratory and the classroom	Teacher uses old textbook and materials he or she created	Teacher uses only materials he or she created	
Component 2: Spends time on science (daily, weekly)					
Variation a	Variation b	Variation c	Variation d	Variation e	Variation f
Teaches science daily	Teaches science 2-4 times a week	Teaches science once a week but in a long block of time	Teaches science once a week	Teaches science less than once a week but teaches science on a regular basis; for example, every 2 weeks	Teaches science only occasionally when there is time
Component 3: Group students for laboratory activities (small groups, individually, large groups)					
Variation a	Variation b	Variation c	Variation d	Variation e	
Groups students individually to conduct experiments	Groups students in small groups of 3-4; students take turns conducting experiments	Groups students in larger groups of 6-8; students take turns conducting experiments	Selects certain students to conduct experiments while others watch	Teacher conducts experiments while students watch as a large group	

Note: Adapted from Hord et al. (2006) Measuring Implementations in Schools: Innovation Configurations, p. 19.

CHAPTER 2

Literature Review

In this chapter, I review literature that forms the conceptual framework for this study. This review is divided into three parts. In Part I, I present literature that defines integrated STEM and presents it as an educational goal. I also review the argument for utilizing engineering as a pedagogical strategy to integrate STEM domains and describe why engineering is an innovation for most K-12 teachers. In Part II, I review literature relating to innovations, how they are constructed and communicated, and barriers to their adoption in education. The Concerns-Based Adoption Model is presented as a framework for understanding the adoption of innovations, and Innovation Configuration Mapping is described as a tool for both facilitating and documenting the process. In Part III, I review content-based and pedagogical concepts that underlie the Make-to-Learn Invention Kits that will be discussed during the IC Mapping process, including constructionism, the engineering design process, and project-based learning.

Part I

Integrated STEM

Despite being commonplace in education vernacular today, there is widespread confusion and disagreement about STEM. (Kelley & Knowles, 2016; Sanders, 2008). Some programs view STEM as four clearly delineated subjects while others use the term STEM to refer to a holistic approach to the subjects (Committee on K-12 Engineering Education, 2009). In this study, I adopt the latter view. The term “integrated STEM” has emerged in the literature to underscore the notion that STEM occurs at the intersection of the four subjects. Beyond the broad notion that STEM represents a blending of the four subjects, a precise definition of integrated STEM is elusive. In STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research, the National Academy of Engineers writes that:

> Developing a precise definition of integrated STEM education proved to be a challenge for the committee because of the multiple ways such integration can occur. It may include different combinations of the STEM disciplines, emphasize one discipline more than another, be presented in a formal or informal setting, and involve a range of pedagogical strategies (p. 23).

In addition, integration can occur over varying periods of time. For instance, integration can occur during a single classroom activity or it may extend over the course of an entire unit or curriculum. Integration can also occur at different social levels. For example, integration may occur between a teacher and a single student, between two peers, or among a classroom, grade level, school, or entire district (National Academy of Engineering & National Research Council, 2014).

Despite these variations, most sources describe integrated STEM curricula using similar ideas and language. Common characteristics include:

- The teaching of two or more of the STEM subjects concurrently (Heil, Pearson, & Burger, 2013; National Academy of Engineering & National Research Council, 2014; Sanders, 2008).
- The teaching of practices, not just facts (National Research Council, 2010).

- A focus on integrating processes used in each of the STEM disciplines, such as the scientific method or the engineering design process (Heil et al., 2013; Wells, 2016).
- The utilization of learner-centered pedagogical approaches such as project-, problem-, inquiry-, or design-based learning (Heil et al., 2013) grounded in constructivism (Brophy et al., 2008; Sanders, 2008).
- An attempt to establish authenticity through real-world connections (Heil et al., 2013; National Academy of Engineering & National Research Council, 2014; National Research Council, 2012).
- The coaching of students to identify problems and develop or build solutions that require multi-disciplinary skills and content (Heil et al., 2013; Kelley & Knowles, 2016).
- A reliance on social interaction and collaboration (Committee on K-12 Engineering Education, 2009; National Academy of Engineering & National Research Council, 2014; National Research Council, 2012; Smith, Sheppard, Johnson, & Johnson, 2005).

Each of these characteristics can be identified in the Make-to-Learn Invention Kits.

Integrated STEM is presented as an antidote to the effects of traditional, siloed approaches to STEM education, which lead students to believe that each discipline stands alone. The results of this view can be diminished student interest and poor performance (Moore et al., 2014; National Research Council, 2010). Traditional approaches leave students “with just fragments of knowledge and little sense of the creative achievements of science, its inherent logic and consistency, and its universality” (National Research

Council, 2010). Students leave school with a list of facts “a mile wide and an inch deep” but have little understanding of how the facts are connected or applied (National Research Council, 2010). The practices and processes used by professionals in each discipline are largely ignored (National Research Council, 2010, 2012). Meanwhile, students miss opportunities to develop important technological and scientific literacies that can help them in the future (Committee on K-12 Engineering Education, 2009).

Often, the benefits of integrated STEM education are described in economic, political, or geo-political terms. For example, real-world connections established through integrated STEM education add relevance that increases “interest, achievement, and persistence” among students. These engaged students will be more likely to pursue STEM-related careers in the future (National Academy of Engineering & National Research Council, 2014). Advocates argue that a large, STEM-ready workforce will help ensure that the US remains competitive in the global economy (Committee on K-12 Engineering Education, 2009). Meanwhile, the country will be better equipped to meet global challenges such as energy production, clean water supplies, and climate change (National Research Council, 2012). STEM literacy may also contribute to national security, both militarily and in terms of cyber security (National Research Council, 2010). Tackling these complex challenges will require not only content knowledge and discipline-specific skills, but will also require collaborative skills, a hallmark of integrated STEM education (National Academy of Engineering & National Research Council, 2014).

Other arguments for integrated STEM focus on its potential to improve society and enrich lives. Advocates project that US citizens educated in STEM will gain the skills to “engage in public discussions on science-related issues, to be critical consumers of scientific information related to their everyday lives” (National Research Council, 2012). A STEM-educated citizenry may be able to apply their STEM-knowledge to cast more informed votes and make wiser purchases (National Academy of Engineering & National Research Council, 2014). They may come to “appreciate that science and the current scientific understanding of the world are the result of many hundreds of years of creative human endeavor” (National Research Council, 2012).

Another category of arguments for integrated STEM points to cognitive benefits. The National Research Council (2014) reports that:

> Integration may be effective because basic qualities of cognition favor connected concepts over unconnected concepts so they are better organized for future retrieval and meaning making. It is these connected knowledge structures that can support learners’ ability to transfer understanding and competencies to new or unfamiliar situations. In addition, being able to represent the same concept within and across disciplines in multiple ways—for example, visually, in physical form, and in writing—can facilitate learning, research shows. (p. 78)

Sanders (2008) cites work from Brunning, Schraw, Norby, and Ronning (2004), which lists the following cognitive themes that emerge in integrative STEM education:

- Learning is a constructive, not a receptive, process.
- Motivation and beliefs are integral to cognition.
- Social interaction is fundamental to cognitive development.
- Knowledge, strategies, and expertise are contextual

As these passages illustrate, learning is an active process that depends on social interactions, personal engagement, and meaningful contexts that enable the learner to make connections among concepts.

Integrating STEM through Engineering – Rationale

A growing number of STEM educators and academics argue that the key to integrating STEM is a focus on engineering. The Committee on K-12 Engineering Education (2009) asserts that, because engineering depends on the application of science, math, and technology, it is a natural "catalyst" to integrate the STEM subjects. Indeed, engineers serve as compelling examples of why students might want to be well-rounded in STEM, and in other subjects.

> Engineers use science and mathematics in their work, and scientists and mathematicians use the products of engineering—technology—in theirs. Engineers use mathematics to describe and analyze data and, as noted, to develop models for evaluating design solutions. Engineers must also be knowledgeable about science—typically physics, biology, or chemistry—that is relevant to the problem they are engaged in solving. Sometimes, research conducted by engineers results in new scientific discoveries. (National Research Council, 2010, p. 7)

In this way, engineers epitomize integration of the STEM disciplines.

Some definitions of integrated STEM education explicitly identify engineering as a strategy for integrating STEM content (Roehrig et al., 2012; Sanders, 2008; Wells, 2016). For instance, Wells and Ernst (2012) define integrated STEM as "the application of technological/engineering design-based pedagogical approaches to intentionally teach content and practices of science and mathematics education through the content and practices of technology/engineering education" (Wells & Ernst, 2012/2015). In reviewing the arguments for integrating STEM education through engineering, Roehrig et al. (2012) identified three primary rationales:

1. engineering provides a real-world context for learning mathematics and science;
2. engineering design tasks provide a context for developing problem-solving skills; and
3. engineering design tasks are complex, and as such, promote the development of communication skills and teamwork. (p.33)

Again, engineering provides a meaningful context to learn, combine, and practice the STEM content and disciplines.

Brophy et al. (2008) assert that engineering is effective as an integrative strategy because it appeals to our natural desire to build things and understand how things work. Students practicing engineering can develop deep conceptual understandings of STEM, while satisfying their natural curiosities. Sanders (2008) and Wells (2016) make similar assertions that engineering education is a powerful integrative strategy because students that are engaged with a problem they want to solve approach unknown STEM content and skills with a genuine "need to know," which provides intrinsic motivation.

Integrating STEM through Engineering – Implementation Challenges

The Committee on K-12 Engineering Education (2009) describes three methods that can be used to bring engineering education to students – through a fully-integrated STEM education (a STEM school, for instance), as a stand-alone course, or as an ad-hoc infusion into existing science, technology, and math curricula. Currently, most users of the Invention Kits are using them in the latter fashion. The Committee on K-12 Engineering Education (2009) describes this option as the least complicated and most common approach. “The main requirements would be (1) willingness on the part of teachers and (2) access to instructional materials. Ideally, teachers would also have a modicum of engineering pedagogical content knowledge to deliver the new material effectively” (p.11). On this latter point, a challenge exists because the task of infusing engineering into existing curricula often falls to teachers that have little or no experience with engineering or integrated STEM pedagogy (Heil et al., 2013). This lack of experience is problematic since the expertise of the educator is often identified as the key factor in determining successful STEM integration (National Academy of Engineering & National Research Council, 2014). According to the Committee on K-12 Engineering Education (2009), few teachers have received formal professional development training to teach engineering-related coursework (p. 23). Instead, most teachers tasked with integrating STEM are certified to teacher either science, technology, or math as isolated subjects. And while they may be skilled end-users of the other STEM disciplines, they do not necessarily have the skills to teach them. Aware of their lack of expertise, those educators are also likely to lack self-efficacy, another crucial factor in determining successful STEM integration (National Academy of Engineering & National Research Council, 2014). Roehrig et al. (2012) point out that teachers that are uncomfortable teaching certain subjects tend to gloss over those subjects and focus on the content that they know well.

To be successful, these teachers require guidance. However, “few general guidelines or models exist for teachers to follow regarding how to teach using STEM integration approaches in their classrooms" (Roehrig et al., 2012). Among the models that do exist, there are wide variations in what concepts and skills are emphasized. According to the Committee on K-12 Engineering Education (2009), this lack of consistency "may be the result, at least in part, of the absence of a clear description of which engineering knowledge, skills, and habits of mind are most important, how they relate to and build on one another, and how and when (i.e., at what age) they should be introduced to students" (Committee on K-12 Engineering Education, 2009, p. 24).

Established learning standards and assessments might clarify what components are essential to engineering, but such standards have not yet been fully developed (Committee on K-12 Engineering Education, 2009). In 2010, the National Academy of Engineering concluded that stakeholders first need to develop a document that describes "the core ideas – concepts, skills, and dispositions – of engineering that are appropriate for K-12 students" (p. 37). This document would allow educators to either actively "infuse" the learning goals of engineering into the existing standards of the other disciplines or to retroactively "map" the connections between engineering concepts and existing standards (National Research Council, 2010). Groves et al. (2014) echo the need for clear documentation of engineering concepts and practices, stating, "To allow engineering to be taught effectively across the K-12 education spectrum, particularly by teachers who themselves may not have studied or practiced engineering, it is critical to articulate the important elements of engineering and to provide specific assessment criteria that can be used to evaluate student proficiency with each element" (p. 2). Since then, engineering design has been included in the 2013 Next Generation Science Standards (NGSS). However, Appendix I of that document clarifies that "the "NGSS do not put forward a full set of standards for engineering education, but rather include only the practices and ideas about engineering design that are considered necessary for literate citizens" (NGSS Lead States, 2013, p. 104).

Efforts to support the implementation and diffusion of engineering-focused STEM units like the Invention Kits must account for the factors outlined in this section. Most adopters will lack experience teaching engineering design. Furthermore, they will attempt to implement the curriculum with few standards, models, and other resources to guide them. The Innovation Configurations Map developed in this study may help these teachers fill in some of these gaps by distilling the essential components of the Invention Kits and clearly describing the behaviors associated with each. A more detailed description of Innovation Configuration Maps and how they facilitate the adoption of educational innovations follows in the next section.

Part II

Innovation and Change

The Change Communication Model

Since innovations are communicated from person to person, the standard communication model is foundational for concepts relating to educational change and innovation. According to this model, messages are communicated from sender to receiver, through an environment, using a medium. Messages are not always communicated successfully. Various forms of interference occasionally come into play, which may disrupt the medium or distort the message Meanwhile, different receivers might interpret the same message in different ways. Some types of media are more effective for communicating messages, depending upon environmental factors and receiver characteristics (Ellsworth, 2000).

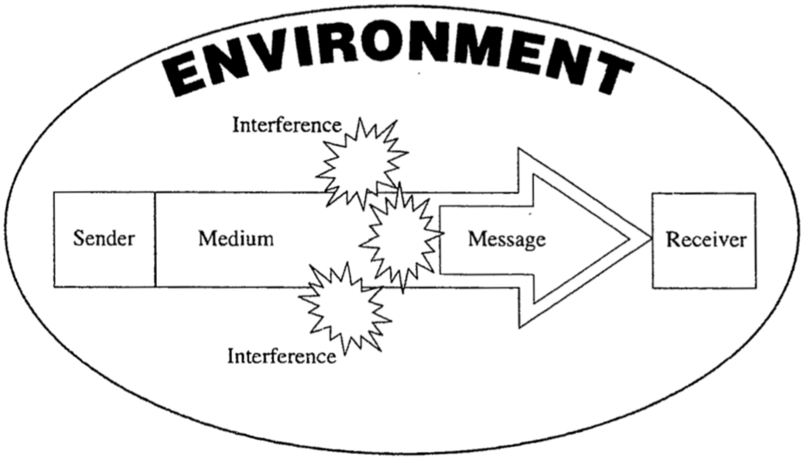


Figure 3. The Communication Model. From Surviving Change: A Survey of Educational Change Models (p. 25) by James B. Ellsworth, 2000, Syracuse, N.Y.: Clearinghouse on Information & Technology, Syracuse University. Copyright 2000 by James B. Ellsworth. Reprinted with permission.

The concept of change is a variation of the standard communication model (Ellsworth, 2000; Rogers, 2003). In the change communication model, the term “innovation” takes the place of “message,” the sender is referred to as a “change agent,” and the receiver is labeled a “potential adopter.” The innovation is communicated by means of a “change process” through a “change environment.” The risk of interference remains, though, in this model, it comes in the form of “resistance.” This communication, while it may appear linear and one-directional, should be fluid; the change agent and the potential adopter must share information back and forth as they work toward a mutual understanding (Ellsworth, 2000; Rogers, 2003). In many scenarios, back-and-forth communication does not change the message itself – rather, it is used to ascertain whether the message was properly conveyed and received. However, back-and-forth communication opens up the possibility that the receiver can influence and shape the message as he communicates back to the sender – in essence, the receiver and the sender can switch roles.

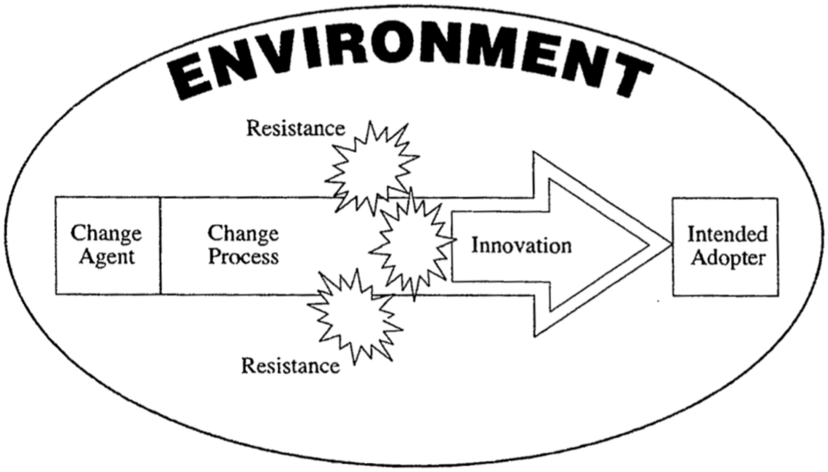


Figure 4. The Change Communication Model. From Surviving Change: A Survey of Educational Change Models (p. 27) by James B. Ellsworth, 2000, Syracuse, N.Y.: Clearinghouse on Information & Technology, Syracuse University. Copyright 2000 by James B. Ellsworth. Reprinted with permission.

In his seminal work about change and innovations, The Diffusion of Innovations (2003), Rogers refers to this process as "diffusion" and divides it into four parts. "Diffusion is the process in which 1) an innovation is communicated through 2) certain channels over 3) time among the members of a 4) social system. It is a special type of communication, in that the messages are concerned with new ideas" (p. 6). By nature, a new idea comes with some degree of uncertainty; either because the idea is vaguely understood or because its potential impact cannot be predicted. Rogers defines uncertainty as "the degree to which a number of alternatives are perceived with respect to the occurrence of an event and the relative probability of these alternatives" (p. 6). Feelings of uncertainty, while natural and unavoidable, can forestall the consideration of a new idea. The potential adopter may wonder how effectively the new idea will solve a problem, or the potential adopter may worry that adopting the new idea will come with unintended consequences (p. 14). Sufficient information about the new idea can help reduce this uncertainty and facilitate a decision to accept or reject the idea (p. 6). This concept regarding the role of information to facilitate adoption is central to the purpose of this study. As outlined in Chapter 1, Innovation Configuration Maps can help clarify the key components of the Make-to-Learn Invention Kits so that the innovation (the Invention Kits) can be more effectively communicated to teachers and other stakeholders. To use the terminology of the communication model, an IC Map serves as a medium to communicate the message of the Invention Kits. Furthermore, because IC Maps use succinct language, they can help reduce interference and ensure mutual understanding.

Innovations

Rogers (2003) defines an innovation as “an idea, practice, or object that is perceived as new by an individual or other unit of adoption" (p. 12). Perception is an important part of this definition. The innovation does not need to be literally new – the idea at hand might be quite old, and perhaps the potential adopter has been aware of it for a long time. However, if the potential adopter lacks substantive knowledge of the idea and has not yet decided to adopt or reject it, the idea remains an innovation, at least to that person (p.12). This distinction is particularly relevant to this study because, while most teachers are probably aware of pedagogical strategies such as inquiry-based learning, few have implemented such strategies themselves. For many teachers, inquiry-based teaching strategies (and curricula that are built upon them) remain innovations.

Rogers describes five key attributes of innovations that impact their diffusion: relative advantage, compatibility, complexity, trialability, and observability.

1. Relative advantage is the degree to which an innovation is perceived as better than the idea it supersedes.
2. Compatibility is the degree to which an innovation is perceived as being consistent with the existing values, past experiences, and needs of potential adopters.
3. Complexity is the degree to which an innovation is perceived as difficult to understand and use.
4. Trialability is the degree to which an innovation may be experimented with on a limited basis.
5. Observability is the degree to which the results of an innovation are visible to others. (p. 16)

While the product of this study, an Innovation Configuration Map, can be used to address each of these attributes, this study focused on its utility for addressing the complexity of an innovation. This was an important focus because, as Rogers states, “the complexity of an innovation, as perceived by members of a social system, is negatively related to its rate of adoption” (p. 257). If teachers perceive that Invention Kits are too complex to understand or use, they will likely reject them. Considering the myriad of terms and technical language associated with integrated STEM and engineering, it is easy to imagine how the Invention Kits could be construed in this way, especially by teachers that are new to this type of teaching and learning. However, while acknowledging that the Invention Kits have numerous components, the Innovation Configuration Map may reduce interference and help teachers understand and focus on the most pertinent features of the innovation.

Technology Clusters

Occasionally, perceptions of complexity are compounded because what is viewed as a single innovation is actually a collection of coordinated, mutually-reinforcing innovations (Ellsworth, 2000). Rogers (2003) refers to this phenomenon as a "technology cluster." "A technology cluster," he writes, "consists of one or more distinguishable elements of technology that are perceived as being closely interrelated" (p. 14). It is important to note that, in this context, the terms "innovation" and "technology" are used as synonyms. He points out that technology clusters can pose a significant conceptual challenge when attempting to determine where one innovation stops and another begins (p. 14). Meanwhile, methodological challenges arise when one seeks to study an innovation or facilitate its adoption and implementation. This problem is common in educational settings, especially when dealing with emerging technologies.

> Successful infusion of such an innovation will generally require accompanying innovations pairing it with appropriate pedagogy, "smart" classroom layouts, power and communication infrastructure improvements, and thorough teacher training with ongoing support. Furthermore, it is frequently not sufficient that these innovations merely be complementary and undertaken concurrently. Active coordination between interdependent efforts is required. (Ellsworth, 2000, p. 32)

In this study, I approached the Make-to-Learn Invention Kits as a technology cluster. This cluster includes a complex mix of engineering pedagogies and practices, project-based learning approaches, and various technological tools and techniques.

Communication Channels

Rogers (2003) states that "the essence of the diffusion process is the information exchange [emphasis added] through which one individual communicates a new idea to one or several others" (p. 18). This information exchange occurs between someone who has knowledge and experience with an innovation to someone who does not. Rogers explains that communication occurs most naturally among individuals or groups that have similar characteristics. Homophilous is the term he uses, meaning "the degree to which two or more individuals who interact and similar in certain attributes, such as beliefs, education, socioeconomic status, and the like" (p. 19). Unfortunately, the opposite is true of communication that occurs between dissimilar (heterophilous) individuals or groups. Rogers describes a change agent that is more technically skilled than the potential adopters he or she is attempting to communicate with. The differences between them "leads to ineffective communication as the two individuals do not speak the same language" (p. 19).

This is an important point to remember when communicating integrated STEM curricula, such as the Invention Kit series. The concepts and terminology of engineering design and project-based learning, which curriculum developers and change agents might perceive as simple to understand, might confuse or alienate teachers who are new to integrated STEM or any of its various components.

The Innovation-Decision Process

During the course of the innovation-decision process, an individual gains his or her first knowledge of an innovation, forms an attitude toward the innovation, decides to adopt it (or reject it), implements and uses the innovation, and seeks confirmation for his or her decision. Embedded in this process are five main steps: 1) knowledge, 2) persuasion, 3) decision, 4) implementation, and 5) confirmation.

1. Knowledge is gained when an individual (or other decision-making unit) learns of the innovation's existence and gains some understanding of how it functions.
2. Persuasion takes place when the individual forms a favorable or unfavorable attitude toward the innovation.
3. Decision occurs when an individual engages in activities that lead to a choice to adopt or reject the innovation.
4. Implementation takes place when an individual puts an innovation into use.
5. Confirmation occurs when an individual seeks reinforcement of an innovation-decision that has already been made, but he or she may reverse this previous decision if exposed to conflicting messages about the innovation.

One of the primary purposes of this study was to develop a tool (in the form of an Innovation Configuration Map) that has utility at each stage of the Innovation-Decision Process. Therefore, the IC Map was developed with multiple audiences in mind, including:

1. Teachers (or other stakeholders) who have no knowledge of the Invention Kits;
2. Teachers who are aware of the Invention Kits and are considering whether to use them;
3. Teachers who have decided to use the Invention Kits and are preparing to implement them; and
4. Teachers who are already implementing the Invention Kits.

In order to accommodate these audiences, the IC Map needed to be crafted as both a communication tool and an assessment tool. Used as a tool to communicate the core ideas of the Invention Kits, the IC Map may influence the Knowledge, Persuasion, and Decision stages of the Innovation-Decision Process. Used as a tool for self-reflection and assessment, the IC Map can address the Implementation and Confirmation stages.

Types of Knowledge

Rogers describes three types of knowledge that were considered when gathering information that can be used to communicate the Make-to-Learn Invention Kits – awareness-knowledge, how-to knowledge, and principles-knowledge. Awareness-knowledge comes when one learns that an innovation exists. At a glance, an Innovation Configuration Map should convey a basic understanding of the nature of the innovation. Having become aware of the innovation, a person may choose to seek how-to knowledge, which consists of the information that is necessary to use an innovation properly. By examining the details of the IC Map more closely, he or she should be able to identify this information as well. The amount of how-to knowledge that is needed will vary depending upon the complexity of the innovation – greater complexity demands greater how-to knowledge. It is important to note that a lack of how-to knowledge generally results in the rejection or discontinuance of an innovation (p. 173). Recognizing that the Invention Kits are complex, it was especially important to document the many things that teachers need to be able to do to implement the Invention Kits effectively. As will be explained in the detailed description of Innovation Configuration Maps that follows later in this chapter, how-to knowledge was operationalized as word pictures.

A third type of knowledge – principles-knowledge – comes from understanding the underlying principles that make an innovation work. Rogers writes that, "It is usually possible to adopt an innovation without principles-knowledge, but the danger of misusing a new idea is greater and discontinuance may result" (p. 173). An individual with adequate principles-knowledge is better equipped to assess whether he or she is using an innovation effectively and has the conceptual understanding needed to determine what adjustments might be necessary.

How-to knowledge and principles-knowledge are essential to the successful implementation of complex innovations. Nonetheless, these types of knowledge often are not adequately fostered in potential adopters. Rogers explains:

> Most change agents concentrate their efforts in creating awareness-knowledge. Change agents could perhaps display their most distinctive and important role in the innovation-decision process if they concentrated on how-to knowledge, which is probably most essential to clients in their trial of an innovation at the decision stage in the innovation-decision process. Most change agents perceive that creation of principles-knowledge is outside the purview of their responsibilities and is a more appropriate task for formal education. But when such understanding of the principles underlying innovation is lacking, the change agents' long-run task is more difficult (p. 173).

Teachers seeking to implement the complex innovation targeted in this study – a series of engineering-focused STEM learning modules – will need significant how-to knowledge and principles-knowledge. For example, special classroom management strategies can be considered how-to knowledge. Meanwhile, iterative design can be categorized as principles-knowledge. Developing language to communicate both types of knowledge about the Invention Kits was a central focus of this study. Therefore, while documenting the essential components of the Invention Kits, I also considered what type of knowledge each component represents. Doing so helped ensure that the final Innovation Configuration Map addresses both the how-to knowledge and the principles knowledge teachers and other stakeholders need to successfully utilize the Invention Kits.

Re-invention

Rogers' concept of reinvention was useful in developing the Innovation Configuration Maps as an assessment tool. Innovations rarely spread as exact copies of the original. The term "re-invention" is used to signify the "degree to which an innovation is changed or modified by user in the process of its adoption and implementation" (p. 180). Re-invention occurs naturally and is not necessarily a bad thing. Higher rates of re-invention correlate with faster adoption rates and higher degrees of sustainability (p. 183). These correlations likely have much to do with the fact that potential adopters value the flexibility to re-invent an innovation to satisfy their particular needs, preferences, settings, or constituents (p. 185).

Rogers describes a range of factors that contribute to the rate and degree of re-invention. I will focus here on only a few that have particular relevance to this study. First, innovations that are complex or difficult to understand are often re-invented to be simpler. It is important to note that such simplifications often reflect misconceptions of the original innovation (p. 186). Second, re-invention sometimes occurs because adopters lack detailed knowledge of the innovation. Such re-invention is particularly common when new adopters have little contact with change agents or previous adopters (p. 186).

Third, re-invention is common when the innovation has a broad range of possible applications. This is especially common when the innovation is actually a loosely-bundled innovation cluster. An innovation that consists of a tightly-bundled cluster of highly-interdependent elements is less likely to be re-invented. Finally, re-invention becomes more common later in the adoption process as users gain more experience with the innovation and begin to experiment with changes (p. 186).

Classroom observations and interviews conducted during the initial exploratory pilot study of the Invention Kits revealed a significant amount of reinvention among the participating teachers. In this study, observed reinventions of the Invention Kits were documented as “variations” – a construct detailed in the next section.

The Concerns-Based Adoption Model (CBAM)

With their Concerns-Based Adoption Model (CBAM), Hall and Hord (2013) build upon Rogers’s ideas and introduce a set of practical strategies designed to facilitate educational change and innovation, including innovative pedagogical approaches and curricula. CBAM consists of three constructs, each accompanied by a diagnostic tool of the same name. The first construct, the Stages of Concern (SoC), addresses the feelings, perceptions, and worries that people experience when they encounter, adopt, and implement an innovation. In the context of education, a teacher will generally progress from worrying about how an innovation will impact him or her personally, to concerns about task management, to concerns about the impact of the innovation on their students and others (Hall, 2013; Hall, Wallace, & Dosset, 1973). The Levels of Use (LoU) describe the different behavioral profiles as individuals progress from non-users of an innovation, to novice users, to advanced users. Again, in the context of education, a teacher may progress from having no interest in an innovation (Level of Use 0), to orienting and preparing to use the innovation (Levels of Use I and II), to struggling through initial attempts and establishing routine competence (Levels of Use III and IVA), to making refinements and branching out (Levels IVB, V, and VI) (Hall, 2013; Horsley & Loucks-Horsley, 1998). The third construct, Innovation Configurations (IC), stems from the recognition that implementations of an innovation can vary considerably from one setting to the next. The related diagnostic tool, an Innovation Configuration Map (ICM), is intended to capture the essential elements of an innovation and describe the range of observable variations of each element in the field (Hall & George, 2000). This study focused on this latter construct. The reason for this focus will be addressed in the next section.

CBAM – Principles of Change

Before describing Innovation Configurations (IC) and Innovation Configuration Maps (IC Maps) in more detail, it is important to understand some of the underlying principles and concepts of the Concerns-Based Adoption Model that are particularly relevant to this study. First, Hall and Hord (2013) explain that "a fundamental understanding required for the adoption and implementation of any change, or innovation, is that those who will be involved with it, whether using it or supporting others in using it, must learn what the new "way" is, and how to use it appropriately and productively (p. 22). Second, change is a process, not an event. It generally takes several years for teachers to learn how to successfully implement an innovation. The third and fourth principles covered here are that successful implementations depend upon interventions, and that appropriate interventions reduce resistance to change. These principles echo a number of assumptions about change that were described earlier in this chapter. For instance, change is a process of communicating knowledge that takes time and is often beset by miscommunication and resistance. Furthermore, certain tools and strategies can help reduce these barriers. In CBAM, an application of one of these approaches is dubbed an “intervention.”

Hall and Hord (2013) define interventions as "any action or event that influences the individual(s) involved or expected to be involved in the process of change” (p.27). Interventions can take many forms, varying in size, scope, and formality – they include informal conversations, professional development workshops, and the sharing of materials and resources. These interventions serve a variety of functions. One function that is key to this study is the development, articulation, and communication of a shared vision of the intended change. Hall and Hord (2013) explain that “many change efforts fail because the participants do not share mental images or pictures of what classroom and/or school practice will look like when and identified changes implemented to a high quality. Picturing the change in operation provides the target for beginning the change journey” (p. 31). Other intervention functions include planning and providing resources, determining professional learning needs, and checking progress of implementation efforts. All of these functions can be addressed through the development of one particular form of intervention, the Innovation Configuration Map.

Innovation Configurations

Efforts to innovate in education are often hampered when those involved in implementing the change do not fully understand the innovation and how it is supposed to be enacted. “When there is such confusion, principals and other facilitators may give conflicting signals, and teachers will create their own versions of the change as they try to understand and use the materials and/or processes that have been advocated" (p. 56). In the end, while a group of teachers might claim to be implementing a single innovation, classroom observations and conversations with the teachers often reveal that each individual conceptualizes and enacts the innovation quite differently.

The construct of Innovation Configurations (IC) was developed as part of the Concerns-Based Adoption Model (CBAM) in recognition of the fact that implementation variations are inevitable. In the CBAM model, these variations are referred to as configurations. Recognizing that variations of an innovation will occur primes one to pay close attention to these modifications and react accordingly. For instance, it is reasonable to expect that some changes will be more desirable (or tolerable) than others depending on how they impact outcomes. Some configurations might correlate with greater student achievement, for example, while others may not. Change agents seeking to facilitate the adoption of educational innovations would be likely to encourage configurations that correlate with positive outcomes, while discouraging those that may be detrimental. In order to do this, however, Hall and Hord (2013) assert that stakeholders need a systematic strategy for describing the nature and degree of implementation variations. The process of Innovation Configuration Mapping was developed to meet this need.

Innovation Configuration Maps

An Innovation Configuration Map has two parts: (1) the idealized images of the innovation created by its developers and (2) the various operational forms of the change that can be observed when it is being implemented in the field. Generally, implementations of an innovation range from versions that are very close to what the developers envisioned to versions that are barely recognizable. Hall and Hord (2013) use a map as a metaphor to describe this phenomenon.

> The concept of a map was deliberately chosen for this work because, just as a roadmap shows different ways for getting from one place to another, so does an Innovation Configuration Map. A highway map will picture interstate highways, U.S. highways, and country roads. These are alternative routes, all of which make it possible to complete the trip. The IC Map does the same thing for change facilitators and users of innovations by identifying the major Components of an innovation and then describing the observable Variations of each component. The IC Map is composed of "word picture" descriptions of the different possible operational forms of an innovation or change. (Hall & Hord, 2013, p. 60).

The basic unit of an IC Map is the “component.” Components represent the core operational aspects of the innovation. “Critical components” include the core components that must present if the innovation is be considered implemented. “Related components” are not essential to the innovation but are recommended by the developer (Hord, Stiegelbauer, Hall, & George, 2006). These components can be operationalized in different ways. Each of these ways is called a “variation” (Hall & George, 2000). For each component, mapping begins by developing a word picture description that captures what the innovation developers envision to be its “ideal” operational form. It is important that this word picture description is visual and action oriented. As Hall and Hord (2013) explain, “the better the word pictures, the easier it will be for teachers, principals, program evaluators, and others to see what successful use of the innovation entails. This cannot be overstated" (p. 61). The developer that provides the "ideal" vision is the person, team, or organization that created or developed the innovation. Often, the developers of an educational innovation are district administrators or curriculum teams, university researchers, publishing companies, or corporate or non-profit groups (Hord et al., 2006). Starting with the ideal, a series of additional word picture descriptions are developed to illustrate additional operational variations. These variations are plotted along a continuum that reflects degrees of similarity to the idealized form. Typically, an innovation is broken into eight to fifteen components, with four to six variations listed for each component. At the top level, components can be organized by topic or theme into "clusters" (Heck, 1981). In structure, an IC map resembles a rubric. However, "unlike with rubrics, as the amount of the ideal tapers off across the variations, the descriptions do not just diminish to 0. In an IC map there is a concomitant building up of what the implementer is doing instead of the ideal" (Hall, 2013, p. 15). If desired, "fidelity lines" can be added to mark when variations veer so far from what was intended that they become something else altogether (Hall, 2010). Upon completion, the IC Map can convey a clear message of what the innovation "should" be, what it could be, and what is not.

Developing IC Maps

Developing an IC Map is an interactive process (Hall & Hord, 2013). Ideally, a team of three to seven key people with some knowledge of the innovation work together over the course of five or six days to create a first draft. A team environment is needed introduce different perspectives, debate the inclusion of components and variations, and reach consensus. Key personnel might include teachers, facilitators, principals, district personnel, and innovation experts. While the innovation developers are consulted throughout the process, they are not typically included as core members of the IC Mapping team (Hall & George, 2000).

Hord et al. (2006) describe four key steps in the IC Mapping process. These are:

Step 1: Identifying Innovation Components. The first step requires the identification of the core components of the innovation. This process generally begins by reviewing all the descriptive material and other media relating to the innovation. When possible, the developers of the innovation and change facilitators are also interviewed. During these encounters, the interviewee might ask questions such as:

1. Would you describe for me [name of innovation]?
2. What would I see in a classroom where the innovation is in use?
3. What do you consider the most essential components of the innovation? (Hord et al., 2006, p. 13)

The interviewee might also ask what kinds of modifications or variations the developers or facilitators anticipate that users might make to innovation. The goal is to establish basic components, dimensions, and variations that can be discussed while developing a first draft of the IC Map. These conversations will also partially reveal the innovation developers' vision of an ideal implementation.

Step 2: Identifying Additional Components and Variations. The next step is to observe the innovation in use and interview some of the individuals who are implementing the innovation. Ideally, the people interviewed should represent a wide range of implementers in diverse settings in order to capture a greater number of variations. Efforts should be made to observe and interview implementers that closely adhere to the vision of the developers as well as those who significantly depart from the developers' guidelines. When interviewing teachers who are implementing the innovation, the following questions may be asked:

1. Would you describe the innovation for me?
2. What would I see if I visited your classroom while you were using the innovation?
3. What would you be doing in the classroom?
4. What would your students be doing? (Hord et al., 2006, p. 18)

Notice that each of these questions is worded to elicit descriptions of various behaviors that accompany the innovation. This kind of information is necessary for developing the operational word pictures in the IC Map. By the end of Step 2, the list of components and variations will have expanded and an IC Map will begin taking shape.

Step 3: Refining the IC Map. During Step 3, it is helpful to return to the developer of the innovation to share the interview and observation data collected during Step 2. It is likely that the data include discussion points that may not have come up in the first meeting. The interviewee can also ask for the developer's opinions of the variations that were observed. Prior to this meeting, it can be useful to create a draft of the IC Map for one's own reference. This draft can help guide the conversation through each of the core components and variations noted thus far. During Step 3, the developers of the IC Map should aim to:

1. standardize the IC Map's format, including repetition of the same dimension within each variation in a single component and utilization of the same subject across the map;

2. use language appropriate for the user;
3. distinguish between critical and related components; and
4. note any differences in variations due to student characteristics – that is, variations for a first grader may be different from variations for a second grader. (Hord et al., 2006, p. 18)

Step 4: Testing and Finalizing the IC Map. Once an initial draft of the IC Map has been completed, it should be tested by using it to observe and interview a wide range of implementers, including those who are perceived to be using the innovation well, those who may be using it poorly, and even those who have not begun using it at all. It is common to discover that the IC Map works well in some settings and is ill-suited for others. Common problems with the Map often include:

> 1. The innovation implementers might use terminology different from the developer or facilitator to describe the innovation. If the map creator has relied solely on interviewing to gather information about innovation implementation, he or she may need to modify the interview questions, the observation guide, and the IC Map to avoid any miscommunication between the interviewer and the user.
> 2. When observing or interviewing additional implementers, variations that are not on the draft IC Map may emerge. The Map creator should work with the innovation developer to determine whether it is appropriate to add additional variations of the IC Map. (Hord et al., 2006, pp. 19-20)

Information gathered during testing should be used to develop a revised draft. Afterward, another round of observations and interviews should be scheduled to test the newer version. This process can be repeated as often as necessary.

Design-Based Implementation Research

In this study, practitioners (teachers) actively participated in the process of developing a practical tool (an Innovation Configuration Map) to aid the implementation and diffusion of an innovation (the Make-to-Learn Invention Kits). This arrangement invites comparison to methods used in Design-Based Implementation Research (DBIR), a methodology marked by collaborations among researchers and practitioners to develop, support, and sustain innovative practices (Fishman, Penuel, Allen, Cheng, & Sabelli, 2003). DBIR employs a two-pronged approach for studying educational innovations that focuses on efficacy as well as practical matters of implementation (Russell, Jackson, Krumm, & Frank, 2013). DBIR projects share four common features, including:

1. A focus on persistent problems of practice from multiple stakeholders' perspectives;
2. A commitment to iterative, collaborative design;
3. A concern with developing theory related to both classroom learning and implementation through systematic inquiry;
4. A concern with developing capacity for sustaining change in systems. (Fishman et al., 2003, p. 143)

A common task associated with the latter goal of sustaining change is "the development and testing of usable tools for improving teaching and learning in specific subject matter domains and settings" (Penuel, Fishman, Haugan Cheng, & Sabelli, 2011, p. 332).

Reflecting the commitment of DBIR to collaborative design, teachers and other practitioners play critical roles in the development and testing of such tools.

In this study, the Innovation Configuration Map is regarded as a “usable tool” in the sense described by the DBIR framework. The development of an Innovation Configuration Map for the Make-to-Learn Invention Kits was consistent with the elements of DBIR because it drew from the perspectives of multiple stakeholders, was iterative and collaborative, depended upon systematic inquiry, and was designed to support systematic change. More broadly, this undertaking was consistent with DBIR in that it is one small part of a much larger effort to develop and support innovative practices in STEM education through the Make-to-Learn Invention Kit project, an initiative that combines the efforts of many different partners, contributors, and stakeholders with unique perspectives.

Part III

Additional Influences

In order to identify the critical components of the Make-to-Learn Invention Kits, it was necessary to examine the concepts and pedagogies upon which the units are built, including integrated STEM, the engineering design process, and project-based learning. The characteristics of integrated STEM were described in Part I. In this section, I describe critical components of engineering education and project-based learning.

Constructionism

The pedagogical philosophy underlying the Invention Kits is heavily influenced by Seymore Papert’s constructionism, which builds on Jean Piaget’s ideas of constructivism. Both Piaget and Papert believed that humans construct their own knowledge by actively examining and reexamining their ideas in light of their experiences with the world (Ackermann, 2001). In doing so, they build knowledge structures that help them make sense of those experiences and inform their views of reality. However, while the knowledge building described in Piaget's constructivism can be done as a purely intellectual exercise, "Papert's constructionism takes constructivist theory a step further towards action. Although the learning happens inside the learner's head, this happens most reliably when the learner is engaged in a personally meaningful activity outside of their head that makes the learning real and shareable" (Martinez & Stager pg. 34). This real and sharable "public entity" can take any form, "whether it's a sand castle on the beach or a theory of the universe" (Papert & Harel, 1991). Such diversity occurs because students are given autonomy, time, and access to a variety of media, which they are encouraged to use to express their own unique interests and ways of thinking. This freedom to personalize reflects a recognition that there is not one right way or style of thinking and learning (Brennan, 2015).

The most important thing is not the nature of the creation, but the process of creating it. During this process, students learn to manipulate tools and materials to achieve their goals and express their ideas. Describing his vision for how children might one day use computers, Papert states:

> Technology is used not in the form of machines for processing children but as something the child himself will learn to manipulate, to extend, to apply to projects, thereby gaining a greater and more articulate mastery of the world, a sense of the power of applied knowledge and a self-confidently realistic image of himself as an intellectual agent. Stated more simply, I believe with Dewey,

> Montessori, and Piaget that children learn by doing and by thinking about what they do. (Papert, 2005, p. 353)

Metacognition is an important aspect of constructionism (Brennan, 2015). Papert viewed the process of creation itself as a metaphor for learning that was accessible to students. In making, children build a model, reflect on it, troubleshoot (debug) it, and then share it (Noss & Clayson, 2015). Papert argued that humans construct knowledge in much the same way.

In addition, by way of creating and iterating, students are able to make sense of ideas that might otherwise seem too complex or abstract. Describing this advantage in the context of children that create their own computer programs, Papert writes, "Much of what has been most perplexing to children is turned to transparent simplicity; much of what seemed most abstract and distant from the real world turns into concrete instruments familiarly employed to achieve personal goals" (Papert, 2005, p. 353). Employing difficult concepts to their own ends, makes those concepts accessible. What is more, students have motivation to learn those concepts and develop positive associations with them. They feel less like the work is being imposed on them from the outside (Martinez & Stager, 2013). Students that are motivated and feel good about learning are more likely to take ownership of their learning, which can change the whole culture of the classroom. Students may become more self-directed and less dependent traditional teacher instruction (Papert, 1984). In this setting, the "amount of teaching done by the adult teacher doesn't diminish, but changes" (Papert, 1984, p. 10). The focus shifts from the transfer of knowledge to students to the development of knowledge by students (Papert & Harel, 1991). Teachers can focus less on instruction and interact with students as facilitators and fellow learners (Stager, 2005). Meanwhile, as students immerse themselves in projects over an extended period of time, a culture of learning can emerge in which students more readily teach, support, and learn from each other (Brennan, 2015; Papert, 1984). The ability to share their creations with one another is an important part of this culture (Brennan, 2015).

Resnick, Berg, & Eisenberg (2000) demonstrated how principles of constructionism can be applied in a project in which students built scientific instruments, a concept not unlike the Make-to-Learn Invention Kit project. The rationale behind the Beyond Black Boxes project was that instrument building is a "physical and tactile tradition" that has long been part of science (p. 8). Historically, these instruments were mechanical in nature, and were often prized, not only for their utility, but for their intricate and aesthetic designs. These instruments could inspire students and pique their curiosity about the natural world. However, in modern times, scientific instruments have become "black boxes." Such "opaque" devices are highly precise, but "their inner workings are often hidden and thus poorly understood by their users" (p. 9). Based on constructionist ideas, Resnick and his colleagues believed that students would develop deeper understandings of science (and scientific instruments) if they were allowed to construct and program instruments to use in their own experiments. Devices that students created would have a "transparency" that factory-made devices lacked. To do this, children in the program were provided small, programmable computational devices called Crickets, which could be combined with motors and sensors.

This program possessed a number of characteristics that are important to constructionism. First, students were learning by constructing an artifact. Second, children had the flexibility to pursue ideas that were personally meaningful. One 11-year-old girl created a bird feeder that tracked the number of visitors using a hand-made touch sensor. Another girl created a "marble machine," in which she rolled marbles down of a series of ramps and motor-driven conveyor belts. Of course, such flexibility required that students have access to a variety of materials. Next, students were given extended periods time to build and collect data. In this way, the developers sought to "shift away from classroom learning to daylong learning" (p. 12). Finally, the students were encouraged to value the aesthetics of design – not just superficial decoration, but functional aesthetics as well.

Resnick and his colleagues reported a number of positive outcomes. They felt that students that created their own instruments were free to design investigations that would not have been possible if limited to conventional, factory-made instruments (p. 25). They also reported that students were motivated and had a strong sense of personal investment in their investigations (p. 25). By designing their own instruments, students were also able to bridge science and the arts. This was achievable in ways that did not diminish the science, but provided spark for students that might otherwise avoid it (p. 26). Finally, Resnick et al. reported that students that created their own instruments were able to develop critical capacity to interpret data they collected (p. 26).

Through the Beyond Black Boxes project, students engaged in scientific inquiry using "transparent" devices developed through informal design processes. The Invention Kits can be implemented using either informal or formal approaches to engineering. The next section relates to more formal approaches to engineering education.

Engineering Education

Essential Characteristics of Engineering Curricula

As mentioned previously, there are no nationally-accepted standards for engineering education. Nonetheless, several NRC committees have offered recommendations on the subject and various organizations have developed their own criteria. What follows is a small sample of this work.

National Academy of Engineering - Committee on K-12 Engineering Education (2009)

The Committee on K-12 Engineering Education (2009) describes three general principles for the development of engineering curricula.

1. Principle 1: K-12 engineering education should emphasize engineering design. Students should be engaged in a highly-iterative design process which underscores the idea that a problem may have many different solutions. They should discover that engineering provides a meaningful context for learning scientific, mathematical, and technological concepts. They should also have opportunities to engage in systems thinking, modeling, and analysis.
2. Principle 2: K-12 engineering education should incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills. At different points, completing engineering design activities requires knowledge and skills from science, mathematics, and technology. These connections should be made explicit and efforts should be made to support these important skills in the context of engineering.

3. Principle 3: K-12 engineering education should promote engineering habits of mind. The Committee for Engineering Education stress that engineering "habits of mind" align with skills that are more broadly considered essential for success in the 21st century. These include: systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations. (Committee on K-12 Engineering Education, 2009)

National Academy of Engineering - Committee on Standards for K-12 Engineering Education (2010)

While the Committee on Standards for K-12 Engineering Education recommended postponing the development of standards for engineering, they asserted that the following eight practices are essential elements of K-12 science and engineering curricula.

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information. (National Research Council, 2010)

Two years later, the Committee on a Conceptual Framework for New K-12 Science Education Standards (2012) described the same list of essential scientific and engineering “practices” in their Framework for K-12 Science Education. In 2013, these eight practices were incorporated into the Next Generation Science Standards (NGSS Lead States, 2013).

Definitions of Engineering

Definitions of engineering vary, but most use similar language. Carr et al. (2012) provide the following definition of engineering.

> Engineering is iterative design and the optimization of materials and technologies to meet needs as defined by criteria under given constraints. Engineers use systematic processes, mathematical tools and scientific knowledge to develop, model, analyze and improve solutions to problems. Engineering design processes are dynamic and include phases of problem definition, problem solving, testing and iteration. (p.547)

Brophy et al. (2008) provide a similar definition.

> Engineering requires applying content knowledge and cognitive processes to design, analyze, and troubleshoot complex systems in order to meet society’s needs. These activities of design, analysis, and troubleshooting are what engineers do to develop new devices (e.g., cars, consumer electronics), processes (e.g., food processing, manufacturing, airport scheduling), and infrastructure (e.g., transportation, power distribution, and waste management) and change existing ones that shape our lives. (p.371)

In both definitions, engineering is described in operational terms. They describe the practices and processes that engineers engage in; action-oriented words like develop, model analyze, iterate, and optimize are common to most definitions. Terms such as criteria and constraints that describe the conditions under which these actions are taken can also be found in most definitions.

Defining the Engineering Design Process

In 2004-2005, a group of engineering education experts led by Leigh Abts at the University of Maryland set out to design learning objectives for engineering that could be accomplished in K-12 settings. One requirement was that these objectives were articulated in ways that were accessible to K-12 students and teachers with little or no experience with engineering. Abt's group decided to use well-established practices of engineering as a framework for the competencies students should be able to master during the study of engineering. Groves, Abts, and Goldberg (2014) describe engineering design as a "structured, deliberate sequence of activities intended to deliver a top quality solution to an identified challenge when well executed." During this sequence, individuals should be able to:

1. Identify a significant challenge and specify a set of requirements that a successful engineering response to the challenge (i.e. a solution) should achieve,
2. Imagine a diverse set of possible solutions to the challenge and use systematic processes to select the most promising solution,
3. Define the solution using scientific knowledge, mathematical techniques, and technology tools and evaluate it via one or more prototypes,
4. Report the findings of the evaluation and conclude whether the prototype dilution can be expected to achieve the previously specified requirements, and
5. Reflect upon the process and recommend iteration or implementation of the solution.

Having agreed upon these competencies, the group began working on a set of assessment tools to benchmark and score student work in engineering design. These efforts resulted in the Engineering Design Process Portfolio Scoring Rubric (EDPPSR).

Engineering Design Process Portfolio Scoring Rubric (EDPPSR)

The EDPPSR was particularly useful for the purposes of developing the Innovation Configuration Map for the Invention Kits because its authors had already broken down and operationalized core components of engineering design. In its current form, the EDPPSR is broken into five Components (one for each step of the engineering process described above), which each contains several Elements. An outline of these Components and Elements follows:

- Component I: Presenting and Justifying a Problem and Solution Requirements
    - Element A: Presentation and justification of the problem
    - Element B: Documentation and analysis of prior solution attempts
    - Element C: Presentation and justification of solution design requirements
- Component II: Generating and Defending an Original Solution
    - Element D: Design concept generation, analysis, and selection
    - Element E: Application of STEM principles and practices
    - Element F: Consideration of design viability
- Component III: Constructing and Testing a Prototype
    - Element G: Construction of a testable prototype
    - Element H: Prototype testing and data collection plan
    - Element I: Testing, data collection and analysis
- Component IV: Evaluation, Reflection, and Recommendations

  - Element J: Documentation of external evaluation
  - Element K: Reflection on the design project
  - Element L: Presentation of a designer's recommendations
- Component V: Documenting and Presenting the Project
  - Element M: Presentation of the project portfolio
  - Element N: Writing like an engineer (Groves, Abts, & Goldberg, 2014)

While the EDSPPSR document itself is not cited among the resources or influences of the Invention Kits, it describes elements of the engineering design process that have become broadly accepted. As will be demonstrated later on, many of these ideas are readily apparent in the Invention Kits' core components.

Project-Based Learning

Project-based learning (PBL) is a pedagogical approach that is often paired with engineering design in integrated STEM curricula, as it is in Invention Kits. Buck Institute of Education (2016) defines PBL as "a teaching method in which students gain knowledge and skills by working for an extended period of time to investigate and respond to an authentic, engaging and complex question, problem, or challenge." As a form of inquiry-based learning, PBL is student-centered and focuses on skills in questioning, critical thinking, and problem solving (B. Barron & Darling-Hammond, 2008). Blumenfeld et al. (1991) describe a series of PBL activities that have strong parallels to the engineering design activities outlined above. In his description, "students pursue solutions to non-trivial problems by asking and refining questions, debating ideas, making predictions, designing plans and/or experiments, collecting and analyzing data, drawing conclusions, communicating their ideas and findings to others, asking new questions, and creating artifacts" (Blumenfeld et al., 1991).

Project-based learning can be used in any discipline, and is often multi-disciplinary (Thomas, 2000). It is used across grade levels in K-12 settings and in higher education (it originated in the field of nursing). Regardless of where it is found, PBL has a number of distinguishing components. Projects that focus on content are central to PBL curricula (Thomas, 2000). Inquiry is organized around a driving question (Blumenfeld et al., 1991) that is derived from an authentic, real-world problem or context (J. S. Krajcik et al., 1994; Ladewski, Krajcik, & Harvey, 1994). The process requires rigorous and systematic investigation involving posing questions, gathering, evaluating, and representing information, and thinking critically (Cook & Weaver, 2015; J. Krajcik et al., 1998; J. S. Krajcik et al., 1994). PBL is student-centered (Cook & Weaver, 2015) – teachers serve as resources, facilitators and guides, but students have the autonomy to choose, define, and carry out projects (Thomas, 2000). While students are empowered as individuals, PBL also has a strong social component. It typically requires collaboration among students (J. Krajcik et al., 1998) and occasionally brings in others from outside the classroom (teachers, professionals, academics, etc.) as part of a broader community of learning (Capraro, Capraro, & Morgan, 2013). Therefore, communication skills are key (Capraro et al., 2013). Working through the problems often requires that students master certain technological tools (J. Krajcik et al., 1998; Ladewski et al., 1994), either for research, modeling, multimedia, or communications (J. Krajcik et al., 1998; Marx et al., 1994). PBL culminates with the development and presentation of an artifact or product that addresses the driving question (J. S. Krajcik et al., 1994).

There is a significant body of research that indicates that a project-based approach benefits students in many ways. For example, students in PBL classrooms have shown gains in academic content knowledge and factual learning when compared to students in traditional classrooms (Mioduser & Betzer, 2008; Thomas, 2000). PBL students have also demonstrated improved critical thinking and problem-solving skills (Mergendoller, Maxwell, & Bellisimo, 2006). Capon and Kuhn (2004) found that students who learned concepts through PBL were better able to explain those concepts later on. Marx (1994) pointed to greater student independence, resourcefulness, self-regulation, and self-motivation, as well as improved collaborative skills (Marx et al., 1994). Mioduser and Betzer (2008) found that students engaged in PBL developed improved design skills and more positive attitudes about technology.

Bolstered by data such as these indicating positive outcomes, project-based learning appears to be a natural fit in efforts to integrate STEM through engineering design. Nonetheless, those who seek to implement PBL face challenges. Enacting project-based learning requires simultaneous changes in curriculum, instruction, and assessment that are foreign to both students and teachers (B. J. S. Barron et al., 1998). Many teachers struggle because they are accustomed to traditional, teacher-centered practices characterized by rigid schedules and curricular sequencing, whole-class activities, textbooks and worksheets, and assessments that focus on fact retention (Blumenfeld et al., 1991; Capraro et al., 2013). In a more loosely-structured PBL classroom, the teacher's role changes dramatically. He or she becomes less of a director, and instead interacts with students as a coach, a mentor, a resource, and occasionally as a peer (Mergendoller & Thomas, 2000). Teachers of PBL provide access to information and resources, model skills and concepts, guide students in task management and monitor their progress, provide feedback, troubleshoot problems, and evaluate results (Blumenfeld et al., 1991). Meanwhile, the teacher is responsible for fostering a classroom culture that supports constructive inquiry, risk taking, cooperation, collaboration, and accountability (B. Barron & Darling-Hammond, 2008; Blumenfeld et al., 1991). Mergendoller and Thomas (2000) identified fifty-three classroom management principles, organized under seven themes and 18 sub-themes, that teachers of PBL need to master. Themes include: Time Management, Getting Started, Establishing a Culture that Stresses Student Self-Management, Managing Student Groups, Working with Others Outside the Classroom, Getting the Most Out of Technological Resources, and Assessing Students and Evaluating Projects.

Amid all of these responsibilities, many teachers struggle. Some teachers have difficulty ceding control and giving students the freedom they need to pursue their own investigations (Ladewski et al., 1994; Marx et al., 1994). In other cases, teachers give students too much autonomy and not enough support, resulting in students floundering or losing focus (Blumenfeld et al., 1991; J. Krajcik et al., 1998; Mergendoller & Thomas, 2000). Often, teachers fail to provide proper supports because they mistakenly believe that inquiry-based learning is “unstructured” (B. Barron & Darling-Hammond, 2008). However, students cannot be simply “turned loose;” teachers must design activities that facilitate student success and meaningful learning, and student progress must be monitored throughout the process (Mergendoller & Thomas, 2000). In order to do this, teachers need to be “aware of the variety of ways that students may understand, or fail to understand, the particular concepts that are embodied in the projects they wish to carry out" (B. J. S. Barron et al., 1998, p. 307).

When project-based learning implementations fail, it is often because teachers lack the information, support, and tools necessary to fully integrate the approach (B. Barron & Darling-Hammond, 2008). Teachers often lack information and strategies for motivating students, facilitating cognitively difficult work, or managing complex classroom environments (Blumenfeld et al., 1991). They may also face practical constraints including inadequate resources (including technologies), inflexible scheduling (Edelson, Gordin, & Pea, 1999), overly-large class sizes, or challenging student groupings (J. S. Krajcik et al., 1994). Sometimes, teachers do not appreciate how long it will take for the (PBL) to begin running smoothly and reject it prematurely (J. Krajcik et al., 1998). Other times, they do not fully appreciate how project-based classrooms are supposed to look and work (Marx et al., 1994).

In and of itself, Project-Based Learning is a complex innovation. Therefore, teachers implementing PBL require support (interventions) that can help them build the awareness, how-to-, and principles-knowledge described by Rogers (2003). First and foremost, teachers need professional development. Barron (1998) argues that professional development should be designed to give teachers opportunities to experience the type of learning they are attempting to provide for their students. Teachers need to understand the underlying theoretical premises of PBL and how it can help them achieve their instructional goals (Ladewski et al., 1994). Professional development should inform teachers about the challenges they will face and provide strategies for addressing those difficulties (Ladewski et al., 1994). Marx et al. (1997) and Ladewski et al. (1994)

underscore that this PD needs to include opportunities for teachers to construct understanding by collaborating with others, trying things out, and reflecting on the results.

As illustrated in this section, both engineering design and PBL are complex ideas. Their inclusion as components of Make-to-Learn Invention Kits compounds the complexity of the series as a whole and underscores its characterization as an innovation cluster. During the Innovation Configuration Mapping process, it was necessary to examine the series through the lens of each idea. In this way, I sought to identify the specific characteristics each construct contributes to the Invention Kits.

Summary

While definitions vary, integrated STEM is generally regarded as a holistic approach to science, technology, engineering, and math (Committee on K-12 Engineering Education, 2009). It is often characterized by the teaching of two or more subjects concurrently (Heil et al., 2013); a focus on processes and practices, not just facts (National Research Council, 2010); and the use of learner-centered pedagogical approaches that emphasize real-world connections, problem-solving, and collaboration (Heil et al., 2013; Kelley & Knowles, 2016; National Research Council, 2012). Many scholars and educators promote integrated STEM as strategy to better prepare students to practice skills and apply content in ways that mirror how professionals practice STEM in the real-world (National Academy of Engineering & National Research Council, 2014).

Engineering-based challenges are often regarded as a natural context for integrating the four STEM subjects. However, few K-12 teachers have training or experience in engineering education (Committee on K-12 Engineering Education, 2009).

At the same time, there are few standards or models of engineering education to guide teachers who wish to use engineering as an integrative strategy (Committee on K-12 Engineering Education, 2009; Roehrig et al., 2012). Therefore, many of these teachers will endeavor to adopt new, engineering-focused approaches to STEM with little experience or support.

Because engineering-focused STEM approaches are innovations to many teachers, research in educational change can be useful. Rogers (2003) describes a process by which teachers choose to adopt or reject an innovation based in part upon whether they perceive the innovation as easy to understand or too complex. Hall and Hord (2013) build upon this idea, stating that a primary reason that innovations fail to catch on or are used improperly is that would-be adopters cannot visualize what the new way should look like in practice. They introduce a strategy called Innovation Configuration Mapping, which is used to communicate the critical components of an innovation, idealized visions of their implementation, and descriptions of implementation variations. This strategy is intended to reduce the complexity of an innovation and facilitate adoption.

In order to develop an Innovation Configuration Map for the Make-to-Learn Invention Kits, it was necessary to consider some of the core concepts upon the Invention Kits are built. Among them is constructionism, which posits that individuals construct knowledge when they are engaged in activities that result in the creation of things that are real, sharable, and personally-meaningful (Papert & Harel, 1991; Stager, 2005). Additional core concepts relate to the engineering design process, which emphasizes identifying challenges, brainstorming possible solutions, prototyping and evaluating solutions, reporting results, and reflecting on the outcomes (Groves et al., 2014). This chapter concluded with a review of literature pertaining to project-based learning, a pedagogical approach that is often paired with the engineering design process. In project-based learning, students work for “an extended period of time to investigate and respond to an authentic, engaging, and complex question, problem, or challenge” (Buck Institute for Education, 2016). The next chapter addresses the methodology of the study.

CHAPTER 3

Methodology

This chapter begins with a description of the primary participants and settings in the study. Next, each step of the Innovation Configuration Mapping process is described in detail along with information pertaining to how it was implemented in the context of this study. Descriptions of potential biases and limitations follow. The chapter concludes with a brief summary of data collected during a pilot study performed during the 2015-2016 academic year.

Purpose and Approach

The purpose of this study was to 1) identify the critical components of a series of engineering-focused STEM activities called the Make-to-Learn Invention Kits, 2) describe those elements in operational terms that convey what an ideal implementation would look like, and 3) describe variations of those elements that were observed in diverse classrooms. To do so, I used a process called Innovation Configuration Mapping developed by Hall and Hord (2013), employing generic qualitative methodology. Patton (2015) states that generic qualitative inquiry "uses qualitative methods – in-depth interviewing, fieldwork observations, and document analysis – to answer straightforward questions without framing the inquiry within an explicit theoretical, philosophical, epistemological, or ontological tradition" (p. 154). Guided by pragmatism, my goal was to provide practical information that can guide the implementation of engineering-focused, integrated STEM curricula.

Description of Participants and Settings

My study included participants with diverse roles and perspectives in the Make-to-Learn Invention Kit project, including members of the development team, individuals supporting the implementation of the Invention Kits, and classroom teachers. The development team primary consists of faculty members from engineering, engineering education, science education, and instructional technology, as well as graduate students working under their supervision. Core members of the development team interviewed for this study were located at the University of Virginia. An additional core developer at Princeton University was not interviewed. Two professors from the University of North Texas and James Madison University that have been intimately involved in various aspects of the project and are facilitating pilot implementations at distant sites were also included.

Table 2
Members of the Invention Kit Development Team

Developer 1	Professor, STEM, Instructional Technology	Curry School of Education, University of Virginia
Developer 2	Professor, Instructional Technology, Mathematics Education	Curry School of Education, University of Virginia
Developer 3*	Professor, Mechanical and Aerospace Engineering	Princeton University
Developer 4	Graduate Student, Instructional Technology	K-12 Engineering Design Lab, University of Virginia
Developer 5	Graduate Student, Instructional Technology	K-12 Engineering Design Lab, University of Virginia
Collaborator/Pilot Site Coordinator 1	Professor, Department of Middle, Secondary & Mathematics Education	James Madison University
Collaborator/Pilot Site Coordinator 2	Professor, Department of Learning Technologies	College of Information, University of North-Texas

Note. Developer 3 was not interviewed as part of this study.

Teachers and classrooms were selected from sites in Virginia that were currently piloting the Invention Kits. The sample included seven teachers and a facilitator representing fours schools and three districts (see Tables 3 and 4). To date, most of the pilot implementations of the Invention Kits are occurring in middle schools, and all of the classrooms in my sample were from this level. The teachers varied in their backgrounds and experience teaching integrated STEM and engineering curricula. Some were new to the Invention Kits, while others have been using the kits for their second and third years. The schools in which these teachers work were diverse in terms of settings and demographic makeups. The sample included urban and suburban districts. At one school, minority populations comprised a small percentage of the student population, while at another, minorities comprised well over 50% of the student population. Free- and-reduced lunch rates ranged from 1% to 72%.

Table 3
Participating Sites

School	**Participants**	**District**	**Demographic Information**
Brandeis Middle School	• 1 classroom teacher	Chester City Public Schools	• Total Enrollment: 489 • Student/Teacher Ratio: 10.83 • Race/Ethnicity o White, non-Hispanic: 39% o Black, non-Hispanic: 41% o Hispanic: 10% o Asian/Pacific Islander: 6% o Two or More Races: 4% • Free/Reduced Lunch: 53%
Seifert Middle School	• 2 classroom teachers • 1 facilitator	Adkins County Public Schools	• Total Enrollment: 584 • Student/Teacher Ratio: 14.22 • Race/Ethnicity o White, non-Hispanic: 73% o Black, non-Hispanic: 7% o Hispanic: 6% o Asian/Pacific Islander: 7% o Two or More Races: 6% • Free/Reduced Lunch: 12%
Mountain Top Middle School	• 1 teacher	Huntsville City Public Schools	• Total Enrollment: 788 • Student/Teacher Ratio: 14.65 • Race/Ethnicity o White, non-Hispanic: 38% o Black, non-Hispanic: 14% o Hispanic: 41% o Asian/Pacific Islander: 2% o Two or More Races: 4% • Free/Reduced Lunch: 72%
Thomas Paine Middle School	• 3 teachers	Huntsville City Public Schools	• Total Enrollment: 813 • Student/Teacher Ratio: 12.6 • Race/Ethnicity o White, non-Hispanic: 43% o Black, non-Hispanic: 8% o Hispanic: 41% o Asian/Pacific Islander: 4% o Two or More Races: 3% • Free/Reduced Lunch: 61%

Table 4
Participating Teachers

Name	Subject(s) Taught	Invention Kit Experience (# of times implemented)	Participation in this study	Additional Information
Erica Q.	Eighth-grade Mechatronics	First year using the Invention Kits • Solenoid IK (1) • Linear Motor IK (1) • Generator IK (1)	• Interviewed once • Observed for one day	• Life science teacher (2 years) • K-12 science outreach programs (4 years) • Science and CTE teacher (current) for 2 years
Brenda F.	Eighth-grade Physical Science	Implemented some or all of the three basic Invention Kits with 24 class sections since 2013	• Interviewed once • Observed for one day • Previously observed and interviewed for pilot study	• Worked as scientist before becoming an educator • Involved for a number of years in STEM outreach programs
Brian N.	Seventh- and Eighth-grade Engineering	Second year using the Invention Kits • Solenoid IK (5) • Linear Motor IK (5) • Generator IK (5) • Telephone (Speaker) IK (3) • Telegraph IK (1) • Charles Page Motor IK (1)	• Interviewed twice • Observed for two days • Periodic member checking (via email or videoconference) • Previously observed and interviewed for pilot study	• B.S. in Systems Engineering • Taught mathematics for 1 year • Engineering teacher (current) for 2 year
Pamela Y.	Eighth-grade STEM	First year using the Invention Kits • Solenoid IK (1) • Linear Motor IK (1) • Generator IK (1)	• Interviewed once • Observed one day	• Graduate certificate in Integrative STEM Education • B.S. in Technology Education • Taught Tech Ed (Grades 7-12) for 6 years • STEM teacher (current) for 5 years

Christine I.	Eighth-grade STEM	First year using the Invention Kits • Solenoid IK (1) • Linear Motor IK (1) • Generator IK (1)	• Interviewed twice • Observed one day	
Jack E.	Eighth-grade STEM	First year using the Invention Kits • Solenoid IK (1) • Linear Motor IK (1) • Generator IK (1)	• Interviewed once • Observed one day	• 34 years of teaching experience • Science teacher (grades 4-8) • STEM teacher (current) for 3 years • Recently earned CTE certification
Dylan T.	Eighth-grade STEM	First year using the Invention Kits • Solenoid IK (1) • Linear Motor IK (1) • Generator IK (1)	• Interviewed once • Observed one day	• Technology Education teacher • Involved in STEM program for 4 years
Richard N.	K-8 STEM Coordinator	Implemented the Invention Kits with approximately 500 students since 2013.	• 2 Interviews • Periodic member checking (via email or videoconference) • Previously observed and interviewed for pilot study	• Former Eighth-grade Physical Science teacher • Current position (1 year)

Development of the Innovation Configuration Map

Developing an Innovation Configuration Map is an interactive and iterative process involving a variety of stakeholders that consists of several phases (Hall & Hord, 2013). Observations, interviews, and document analyses were the primary sources of data. Qualitative data analysis occurred throughout the process. In the paragraphs that follow, I describe how each of the four steps of the IC Mapping process was applied in this study.

Step 1: Identifying Innovation Components

The first step requires the identification of the core components of the innovation. This process generally begins by reviewing all the descriptive materials and other media relating to the innovation (Hord et al., 2006, p. 16). During this phase, I analyzed approximately 30 documents written by the Invention Kit developers. These included descriptions of the Make-to-Learn Invention Kit project that were available on several webpages and in press releases, news articles, and videos. A number of white papers and trade journal articles were also available, as were descriptions of the project that were submitted in grant applications. The most-current materials for the Invention Kits being piloted – the Solenoid Invention Kit, the Linear Generator Invention Kit, and the Linear Motor Invention Kit – were available on the project website. In addition, the developers granted me access to a private, online document repository (Dropbox) which contained draft materials for other Invention Kits that are planned for future development. This folder also contained previous versions of Solenoid, Linear Generator, and Linear Motor Invention Kits that provided insight into the evolution of the project. Michael Quinn Patton (2015) states that "documents prove valuable not only because of what can be learned directly from them but also as a stimulus for paths of inquiry that can only be pursued through direct observation and interviewing" (p. 377). In this way, an analysis of the project materials at the outset allowed me to enter interviews with sufficient conceptual and contextual understandings of the project to anticipate some responses and more effectively probe interviewees for additional information.

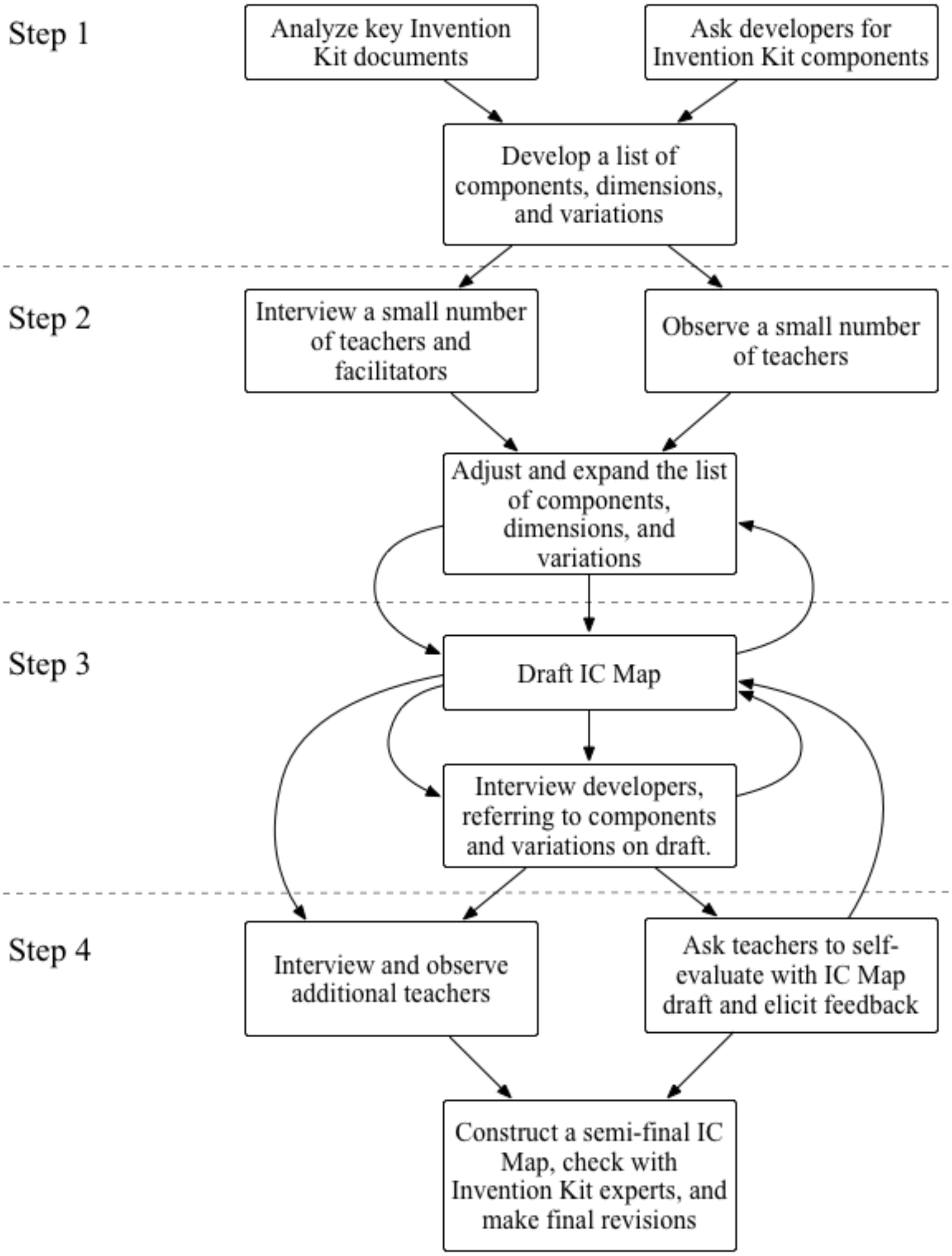
Next, the developers of the innovation and change facilitators were interviewed (Hord et al., 2006, p. 16). In this case, I interviewed faculty and graduate students at several universities that comprised the project leads and the core group of developers. During these encounters, I utilized an interview protocol (see Appendix B) that included questions derived from Hord et al (2006) such as:

1. Would you describe for me the Make-to-Learn Invention Kit series?
2. Ideally, what would I see in a classroom where the Invention Kits is in use?
3. What do you consider the most essential components of the Invention Kits?

Following the guidelines set out by Hord et al (2006), I also asked what kinds of modifications or variations they anticipated or observed that teachers might make to the Invention Kits. Additionally, I asked the developers to consider what types of knowledge – how-to knowledge and principles-knowledge – are embedded in the components they describe.

According to the creators of Innovation Configuration Mapping, it is common to discover there is a lack of consensus regarding what the targeted innovation should look like when it is in use (Hord et al., 2006, p. 16). In order to more easily capture these differences of opinion, I interviewed each of the developers separately. These conversations partially revealed the innovation developers' vision of an ideal implementation. The goal of this phase was to establish the basic components, dimensions, and variations of the Invention Kits (Hord et al., 2006, p. 16). These components, dimensions, and variations were compiled in a tentative list that guided the classroom observations that followed.

Figure 5. Steps for Constructing the IC Map.



Note: Adapted from Hord et al. (2006) Measuring Implementations in Schools: Innovation Configurations, p. 14.

Step 2: Identifying Additional Components and Variations

The next step was to observe the innovation in use and interview some of the individuals who were implementing the innovation (Hord et al., 2006, p. 17). I traveled to four pilot sites to observe implementations of the Invention Kits and interview teachers and district support staff. Two of these sites were schools close to the University of Virginia that are part of the Lab School venture. These sites have been involved in the Invention Kit project from its inception, and the three of the four teachers there had significant experience with the Invention Kits. These sites also had direct support from the developers at the University of Virginia. Preliminary observations and interviews conducted as part of a pilot study indicated that the implementations at these sites could be considered higher fidelity implementations, though there were significant differences between them.

Two additional middle school sites in a district an hour away from the University of Virginia were sources for additional observations and interviews. The teachers at these schools were implementing the Invention Kits for the first time. Since these schools were receiving considerably less support from the University of Virginia, I anticipated that these sites might represent lower-fidelity implementations.

The classroom observations were used to vet the tentative list of components, dimensions, and variations of the innovation that I developed in Step 1. I employed an ethnographic approach during these classroom visitations, taking care to document all innovation-related activity I observed (Hord et al., 2006, p. 17). I looked carefully for evidence of additional components, dimensions, and variations that did not emerge during the analysis of project materials or the interview with the Invention Kit developers. These observations were also used to validate the information provided by the teachers in pre-observation interviews (Hord et al., 2006, p. 18).

After each observation, I interviewed the teacher. My protocol for teacher interviews included questions such as:

1. Would you describe the Make-to-Learn Invention Kits for me?
2. What could an observer expect to see while you are implementing the Invention Kits with your students?
3. What would an observer see you doing in the classroom?
4. What would an observer see your students doing?

Each of these questions was worded to elicit descriptions of various behaviors that accompany the innovation. This kind of information is necessary for developing operational word pictures in the IC Map (Hord et al., 2006, p. 18). At one of the districts, the current STEM coordinator was previously a classroom teacher and a key implementer of the Invention Kits. While I was unable to observe him implementing the Invention Kits for this study (though I was able to observe him during my pilot study), I also conducted an interview with this individual. For this interview, I used the same protocol but asked him to respond to the questions from his previous experiences as well as his current perspective as a facilitator.

Following each site visit, observation and interview data was analyzed and compared to the initial list of innovation components. These data were used to draft word picture descriptions of the observed implementation variations that were plotted on iterative drafts of the IC Maps under the appropriate component categories. These word pictures were drafted to be as visual and action-oriented as possible in order in order to effectively convey to stakeholders what successful implementation of the Invention Kits entails (Hall & Hord, 2013, p. 61).

Step 3: Refining the IC Map

For Step 3, I arranged a second meeting with several members of the Invention Kit development team to share the interview and observation data collected during Step 2. During the meeting, I also shared the latest version of the Innovation Configuration Map and asked them to comment on its organization and contents. The conversation was an opportunity to raise issues or discussion points that did not come up in the first meeting. Additionally, I was able to ask the team to comment on the implementation variations that I observed. Because the developers had also conducted extensive observations, this meeting was also an opportunity for the team to comment on the credibility of my analysis (Creswell, 2013).

While the initial draft of the IC Map – completed prior to these follow-up interviews – was useful to guide the conversation through each of the core components and variations identified in Step 2, I also sought information to guide specific refinements. In accordance to guidelines laid out by Hall et al. (2006), my goals included:

1. standardizing the IC Map's format, including repetition of the same dimension within each variation in a single component and utilization of the same subject across the map;
2. confirming that the IC Map included language appropriate for the user;
3. distinguishing between critical and related components (p. 18)

Step 4: Validating and Finalizing the IC Map

Using the feedback gathered in Step 3, Step 4 began with another revision of the IC Map. The newest version – the 3rd major iteration – was then shared with three individuals with significant experience implementing the Invention Kits. All three individuals were previously interviewed in either Step 1 or Step 2. The first individual was the teacher from Brandeis Middle School, whose implementation is regarded by the developers as high quality and who has made significant contributions to the development of the Invention Kits. The second individual was the district STEM coordinator, who also previously led high-quality implementations and significantly contributed to the development of the Invention Kits. The third individual was one of the core graduate student developers, whose had not only helped implement the kits, but had also studied and written about their implementation. These three individuals served an important function of not only suggesting revisions for the IC Map, but also member-checking my findings. They were chosen for this latter role because of their in-depth knowledge of the intent of the Invention Kit project, its developmental history, and the ground-level intricacies of implementing the Kits.

Initially, I asked the individuals to review the Innovation Configuration Map on their own and consider its effectiveness in communicating the major components of the Invention Kits and its suitability for assessing themselves or others. Afterward, I arranged to meet with each of the three individuals to review the Map and pose a few questions (see Appendix D). The purpose of the conversation was to elicit the teachers' "gut-level" reactions to the tool. Questions included:

1. Is the IC Map organized in a way that easy to read and understand?

2. Is the language used in the IC Map adequately descriptive, concise, and free of jargon?
3. Is the tone of the IC Map appropriate? In other words, is the tone of the IC Map constructive rather than critical?
4. Does the IC Map allow you to accurately convey your implementation of the Invention Kits?

Information gathered during the interviews was used to make a final set of revisions to the IC Map.

The IC Map developed during the course of this study should not be considered a final product. As recommended by Hall and Hord (2013), the latest version of the Map is clearly marked with the word "DRAFT" to indicate that additional modifications and refinements will almost certainly be necessary. Because the Invention Kits are still under development and have not yet been publicly released, the sample size of this study was necessarily small. In the future, as more teachers adopt the Invention Kits and implement them in diverse settings, additional implementation variations will inevitably emerge and necessitate changes to the IC Map.

Data Collection and Analysis

The primary sources of data for the study were observations, in-depth and informal interviews, and Invention Kit publications, descriptions, and materials. Observation field notes were completed after each visit to prompt reflection and facilitate recall. All interviews were recorded and transcribed. These data were analyzed using NVivo coding and qualitative data analysis software. Initial codes were derived from elemental coding methods including descriptive coding and process coding (Saldaña, 2009). Analytic memos were used to stimulate and document thinking regarding coding choices, lines of inquiry, and emerging patterns, categories, and themes (Maxwell, 2013; Saldaña, 2009).

While some of the elements identified during this initial analysis were retained as critical or related components of the Invention Kits, the list of codes generated during first cycle coding lacked organization and contained redundancies and extraneous information. Second cycle, axial coding was used to reanalyze and reorganize data coded during the first cycle in order to further refine and distill the data into categories (Saldaña, 2009). Redundancies were eliminated by combining codes. This process of categorization employed the constant comparative method. As Merriam & Tisdell (2016) explain:

> …the constant comparative method involves comparing one segment of data with another to determine similarities and differences. Data are grouped together on a similar dimension. The dimension is tentatively given a name; it then becomes a category. The overall object of this analysis is to identify patterns in the data. (p. 32)

In this study, most of the categories resulting from second cycle coding were included as components on the first draft of the Innovation Configuration Map. As the study progressed and new data was collected, coded, and analyzed, these categories were slightly modified.

Researcher as Instrument

From 2009 to 2011, as a full-graduate student in the Instructional Technology program at the University of Virginia, I was involved in some of the early work in children's engineering and digital fabrication that contributed to the knowledge base for the Make-to-Learn Invention Kit project. These experiences provided valuable insights when I was first exposed to the project and began to study its implementation. It is important to note that I was no longer a full-time student at the University when work began on the project, and I am not a member of the development team. This situation was advantageous because Hall and George (2000) suggest that Innovation Configuration Mapping should be done by individuals that are well-versed in the innovation but not among its developers.

Although I am not a member of the development team, I have been involved with the Invention Kits project for almost two years. During the 2015-2016 school year, I facilitated a pilot implementation of two Invention Kits with a group of 25 students at a rural middle school in Central Pennsylvania. During the implementation, I served dual roles as researcher and facilitator. In the latter role, I was involved in both planning and teaching the units. As a participant observer, I was in the classroom several days a week over a two-month period, during which time I collected field notes and conducted informal and formal interviews with the teachers using primarily ethnographic methods (Spradley, 1980). Later, I visited two additional implementations at schools in Virginia, where I also collected field notes and conducted interviews.

These experiences contributed to my conceptual understanding of the Invention Kits and provided strong insights into the issues that arise during implementation. However, my proximity to the project may raise concerns about what Rogers (2003) calls "pro-innovation bias." Pro-innovation bias is the implication that an innovation is superior to the status quo and should be adopted by everyone. It can also include a belief that the innovation should not be re-invented or rejected. This bias can lead a researcher to overlook serious flaws with the innovation or discount legitimate reasons for rejection or re-invention (p. 106). To a certain extent, I was protected from this threat because modifications to Invention Kits are expected and even sought after. Nonetheless, it is true that I believe that this approach to teaching STEM is valuable, and I hoped to observe positive effects. At the same time, I experienced many of the difficulties of implementing the Invention Kits first-hand. My strategy for minimizing pro-innovation bias and other validity threat was to practice reflexivity and mindfulness through frequent memo writing and keeping a research journal (Patton, 2015, p. 70).

The fact that I do not have an engineering background or formal training in STEM education might also be an area of concern. However, I taught in a middle school language arts for six years, which gives me a strong pedagogical foundation with that age group. Meanwhile, my training and experience as a language arts teacher proved useful when considering cross-curricular aspects of the Invention Kits, including writing, speaking, and the discussion of historical themes and narrative arcs. Over the last seven years, I have worked with teachers and students as an instructional technologist across a range of subjects. During that time, I learned a great deal about implementing new curricula and facilitating change. Many of the innovations that I helped implement over the years were related to STEM, including engineering-focused activities. While preparing for and facilitating these implementations, I had many opportunities to learn and practice engineering pedagogy. Nonetheless, I am not an expert. While reviewing the literature, I attempted to broaden my understanding of engineering pedagogical content knowledge, but knowledge gaps remain. During the course of this study, I periodically consulted with experts on engineering and integrated STEM curricula and pedagogy to help address these gaps

Validity

I sought to minimize other validity threats through conventional methods. First, I attempted to amass a larger and more varied data set by observing teachers lead groups of students on more than one occasion. When this could not be arranged, I sought to observe the teacher lead multiple groups of students on a single day. A greater number of classroom observations provided additional opportunities to test and confirm inferences and observations (Maxwell, 2013). Next, intensive observations and interviews also allowed me to collect detailed notes – rich data – that accurately captured what was happening at each implementation site (Maxwell, 2013). Rich data served two purposes – it gave me greater confidence in my data, and it was useful for developing descriptive word pictures for the Innovation Configuration Maps. Third, member checks were used to validate data and analysis following successive iterations of the IC Map. Following the development of the first draft of the IC Map, I shared the map with four developers, who provided feedback on my analysis and the organization of the data. After the development of the most current draft, several teachers were asked to comment on the extent to which drafts of the IC Map (developed using information provided by them) accurately reflect their perceptions of the Invention Kits. In addition, I periodically arranged informal meetings with my dissertation committee co-chairs to share data and analysis. On one occasion, one of my co-chairs provided a more formal data audit in which she reviewed my codebooks and concept mapping. Finally, data triangulation was addressed by collecting, analyzing, and comparing different types of data (observations, interviews, and documents, and artifacts), collected from a variety of classroom settings (Maxwell, 2013). In particular, I noted carefully whether there was consistency between what individual teachers described as important components of the Invention Kits when interviewed and what aspects of the Invention Kits they appeared to emphasize in practice when observed.

Pilot Study

Overview

In the spring of 2016, I conducted a pilot study to explore possible research questions and conceptual frameworks for a dissertation study. The pilot study focused on a middle-school implementation of the Invention Kits. While designing the pilot study, conducting fieldwork, and analyzing pilot data, I gained experience that that led to my current research focus. What follows is a description of the study's evolution and a summary of the data.

Purpose and Research Questions

At the outset, I proposed to examine how four new, middle school STEM teachers would implement the newly-developed Make-to-Learn Invention Kits. I was particularly interested in how the teachers would facilitate student-centered, constructivist activities. My central research question was; "How does a team of four new STEM teachers implement a newly-developed, constructivist, engineering curriculum entitled American Innovations in an Age of Discovery in a middle school classroom?" Among the sub-questions were:

1. How do the teachers support the students as they engaged in engineering activities?

2. Do the teachers implement Invention Kits with fidelity? What kinds of changes do the teachers make to the Invention Kits?
3. What challenges do the teachers face?
4. How do the teachers describe their learning?

Participants

My sample focused on a first-time implementation of the Invention Kits with a single section of 7th and 8th grade students co-taught by a team of four STEM teachers. None of the teachers had formal training in engineering or engineering education, and they had limited experience leading students through hands-on engineering activities. The sample was chosen for convenience, but I anticipated that the sample might yield valuable insights into how teachers experience teaching engineering for the first time. For my part, I served dual roles of researcher and facilitator. In the latter role, I was involved in both planning and implementing the units with students.

Initial Experiences

As a participant observer, I was in the classroom several days a week over a two-month period, during which time I collected field notes based on observations and informal debriefing conversations lasting 10 to 15 minutes following each lesson. In addition, I conducted formal interviews with each teacher before and after the Invention Kit implementation and led one focus group. Problems with my research questions were apparent early on. For example, fidelity was impossible to measure. Ideals for implementation had not been articulated, nor had any specific implementation been presented as a model. Meanwhile, the lesson plans that the teachers were given were rather skeletal. Descriptions of the primary activities were included, but the plans lacked clear procedures. The idea that I might document how teachers deviate from the lesson plans implied that there was an established path from which to wander. This was not the case.

Meanwhile, the sub-question relating to how the teachers facilitated student-centered, constructivist activities was based on an understanding that constructivism was a core component of the Invention Kits. In practice, however, I observed that the teachers struggled with this approach and quickly shifted to more teacher-centered practices. I felt that these particular teachers shifted approaches rather quickly because they lacked experience facilitating open-ended activities. At the same time, there was nothing in the Invention Kits materials that explicitly recommended any particular pedagogical approach. It occurred to me that I had never actually heard the developers discuss specific pedagogical approaches and my "understanding" of the centrality of constructivism was perhaps only an impression. The lack of clarity on the matter raised a serious question. If a facilitator, like myself, who was in regular communication with the Invention Kits developers could only describe impressions of the pedagogical foundations of the Invention Kits, how well was the vision of the Invention Kits being communicated to those further removed? Not well, I concluded.

As an instructional technologist, my job is to facilitate the adoption of new technologies and related pedagogies. The literature and my experience tells me that teachers need to understand an innovation and visualize its application in their classrooms before they will be able to successfully implement it. I concluded that the Invention Kits need support materials that communicate how the vision of the kits can be put into practice. This conclusion led to my current focus on defining the Invention Kits.

Impacts on Sample, Methods, and Analysis

In order to better understand the Invention Kits, I expanded my sample to include two additional middle school sites. The three teachers at these sites had significant experience leading integrated STEM/engineering activities and two of the three had been piloting parts of the Invention Kits since the beginning of the project. These teachers received direct support from the Invention Kits development team and their efforts represented the most advanced pilot implementations available. I was able to observe and interview one teacher on two occasions. I observed and interviewed each of the remaining teachers a single time. The observation and interview protocols for these visits are included in Appendix F and G. The data collected during these observations and interviews had an immediate impact by allowing me to compare teachers and implementations. It was particularly helpful that the additional teachers were more experienced with the Invention Kits and student-centered activities. Previously, I was only able to compare what I observed in the original classrooms with my own interpretations of the Invention Kits activities. Now, I could compare my observations at the original pilot site with implementations that were considered representative of the intentions of the Invention Kits development team.

Summary of Pilot Study Data

All interviews were recorded and transcribed. These data, along with field notes, were analyzed and coded using qualitative data analysis software. First pass coding of the data collected at the original pilot site generated mostly descriptive codes. A sampling of these first-pass codes is included in Table 5.

Table 5
A sample of first-pass codes derived from initial pilot data

Student engagement	Student capacity	Teacher capacity
Guiding students	Resourcefulness	Student autonomy
Materials/Resources	Pacing and sequence	Content Knowledge
Teaching strategies	Student reflection	Classroom Management
Answering questions	Technological skills	Student-centered learning
Engineering processes	Misconceptions	Scheduling
Accountability	Knowledge gaps	Making connections
Real-world connections		

As my focus shifted to defining the Invention Kits, I began using sensitizing concepts to guide data collection and analysis. “Processes” and “interactions” were among the first sensitizing concepts I used. These concepts led to more action- and process-oriented codes such as “Addressing Needs,” “Building Culture,” and “Assessing Learning.” A more complete list of second-pass codes is included in Table 6.

Table 6
A collection of second pass codes derived from pilot data

Addressing Needs	Assessing Learning	Establishing an engineering culture
Coaching through challenges	Facilitating collaboration	Making connections
Presenting tasks/challenges	Managing workflows and the environment	Teaching design practices
Addressing content	Utilizing technology	Promoting knowledge sharing
Promoting reflection		

As a final exercise, I used data collected during the pilot study to draft a series of possible innovation components for the Invention Kits. According to Hord et al. (2006), components include major operational features of an innovation – generally, materials, teacher behaviors, or student activities (Hord et al., 2006, p. 5). At that point, I had not attempted to distinguish between critical components (components that must be used) and related components (those that are simply recommended). Nor did I describe variations for each of the following components. The first draft of the Innovation Configuration Map, developed according to the procedures described in "Step 1" above, would include this additional information. Instead, the development of the following list was undertaken to help anticipate some of the components the Invention Kits developers and teachers might describe during the IC Mapping process. Components are not listed in any particular order.

Potential Invention Kits Components

1. The teacher helps students understand historical and cultural relevance of the artifact at the center of the Invention Kit.
2. The teacher guides students to understand how the artifact at the center of the Invention Kit was developed using engineering design principles and practices.
3. The teacher connects the Invention Kit artifact and its underlying concepts to the artifacts and concepts contained in previously-completed Invention Kits.
4. The teacher makes embedded STEM concepts explicit to students as they are used during the Invention Kit activities.
5. The teacher promotes student collaboration though each Invention Kit activity and through all phases of the engineering design process.

6. The teacher accepts and encourages diverse approaches and solutions to design problems posed in the Invention Kits.
7. The teacher requires students to develop tests for their designs, collect data, and use collected data to engineer improvements.
8. The teacher acknowledges failure as an important part of the learning process and provides opportunities for design iterations.
9. The teacher provides opportunities for students to share their designs with peers and elicit feedback.
10. The teacher helps students apply the understanding and skills developed through the Invention Kit activities to other solve other problems.

Summary

This chapter outlined the methodology of the study, which used qualitative methods including document analysis, in-depth interviews, and classroom observations. These methods were employed in the process of Innovation Configuration Mapping, a strategy developed by Hall and Hord (2013) to document the critical components of an innovation along with observed implementation variations. The steps of this iterative process were described in detail. Next, I described myself as a researcher and addressed issues of validity. This chapter concluded with a brief summary of an exploratory pilot study that helped inform the design of this study. The next chapter addresses the results of this study.

CHAPTER 4

Results

This chapter summarizes the results of the study. This study focused on answering three questions: (1) What are the critical components of the Make-to-Learn Invention Kits? (2) How do developers and facilitators describe their visions for how the components should be implemented? and (3) How do teachers adapt and implement the components in practice? One of the products of this study is an Innovation Configuration Map. The practice of Innovation Configuration Mapping was developed by Hall and Hord (2013) as a strategy for communicating educational innovations to would-be adopters and other stakeholders. While I am hopeful that the Innovation Configuration Map developed during this study will be useful to that end, more immediately, the Innovation Configuration Map serves as the organizational structure for reporting results to the questions above. I begin with an overview of the four major components that were identified. Then, addressing the four components in turn, I present data that relates to each component. Following each section of data, I present segments of the Innovation Configuration Map that rest upon and distill the data in that section. Each table of the IC Map includes an operational recommendation for teachers (e.g. “Establish the Purpose and Utility of the Tool or Mechanism”) that targets a subcomponent, stated as “The Big Idea.” Each recommendation includes several dimensions. These dimensions convey certain aspects and considerations of each subcomponent. The information in these sections addresses the first research question: What are the critical components of the Make-to-Learn Invention Kits?

Below these headings, table columns contain descriptions of implementation variations. The information in these columns addresses the second and third research questions: “How do the developers describe their visions for how the components should be implemented?”; and “How do teachers adapt and implement the components in practice?” Column A describes teacher behaviors that most closely reflect the visions of the Invention Kit developers. The columns to the right of Column A contain descriptions of variations that are arranged to reflect increasing dissimilarity to the behaviors in Column A. My intention is **not** to suggest that the behaviors described in Columns B, C, and D should be interpreted as increasingly unacceptable. For certain components, a “C Variation” or a “D Variation” is a viable alternative depending upon objectives and constraints. This matter is addressed in greater detail in Chapter 5 in the discussion of “fidelity lines.” Nor should the variations described in the IC Map be considered exhaustive; one can imagine other ways that the Invention Kits could be implemented. The data reported here was collected from a rather narrow set of middle school science and engineering teachers that are currently pilot testing the kits. All data should be considered with that context in mind. This matter is discussed in greater detail in Chapter 5, under “Limitations.”

Four Primary Components

Based on the data collected, four themes emerged as the primary components of the Invention Kits. While these themes are based on interpretation, I present them early in this chapter because I have used them to organize the data in this chapter and to frame the discussion that follows in Chapter 5. The top-level themes – or components – correspond to the core activities that students engage in through the Invention Kits – Making, Exploring, Inventing, and Connecting. While there is overlap, the first three components are essentially phases that are rooted in a specific task that the students move through sequentially. As one developer put it, “There's the make component, the lab component, and then there's the invent component. That's really the constructing the artifact, experimenting with the artifact, and then designing a new artifact.” Developers also variously described a “value component,” which I refer to here as “Connecting.” Students engage in Connecting throughout the process, as it consists of historical themes and maker values that encompass and permeate the first three components (See Figure 6).

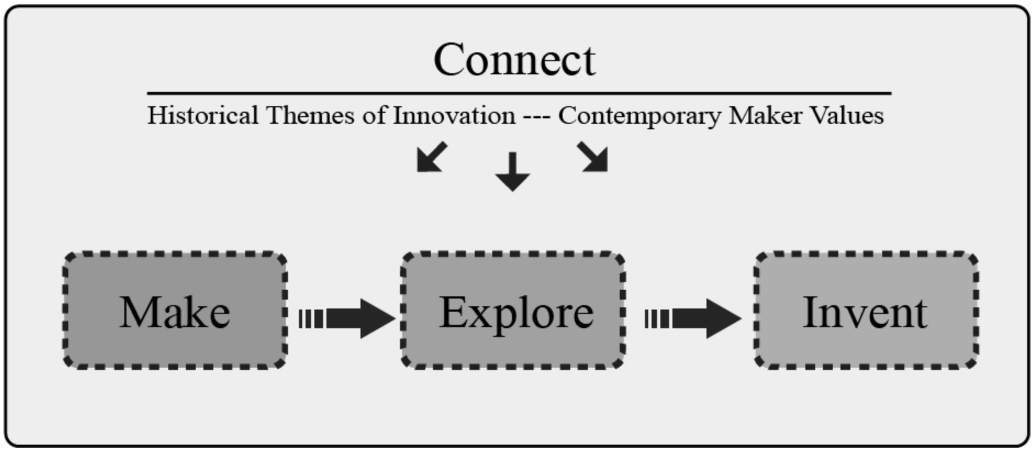


Figure 6. Graphic representation of the four primary components of the Invention Kits.

Each of the four main components and its accompanying task has a core focus. These are outlined in Table 7 below. For example, during the Make phase, students are tasked with reconstructing an historical invention (e.g. a linear motor). While the invention that students replicate will be used to explore scientific concepts in the next phase, the core focus at the Make phase is the development of the technological and mechanical competencies (e.g. CAD, 3D printing, soldering, etc.).

Table 7
Core focus and task for each Invention Kit component.

Component:	**Make**	**Explore**	**Invent**	**Connect**
Task:	Reconstruct an invention	Experiment with the invention	Extend the invention to something new	Explore the history and impact of the invention
Focus:	Technological and Mechanical Competencies	Scientific Principles	Engineering and Engineering Design	Innovation - Past and Present

It should be noted that the foci outlined above are not exclusive to any one component; to an extent each is addressed in all phases. Developing competencies, for example, is a significant part of both Making and Inventing. Later in this chapter, I will show that the prominence and depth of these foci also vary depending on the teacher and his or her objectives and constraints.

The Make Component

During the Make phase, students reconstruct working models of an invention, such as a solenoid, a linear motor, or a linear generator. For example, in the Linear Motor Invention Kit, students are tasked with constructing a working model of a linear motor using a neodymium magnet, coat hanger wire, a solenoid coil (constructed in a previous Invention Kit), and a base constructed from wood, cardboard, cardstock, or plastic. While constructing the motor, students develop technological and mechanical competencies. Depending on the tools and materials available, this may involve learning to use Computer-Assisted Design (CAD) software to view and modify a motor design before fabricating the design using a Computer-Assisted Manufacturing (CAM) technology such as a 3D printer or laser cutter. Regardless of the technology used to cut or print the parts of the motor, students must then use a variety of tools and methods to assemble their motors and ensure they function properly. Targeted skills include cutting, adhering, soldering, testing electrical continuity, etc.

Key Findings

Constructing Tools and Artifacts

Generally, students were presented the task of reconstructing artifacts in one of two forms. In one case, they were shown an exemplar of a device, which they were allowed replicate or re-envision with their own unique designs. In the other case, students were tasked with reproducing the models using tested designs that could be downloaded from the Make-to-Learn website. The former approach is closest to the developers' original intent. However, some teachers found the nuances of producing a reliable device too challenging or time consuming for their students and moved to the latter approach. The developers support either approach. Brian, an engineering teacher who had his students create their own designs based upon an exemplar, perceived a tradeoff when choosing to have students work from a pre-established design.

> I hope that as it [the Invention Kit series] is being implemented, people don't see it as assembling kits and putting them together and then learn about them. The learning happens when they are designing them themselves. Sure, they look a lot different and they look a little bit flimsier and are not as well designed. But the concept still holds true. They've built a motor that can perform some task or a speaker that plays music.

Brian felt that the learning is in the designing and making. However, he conceded that this approach takes a significant amount of time – more time than some teachers are willing or able to commit.

Richard, a teacher that had his students use a pre-established designs, stated that he felt that students still benefited from fabricating and assembling the artifacts, even if the designs were not their own. He stated:

> You appreciate a puzzle that you put together way more than walking by and seeing someone else put the puzzle together and say, "Oh yeah, that's a nice picture." The person who put together it and then sees the picture likes that puzzle way more. There's something about it, it's meaningful to the person. I think building is important. I think it's really important.

Though the designs were not their own, these students still developed a sense of ownership and an appreciation for the artifact.

Nonetheless, the developers clearly preferred students to design their own artifacts. One developer used an analogy to illustrate why:

> If you ask a kid to xerox a book in the library, what do they learn by xeroxing it? The answer is, “Nothing.” Well, they might learn something about how a Xerox machine works, but that's about it. And, in the same way, if you simply download an STL [Computer-Assisted Design] file and print it out, you haven't really learn`ed anything other than how to load a file in the printer. But, you've done no design. You really learn when you make your own design.

However, the developers acknowledged that having students design their own artifacts was not feasible in all classrooms, which prompted the creation of the downloadable designs.

While some teachers opted to have their students cut or print designs provided by the Invention Kit developers, others chose to pre-build at least some of the components themselves. Some cited limited access to tools and resources as reasons for pre-building components – one teacher had a single 3D printer and the school's laser cutters were located in another part of the building). However, limited time was generally the primary motivation for the adaptation. Christine, an eighth-grade STEM teacher, explained:

> We really felt like we needed to pre-make everything because we just have to move on. We have to do the unit, but we have to be prepared to move on in a timely fashion. We don't mind it taking a little bit longer than we might normally spend on this unit, but we can't have it take twice as long. More than that would be detrimental to what else our responsibilities are.

This teacher went on to explain that those responsibilities included the state science curriculum, the size of which precluded her from spending too much time on any one topic. This was a common response from the science teachers in the sample. The engineering teachers described greater flexibility in this regard.

Developing Competencies

Technological and mechanical competencies have been a primary focus of the Invention Kits from their inception. The following description was included in early Invention Kit documentation:

> Advanced manufacturing technologies such as 3D printers, digital die cutters, and computer-controlled milling machines now make it possible to reconstruct these key inventions and discoveries. By using these modern technologies to transform digital patterns and bits back into atoms, students can retrace the steps of early pioneers and inventors. In the process, they gain insight into the

> way our current civilization came into its present form and some of the skills needed to help shape its future path. (Bull, Littman, & Hoffman, 2015)

During observations, teachers were observed using the Invention Kits to target a range of skills relating to both advanced manufacturing technologies and traditional skills for constructing mechanisms by hand. Technological skills generally included the use of CAD software in combination with advanced manufacturing technologies such as 3D printing and laser cutting. Traditional skills included basic methods for cutting, adhering, and measuring, etc., as well as more specialized skills used for building electronics, such as soldering and bread-boarding. The construction of artifacts also allowed students to learn and apply of principles of mechanics through simple machines. For example, one teacher included a successful application of rotational motion as a required criterion in a design challenge. The Make-to-Learn website states, “Mechanical proficiency is an important part of our heritage. This mechanical proficiency led to the invention of pivotal electromechanical innovations in the nineteenth century, including the telegraph, the telephone, and the electrical grid.” The implication is that such mechanical proficiency is an important skill that students need to create their own designs later on.

Not all teachers approached teaching technological and mechanical skills in the same manner or degree. Richard explained that his approach to teaching CAD was to give students a brief, thirty-minute overview. This was not enough time for students to learn it all, but it got them started. From there, the students quickly learned and taught each other the ins-and-outs of CAD. He went on to explain that students were motivated to teach themselves because the project had established a “need-to-know,” by which he meant his students were intrinsically motivated to learn the skills so that they could finish a project in which they were invested.

In his “Introduction to Engineering” class, Brian spent considerably more time helping students learn CAD and other skills related to the 3D printers, laser cutters and other tools in his classroom. While in past years, students acquired these skills exclusively in the context of the Invention Kits, more recently, he created activities to help students learn them in advance. He explained:

> They're going to need some design skills to do these things [the Invention Kits]. Let's put those at the front end to facilitate. That way, they're only worried about the application of the science and not actually application of science and design skills learning simultaneously.

In the past, much of his time was spent helping students use the tools. By “frontloading” these skills, he was able spend more time helping students on content-related issues. He explained that students that seek additional skills while engaged in the Invention Kits often look to online resources, such as tutorials found on YouTube. This strategy is encouraged as an example of autonomy and self-reliance.

On the whole, teachers that were implementing the Invention Kits in regular science classrooms felt that they had less time and need to spend a lot of time on CAD and advanced manufacturing technologies. Brenda, an eighth-grade physical science teacher explained that the practicality of teaching these skills could also be impacted by the characteristics of different classes.

> So, I’ve used some of this Make-to-Learn readiness component, in terms of doing 2-D design and using the Silhouettes [digital die cutters] and having projects that

> showcase that and the moving to 3-D and I've done like a density project where people designed a shape and did density work with that. That was all ramping up to be able to do this project, but each one of those preps takes a lot of time and, if you have a group or a cohort that is challenging, you can't do it. You can't do it.

Brenda suggested that managing such activities was especially difficult if the students were not self-motivated and invested in the project. Other teachers described similar experiences.

Make Subcomponents

On the IC Map, the Make component is organized under three subcomponents that relate to the reconstruction of an artifact, building competencies in design and advanced manufacturing, and building competencies for constructing by hand. (See Table 8). The "Big Idea" is included to convey to teachers to overall purpose or rationale for the subcomponent. The dimensions listed next to each action statement describe more specific aspects or parts of the component and are often points of variation across the columns of the IC Map. In the Make component, dimensions relate to the level and type of student participation, the types of competencies addressed, themes relating to innovation in the 21^{st} century, and values such as self-reliance. Variations of these dimensions are described on the corresponding pages of the IC Map that follow.

Table 8
Overview of the Make component – subcomponent statements and dimensions.

Subcomponent Statement	The Big Idea	Dimensions
1. Have students construct tools and/or replicas for learning.	Students benefit from building their own artifacts.	• Student participation • Managing tools and materials
2. Build competencies for modern design and manufacturing technologies	Students develop high-tech skills.	• CAD • CAM • Themes of modern innovation
3. Build competencies for constructing by hand	Students develop low-tech skills.	• Building proficiency with hand tools • Learning about materials • Developing self-reliance

Table 9.1
IC Map Subcomponent 1

<table>
<tr><td colspan="4">Make – Reconstructing Tools and Mechanisms</td></tr>
<tr><td colspan="4">1. Have Students Construct Tools and Artifacts for Learning</td></tr>
<tr><td colspan="4">The Big Idea: Students benefit by building their own artifacts.</td></tr>
<tr><td colspan="4">Dimensions: Student Participation, Tools and Materials</td></tr>
<tr><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr>
<td>• All students participate in constructing the tool (e.g. continuity tester) and/or artifact (e.g. linear motor) they will be using.
• The teacher provides all the tools and materials needed to successfully construct the tool and/or artifact.</td>
<td>• All students participate in constructing some portion of the tool and/or artifact that they will be using.
• The teacher provides all the tools and materials needed to successfully construct the tool and/or artifact.</td>
<td>• The teacher allows only some of the students to participate in constructing the tool and/or artifact that they will be using.
and/or
• The teacher does not provide sufficient tools and materials to successfully construct the tool and/or artifact.</td>
<td>• Students do not construct the tool and/or artifact that they will be using. Tools and/or artifacts are pre-built.</td>
</tr>
</table>

Table 9.2
IC Map Subcomponent 2

<table>
<tr><th colspan="4">Make – Reconstructing Tools and Mechanisms</th></tr>
<tr><td colspan="4">2. Build Competencies for Modern Design and Manufacturing Technologies</td></tr>
<tr><td colspan="4">The Big Idea: Students develop high-tech skills.</td></tr>
<tr><td colspan="4">Dimensions: Computer-Assisted Design (CAD), Computer-Aided Manufacturing (CAM), Themes</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td>D</td></tr>
<tr>
<td>• Students use CAD software for exploring and modifying existing designs (e.g. historical devices) or for creating their own designs.
• Students use CAM technologies such as 3D printers, laser cutters, or digital die cutters to fabricate their own designs.
• The teacher leads explorations about how CAD and CAM technologies impact modern invention and innovation. The teacher shares examples from the news, magazines, and other media. Students discuss how the rising accessibility of these tools has made it easier for ordinary Americans to invent and innovate.</td>
<td>• Students use CAD software for exploring existing designs (e.g. historical devices) but not for making modifications or creating their own designs.
• Students use CAM technologies such as 3D printers, laser cutters, or digital die cutters to fabricate designs that are provided to them.
• The teacher leads explorations about how CAD and CAM technologies impact modern invention and innovation. The teacher shares examples from the news, magazines, and other media.</td>
<td>• Students are exposed to CAD software (e.g. teacher demonstration or isolated student activity) but do not have opportunities for exploring and modifying existing designs or creating their own designs.
• Students are exposed to CAM technologies (e.g. teacher demonstrations, videos, photos, or articles), but they do not have opportunities to use the technologies.</td>
<td>• Students are not exposed to CAD software.
• Students are not exposed to CAM technologies.</td>
</tr>
</table>

Table 9.3
IC Map Subcomponent 3

<table>
<tr><td colspan="4">Make – Reconstructing Tools and Mechanisms</td></tr>
<tr><td colspan="4">3. Build Competencies for Constructing by Hand</td></tr>
<tr><td colspan="4">The Big Idea: Students develop low-tech skills and a “can-do” spirit.</td></tr>
<tr><td colspan="4">Dimensions: Hand Tools, Methods, Materials, Support</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td></td></tr>
<tr><td>● Students regularly use tools and methods for assembling designs created using CAM technologies or for building entirely by hand. The teacher provides instruction on methods that relate to safely measuring, cutting, shaping, adhering, fastening, etc. Tools include saws, utility knives, soldering irons, etc.
● Students regularly build using a variety of materials. These may include plastics, woods, metals, and paper. They have opportunities to learn and practice special techniques that are used to work with various materials. They are able to consider the suitability of a material for a given purpose and consider trade-offs among them.
● The teacher uses a variety of strategies to help students extend their know-how. The teacher guides students to outside sources such as Instructables or YouTube. He or she regularly asks students who have mastered a skill to teach their peers.</td><td>● Students occasionally use tools and methods for assembling designs created using CAM technologies or for building entirely by hand.
● Students occasionally build using a variety of materials. These may include plastics, woods, metals, and paper. They have opportunities to learn and practice special techniques that are used to work with various materials.
● The teacher sometimes uses a variety of strategies to help students extend their know-how. The teacher may occasionally point students to outside sources or ask students who have mastered a skill to teach their peers.</td><td>● Students rarely or never use tools and methods for assembling designs created using CAM technologies or for building entirely by hand.
● Students rarely or never build using a variety of materials.
● The teacher is the sole source for know-how.</td><td></td></tr>
</table>

The Explore Component

During the Explore phase, students complete a series of Lab Activities that are designed to help students learn fundamental scientific principles. In most cases, the artifacts constructed in the Make phase are the centerpieces of these activities. For example, in the Linear Motor Invention Kit, groups of students attach leads to the solenoid of their newly-constructed linear motors then touch those leads to 9-volt battery terminals. Having observed the armatures of the motors move in one direction, the students then switch the leads and again touch them to the battery terminals. The students should now observe that the motor armatures move in the opposite direction. Thus, a series of activities that allow students to explore the properties of alternating current begins.

Key Findings

Utilizing the Sequence to Facilitate Knowledge Construction

Helping students construct knowledge of scientific content was cited as a key goal during the Explore phase of the Invention Kits. Developers and core teachers described three levels of sequencing that is intended to scaffold such learning - within Lab Activities, across Lab Activities, and across Invention Kits. One developer described the sequence within an individual Lab Activities in the following way:

> I would say the sequence of a lab is to answer an essential question from the ground up in a hands-on manner. We want the students to create their own knowledge. We want them to confront their misconceptions, to test them, and then to reevaluate them and create new ones themselves.

Another developer described how sequencing across Lab Activities is used to facilitate the process of knowledge construction.

> The unit has sort of a goal, what we want them to get out of it, and the Labs sort of break that down into pieces. And there is an order to them. I don't know if it’s a strict order all the time but there is a sensible order to them…. They’re helping them make discoveries, or, sometimes, it’s just develop some skills.

Richard described the sequence from one Invention Kit to the next in the following way:

> They [the Invention Kits] are designed to scaffold upon each other. You have to know how to build a solenoid to build the linear motor. By understanding the linear motor, and then building a generator, and studying the generator, you understand how the generator functions to move the linear motor, you move the motor fast enough it makes a sound, which helps you understand the speaker… You do the speaker in reverse – that generates a current that can move a motor or move another speaker, which is mechanical. The scaffolding is very real and doing them in order does help a lot.

In all three cases, the implication is that students can actively combine smaller units of knowledge or discovery to construct a deeper, more complete understanding of scientific content. In explaining this idea, Richard went on to describe how his students reacted when they operated their linear motors at such a high frequency that motion was no longer visible but was entirely audible.

> The fascinating part is that, at one point…, the thing is going back and forth so quickly that it makes a sound. The sound is the frequency that it's going at. All of a sudden, you turn a linear motor into a speaker. For the first time, kids seem to

> understand what a sound is. They're blown away that this thing moving back and forth is making a sound and that's a frequency. They get it. You can't have a kid understand a speaker by pulling out a boom box and saying, "This is how sound works." They can't get that abstract thing. I would argue – teachers when they go through this process – when I've shown this kit, when I've had kids show this kit, teachers, adults, are blown away. They've never understood the concept that sound is physical movement. It is this epiphany that these kids have that, my opinion, that is the strongest kit that has been developed because it really does connect everything together, tie everything, and let kids discover sound.

As Richard explained it, physical experiments with the linear motor allowed students to “see” sound with a clarity they had never experienced before, which helped them construct an accurate understanding of how sound works.

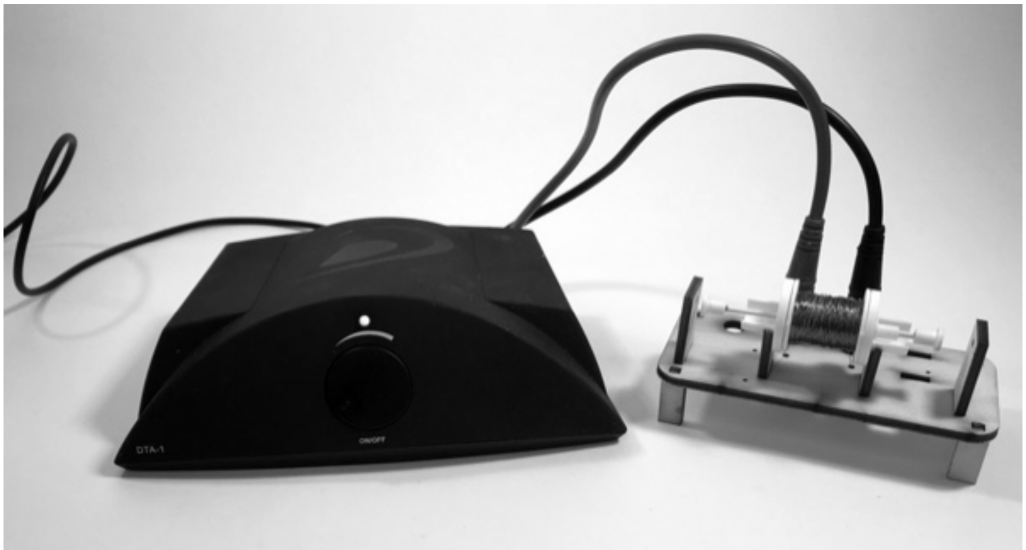


Figure 7. A linear motor connected to an amplifier, which is used to send a signal to the motor

Leveraging Transparency

Richards's description of linear motor and its connection to sound is an example of transparency, which developers and teachers pointed to as one of the most important features of the Invention Kits. Many modern technologies are complex and opaque – few people can explain the scientific principles behind their cellphones, and peering at them provides no clues. Many of those interviewed described such devices as "black boxes." However, the historical inventions at the heart of the Invention Kits are different. As one developer explained:

> If you try to look at a smart phone, there really is no way to understand what's inside it or how it works, but if you take a 19th century telegraph relay, it's an electromechanical mechanism that can be taken apart, and you can understand how all of the parts work so that students can get this foundational knowledge.

Because of the relative simplicity of the Invention Kit artifacts, it is easier for students to see and understand the scientific principles at play. What is more, the transparency of the devices is enhanced because the students understand how the pieces fit together, having built them themselves. And they can just as easily take them apart as they explore how each individual part contributes to the whole. One developer explained:

> The learning part – once you have them at that point that they're fully engaged, they've done it, they've built it, the transparency of the kit is what makes it so powerful. I would say they can see it, there's no other explanation of what it could be. Again, with the [modern] speaker – the cone, the box that's put around it, kids can't see or understand – there could be a dozen reasons why that speaker works. I know for a fact as a kid you have to have that cone in order to hear things and

> they're seeing it without the cone. What's the point of a cone, then? It takes away all the mystery through its transparency and that's what I would consider the most critical part of the kit.

Again, the ability to deeply explore a relatively simple mechanism they have built themselves allowed his students to confront their existing theories about sound and hone in on how a speaker actually works.

Adjusting the Lab Sequence

While nearly everyone who was interviewed pointed to the sequence of the Lab Activities as deliberate and useful, several were careful also to point out that the Labs are not intended to be implemented rigidly or mechanically. One developer explained:

> I personally don't see [the Lab Activities] as something that we want teachers to follow step by step all the time. And we don't think they're all gonna do it the same way. And certainly, I don't intend these to be taught that way where somebody follows the exact sequence in the exact way, giving them the step by step. It's like paint-by-numbers versus learning how to create a painting. Not the same thing.

Skilled teachers may decide that certain adjustments are needed to meet the needs of their students or to better suit their own teaching styles. The Lab Activities are not meant to be viewed as scripted activities.

Assessing Learning

Christine explained that while the hands-on activities may have value unto themselves, teachers still need to ensure that students are learning.

> That would be the thing where if I was a teacher just trying to incorporate more project-based learning, I would be like, "This is great. They're going to get so much out of it." Well, unless you really force them to think about it and direct them – you're the one who knows what you want them to understand. How can you set it up to where you're pulling that out of them? It won't happen on its own. We've done so many things where [we say to ourselves] – "Why did we just end up doing that? They still don't get it. They just did stuff with their hands."

Having had the students build the artifacts and perform the Lab Activities, it was tempting for the teachers to assume that students understood the content, but that was not necessarily the case. Several developers described this phenomenon as the "illusion of knowledge." In a recent article, they explained:

> Scaffolding is required to ensure that the process of making a mechanism results in a corresponding understanding of its underlying principle of operation. We refer to the latter phenomenon as the illusion of knowledge. This is the unfounded belief, noted by Philip Sadler in the documentary Minds of Our Own, that knowledge acquired in a rote fashion is the same as actual understanding. In a school makerspace project, the fact that a student successfully completes a competency by building a working mechanism is not by itself an indication of an understanding of the underlying principles. (Bull & Garofalo, 2017, p. 18)

The article goes on to explain that additional assessment is needed to ensure that students have developed clear and accurate understandings of the science content.

All teachers pointed to formative assessment as an important part of implementing the Lab Activities. Requiring students to document their work was one strategy for formatively assessing learning. Most of them used some variation of the student handout included in the Solenoid Invention Kit, which required students to respond in writing to three questions while performing the Lab Activities: (1) “What do you see?”; (2) “What do you think about what you saw?”; and (3) “What does it make you wonder?”. The Invention Kit documentation explains that these questions, developed by Project Zero at Harvard University, were included to “help drive student thinking and promote deeper learning” (Laboratory School for Advanced Manufacturing, 2017b).

Christine explained that she determined that her 8th graders needed more guidance than was provided by these questions. She stated:

> In some ways, I stepped up the reflection pieces – a little more guided reflection, I would say, as far as, “I really want a response to this, really want a response to that.” I incorporated more of those as you went - when they have to specifically address a question. Otherwise, it’s very surfacey [sic]. They have to go deeper, but our kids, we have to be very clear that’s what we want.

Christine and her colleague Jack provided this direction by revising the handouts to target specific ideas and to require students to respond thoroughly and thoughtfully.

Confronting Misconceptions

Several of the teachers described interactions with students that were intended to help students engage naturally with the content, make discoveries, and come to accurate conclusions on their own. Richard explained that he prefers to let students realize and correct their own mistakes.

> I'm asking questions that are going to make them wonder and have guesses, but there would be right and wrong answers. The difference would be that being wrong is absolutely okay. There's nothing wrong with being wrong because that's how you're learning through. 'Oh, I think it's direct current,' and then I [the student] explore through and it's like, "Oh, it's alternating current. I got it. That makes sense.'

Richard explained that sometimes students will not discover their misconceptions on their own, which he prefers to address by asking students to justify or "prove" their assumptions. He provided a hypothetical exchange with a student in which the student incorrectly explains that the electrical current he or she is observing is direct current:

> So, alternating current. [Teacher:] "So, what have you discovered about that current?" [Student:] "Oh, I think it's direct current." [Teacher:] "That's interesting. Tell me why you think it's direct current." [Student:] "Well, the electricity is going directly from here to here." [Teacher:] "Can you prove that? Prove that to me and I'll come back. I'd be very curious to see what you find." Then, [I] come back and see what happens.

His experience was that, while trying to prove their assumptions or conclusions, his students confronted inconsistencies or contradictions that forced them to revise their thinking.

Facilitating Collaboration

All the teachers observed allowed students to collaborate on the Lab Activities in pairs or in small groups. One developer explained that small groups allowed teachers to put students in charge of the learning.

> When I walk into a classroom and observe these kits being done, what I like to see best is a student-centered approach. So students are working on their own or in small groups. The teacher is available as a resource, but is kind of walking around the classroom and observing what's going on.

As he described it, small groups allowed students to teach and learn from each other, many times arriving at a solution without teacher intervention. In this setting, the teacher could truly become a facilitator rather that the sole source of knowledge. He went on:

> So students, they ask a peer before they ask a teacher. They might ask another group before they ask the teacher. Once they ask the teacher, they don't ask the question alone. They ask, where can I find an answer, right? So the teacher then gives a resource for that question instead of an answer to that question.

Requiring students to first consult with peers or other groups helped nurture collaboration and encouraged students to view one another as sources of knowledge. Meanwhile, when the teacher's help was indeed needed, providing students with resources for their question rather than answers helped students develop self-reliance.

Managing Workflows and Materials

When students followed the procedure described above to find answers to their questions, they were following a routine that the teacher had to work to establish. Teachers reported that employing these kinds of classroom management strategies was a large part of implementing the Invention Kits, requiring significant time and energy. Brian explained:

> I'd be mistaken if I said that in deploying these kits, the management piece or classroom environment piece doesn't matter. It absolutely does. It's a hugely

> critical thing. You're seeing us probably five weeks into the course right now, so we've spent a lot of time building in those structures. There are still some teaching happening of the structures and there's still this idea of redoing things if they're not done the way they're supposed to.

This teacher had established routines for each part of the day which allowed them to become “stewards of their own learning.” For example, when students arrived in his room, they gathered laptops and stood at lab tables with their group mates for daily goal setting, followed by a brief discussion of the day’s objectives. "Autonomy is our third pillar. You are in the driver’s seat," he reminded them before setting them loose to gather their materials and begin the day’s work. At the end of the class period, a similar meeting was held for teams to review and document their progress on their “Scrum Boards” – a project-management strategy borrowed from Agile, a popular software development framework. "Real companies use this; this is not busywork!" he announced to the class. These are but two examples of the many routines that this teacher had established to govern teamwork, productivity, safety, and organization. He reported that such routines were essential to his self-paced, project-based approach and allowed him to focus his attention on supporting the students’ learning as they worked through the Lab Activities or created their inventions. As he explained, it is important to “set up and structure your environment so that you as the teacher are not cognitively bogged down with lower-level things, but you can then really focus on those interactions that are teaching- and learning-focused. Not just like, where is this and where is that”. Without these routines and structure, a teacher can become overwhelmed by the logistics of implementing of the Invention Kits, which impedes one's ability to focus on student learning.

Teachers reported that managing materials was also important. Most of them spent a significant amount of time outside of class preparing and organizing the tools and materials that students would need for whatever Lab Activities they would be working on that day. They employed various strategies for this. Pamela, an eighth-grade STEM teacher, put all the materials needed for a particular Lab Activity – a length of wire, a compass, a 9-volt battery, and alligator clips – into Ziploc baggies that students picked up at the back of the classroom. Others arranged these materials separately in bins. In each case, the goal was to get the students what they needed as quickly and efficiently as possible. Christine noted that the amount of preparation that was needed was significant, but that it was only one of many challenges that teachers needed to address.

> So, I could imagine that prep could be prohibitive for some people…, but that happens a lot with activities in science environments. You can do all these things, but also, can you manage to fit it all in in a timely manner? Can you prep it? Can you break it down? Can you have clean-up?

As Christine explained, there was more to implementing the Lab Activities than simply going through the steps.

The teachers found that lacking tools or materials could cause significant downtime or confusion. Several teachers had difficulty getting through the solenoid activities in a timely manner because they only had two or three of the battery-powered winding mechanisms that the students used to wrap their solenoids, which limited the number of students that could be completing this task at any given time. Pamela explained how her students became confused when they were not provided the same tools and materials that were shown on the Make-to-Learn website. For one Lab Activity that was designed to demonstrate alternating current by means of the oscillating needle of an analogue ammeter, she explained that she had to replace the analogue ammeter with a digital multi-meter. “We wound up just using the multi-meter… and talking about, “Well, why does the [number representing the] current go from positive to negative on the multi-meter?” Pamela did not suggest that she felt that the students learned any less, but that some of her students had difficulty navigating the differences between what was shown on the website and what they had available.

Priming Students for the Invent Phase

Both developers and teachers explained that an important objective during the Make and Explore phases was to get students thinking about how they might extend the artifacts and scientific principles during the next phase – Invent. One developer explained:

> For me, the idea is to take this stuff and be able to sort of think about it beyond. So, kids don’t need to make linear motors. There are plenty of motors around, right? But what do they gain from it? They’re thinking about how electricity works and how mechanisms work. It helps them think about other things.

Those things include possible uses. The teachers described leading discussions about modern-day applications to stimulate this thinking. Richard stated, “These Invention Kits are a method of getting kids to… meaningfully interact with things that are real-world applicable. The relay in particular… we use it everywhere, every day.” Another teacher explained how he and his students discussed how electromagnets are used in doorbells, door locks, and in cranes that move steel.

While his students learned to manipulate the artifacts and consider their modern-day applications, Richard explained that he regularly engaged them in conversations that invited them to think about how they might use the artifacts for their own purposes.

> Throughout the lesson, anytime we got to a point after they had their time in class, we'd be talking about, “What did you figure out? Where did we see this? Have you ever seen this before? You just moved this piece of metal, what could you do with that? Why is this significant?” It builds and it builds, and you kind of use that same theme throughout the Invention Kit. At the very end, you have something, “Okay, now what can you use this for? Where did we see this?” We've gone from motor to speaker and they're like, “I can literally build my own speaker now. I can build my own telephone now because a speaker in reverse is a microphone. I'm gonna figure that out, I'm gonna explore that.

As Richard and others explained, it was important to get students thinking about these things from the outset. He further explained that once he got his students thinking about inventing, he felt that it was important to stay attuned to their thinking with an open mind. He stated:

> One of the powerful parts about an Invention Kit is that kids can actually make things, or it can inspire their building of something else later on. You have to be open to that because you don't know what it's going to inspire them to do. You never know what it's going to probe kids to want to do next, but you gotta give

> them that opportunity to do that. I'm always thinking and looking and listening to those opportunities for those kids.

The conversations that he had with his students during the Make and Explore phases sparked ideas in students that he could later draw upon during the upcoming Invent phase.

Explore Subcomponents

On the IC Map, the Explore phase includes six subcomponents. Each subcomponent contains a number of dimensions. Both are listed in Table 10. A sampling of key findings that contributed to the development of these subcomponents and dimensions follows.

Table 10
Overview of the Explore Component – Subcomponent Statements and Dimensions

Subcomponent Statement	The Big Idea	Dimensions
4. Leverage the Lab Sequence to Scaffold Learning	The Lab Activities are deliberately sequenced to build conceptual understanding.	• Lab activities • Essential and guiding questions • Reflection guides • Formative assessment • Multiple representations
5. Let Students Engage Naturally with the Content	Students engage in scientific inquiry to construct knowledge.	• Autonomy • Time • Flexibility
6. Use the Tool or Artifact to Actively Facilitate Deep Understanding of Scientific Principles	Teachers actively facilitate knowledge construction.	• Asking questions • Addressing misconceptions
7. Facilitate Collaboration	Students benefit from discussing ideas with their peers.	• Size • Interactions • Self-reliance
8. Manage Materials and Workflows	Teachers create and manage a classroom environment that is conducive to exploring the artifact.	• Materials • Organization • Workflows
9. Establish the Purpose and Utility of the Tool or Mechanism	Teachers establish relevance and set the stage for invention.	• Functionality • Real-world applications • Extensions

Table 11.1
IC Map Subcomponent 4

<table>
<tr><th colspan="4">Explore – Exploring Science through Lab Activities</th></tr>
<tr><th colspan="4">4. Leverage the Lab Sequence to Scaffold Learning</th></tr>
<tr><td colspan="4">The Big Idea: The Lab Activities are deliberately sequenced to build conceptual understanding.</td></tr>
<tr><td colspan="4">Dimensions: Lab Activities, Documentation of Student Thinking, Formative Assessment, Multiple Representations</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td>D</td></tr>
<tr>
<td>• The teacher implements all the Lab Activities in order. Any modifications or substitutions preserve all aspects of the conceptual learning progression.
• The teacher requires students to address the essential and guiding questions in each Lab Activity and document their observations using the Lab Handouts or similar materials.
• The teacher frequently interacts with students, while they are engaged in the activities, to ensure they are having success. He or she poses thought-provoking questions that require students to articulate their thinking regarding the essential questions and make connections among the Lab Activities.
• The teacher utilizes multiple representations (videos, computer simulations, hands-on or digital manipulatives, etc.) from the Invention Kits and elsewhere (e.g. YouTube) to further illustrate essential concepts as needed. The teachers helps students connect them to the Lab Activities.</td>
<td>• The teacher implements most the Lab Activities in order. Any modifications or substitutions preserve most aspects of the conceptual learning progression.
• The teacher requires students to address the essential and guiding questions in each Lab Activity and document their observations using the Lab Handouts or similar materials.
• The teacher occasionally checks in with students to ensure they have successfully completed the lab activities. He or she occasionally poses questions to assess their thinking and prompt connections.</td>
<td>• The teacher implements only some the Lab Activities. Not all concepts are addressed.
or
• The teacher implements all of the Lab Activities but implements them out of order. The learning progression is significantly altered.
• The teacher asks students to address essential and guiding questions but does not require students to document their observations.</td>
<td>• The teacher implements few or none of the Lab Activities.</td>
</tr>
</table>

Table 11.2
IC Map Subcomponent 5

Explore – Exploring Science through Lab Activities			
5. Let Students Engage Naturally with the Content			
The Big Idea: Students engage in scientific inquiry to construct knowledge.			
Dimensions: Autonomy, Time, Flexibility			
A	B	C	
• The teacher gives students the autonomy to work through the Lab Activities on their own and take ownership of the process. • The teacher provides ample time for students to engage in scientific inquiry in a hands-on fashion – observe, hypothesize, investigate, draw conclusions, make discoveries, etc. • Students have the flexibility to extend the activities pursue additional connections.	• The teacher gives students some autonomy to work through the Lab Activities on their own. • The teacher provides a moderate amount of time for students to engage in scientific inquiry in a hands-on fashion – observe, hypothesize, investigate, draw conclusions, make discoveries, etc. • The pacing of the Labs or other teacher-imposed constraints do not provide flexibility for student to pursue additional connections.	• The teacher exerts total control over the Lab Activities. Students do not have the autonomy to work through the activities on their own. • The Lab Activities are rushed – students do not have time to engage in scientific inquiry.	

Table 11.3
IC Map Subcomponent 6

<table>
<tr><td colspan="4">Explore – Exploring Science through Lab Activities</td></tr>
<tr><td colspan="4">6. Use the Tool or Artifact to Actively Facilitate Deep Understanding of Scientific Principles</td></tr>
<tr><td colspan="4">The Big Idea: Teachers actively facilitate knowledge construction.</td></tr>
<tr><td colspan="4">Dimensions: Asking Questions, Addressing Misconceptions</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td></td></tr>
<tr><td>● The teacher asks thought-provoking questions that probe for deep understanding of how scientific principles govern the functionality of the tools and/or mechanisms. The teacher requires students to justify their thinking (e.g. “What type of electrical current is at play? How do you know that?).
● When students demonstrate misconceptions, he or she asks thought-provoking questions that help students reveal those misconceptions themselves (e.g. “Can you prove that?”)</td><td>● The teacher asks students to explain what they observed, but does not require them to justify their thinking. Questions can be answered by regurgitating definitions (e.g. “Why is this an example of alternating current?”).
● When students demonstrate misconceptions, he or she asks students to perform additional actions that will reveal those misconceptions (e.g. “Try this.”).</td><td>● The teacher asks few questions that facilitate learning or reveal misconceptions.
● When students demonstrate misconceptions, he or she corrects their misconceptions by telling them what is actually happening.</td><td></td></tr>
</table>

Table 11.4
IC Map Subcomponent 7

Explore – Exploring Science through Lab Activities			
7. Facilitate Collaboration			
The Big Idea: Students benefit from discussing their ideas with peers.			
Dimensions: Size, Interactions, Self-Reliance			
A	B	C	D
• The teacher organizes students in pairs or in small groups. • The teacher requires students discuss their observations with one another. The students pose questions and help test each other's ideas. • When problems arise, they work together to find solutions, only seeking teacher assistance when necessary. When approached by students for help, the teacher generally avoids giving students the answer. Instead, he or she coaches them how to find their own answers.	• The teacher organizes students in pairs or in small groups. • The teacher requires students discuss their observations with one another. • When problems arise, they sometimes work together to find solutions but often seek teacher assistance.	• The teacher organizes students in large groups (over 5). • The students have limited opportunities to discuss their observations with one another. • When problems arise, they are unable to work together and seek teacher assistance.	• The teacher does not use collaborative grouping. The Lab Activities are done as teacher-led, whole-class activities.

Table 11.5
IC Map Subcomponent 8

Explore – Exploring Science through Lab Activities			
8. Manage Materials and Workflows			
The Big Idea: Teachers create and manage a classroom environment that is conducive to exploring the artifact.			
Dimensions: Materials, Organization, Workflows			
A	B	C	
• The teacher provides ample supplies of all the materials necessary for students to have successful Lab Activity experiences. • The teacher organizes tools and materials so that can be distributed by the teacher or retrieved by students easily. • Workflows are established that allows students to work productively. The teacher ensures that students understand the tasks at hand. Students understand procedures for getting materials they need. The teacher ensures that the students make steady progress throughout the activities.	• The teacher provides adequate supplies of most of the materials necessary for students to have successful Lab Activity experiences. Materials substituted or omitted only minimally impact the Lab Activity experiences. • The teacher organizes tools and materials so that can be distributed by the teacher or retrieved by students somewhat easily. • Workflows are established that allows students to work productively.	• The teacher does not provide the necessary materials for students to have successful lab activity experiences. • A lack of organization or clear workflows results in significant downtime and disruptions. Opportunities for learning are substantially impacted.	

Table 11.6
IC Map Subcomponent 9

<table>
<tr><td colspan="4">Explore – Exploring Science through Lab Activities</td></tr>
<tr><td colspan="4">9. Establish the Purpose and Utility of the Tool or Mechanism</td></tr>
<tr><td colspan="4">The Big Idea: Teachers establish relevance and set the stage for invention.</td></tr>
<tr><td colspan="4">Dimensions: Use, Real-World Applications, Extensions</td></tr>
<tr><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr>
<td>● The teacher ensures that students can use the tool or artifact properly.
● The teacher helps students understand the purpose and utility of the tool or artifact. He or she provides examples of real-world applications and invites students to research other applications. He or she helps students appreciate that many innovations are built upon basic ideas.
● The teacher poses open-ended questions that prompt students to consider novel uses of the tool or mechanism (e.g. “What could you use this for?”). If the object is an ancillary mechanism (e.g. a continuity tester), the teacher guides students to understand how such devices support and facilitate the process of invention.</td>
<td>● The teacher ensures that students can use the tool or artifact properly.
● The teacher helps students understand the purpose and utility of the tool or artifact. He or she provides examples of real-world applications and invites students to research other applications. He or she helps students appreciate that many innovations are built upon basic ideas.</td>
<td>● The teacher ensures that students can use the tool or artifact properly but does not help students understand how it is used in the real-world.</td>
<td>● The teacher neither ensures that students can use the tool or artifact properly nor helps students understand how it is used in the real-world.</td>
</tr>
</table>

The Invent Component

During the Invent phase, students are challenged to extend the skills and content knowledge learned during the Make and Explore phases to design and create something new. Ideally, the students develop applications that are personally meaningful to them. Often, their creations are playful. For example, for the Linear Motor Invention Kit, one group of students developed a miniature bowling game in which a small ball was launched toward the pins by an armature linked to a magnet and solenoid. The Invent phase requires students to practice engineering and engineering design and further develop their technological and mechanical competencies. It also allows them to meaningfully apply scientific content.

Key Findings

Building upon a Foundation

Most developers described the Invent phase as an open-ended extension that builds upon a foundation of skills and content knowledge developed during the previous phases. As one developer put it:

> I think maybe an essential component to the Invention Kit is that it doesn't necessarily have an end…. It's not bookended by anything, really. It's we're trying to lay a foundation, and then have them build on that foundation in whatever they choose to build. We hope that it’s a strong enough foundation for them to build many different things, and that they're inspired and they reach into their creative side and do something fun with it.

Meanwhile, on the Make-to-Learn website, the developers used the analogy of building blocks:

> Engineering projects will allow students opportunities to employ the mechanism or device in extensions that allow them to create inventions of their own. For example, there are multiple ways in which relays or electric motors could be incorporated as building blocks in students' own inventions. This will also pave the way for students' use of modern-day counterparts of these artifacts in subsequent engineering courses. (FabNet Invention System, 2016)

The idea is that, by the time students arrive at the Invent phase, they will be well prepared – they will have developed foundational skills for building; they will understand how a device like a solenoid can be used for many different purposes; and they will have been inspired to consider what they might be able to invent themselves.

Making to Learn

One of the core tenets of the project is that children learn through making. As one developer stated:

> These kits were created because we have the philosophy that children can learn meaningful content and meaningful skills by making something – that they have the ability to create and learn on their own.

However, the developers explained that it's not enough to make just anything – the learning happens when the creation is personally meaningful to the student. The meaningful project leads to the meaningful learning. This was described as a critical aspect of the Invention Kits. One developer stated:

> If they only replicate the invention, that may be useful; but we haven't achieved our goal until they – There's a series of things where you make knowledge of your own called "appropriation." So, first you have to assimilate the knowledge, and

> you have to appropriate it where you take ownership, and unless they extend it in some way with their own invention, they'll not get ownership of the knowledge.

In other words, the recreation of an artifact that occurred in the Make phase is not enough. Students do not truly own the targeted content and skills until they apply them to something meaningful – in this case, an invention.

Design Challenges

The Invent phase begins with a design challenge, which is described as a "practical open-ended exercise" that "challenges students to apply their new understanding gained from the lab activities" (Laboratory School for Advanced Manufacturing, 2017b). The developers explained that design challenges could be implemented in a variety of ways, so long as the spirit of invention was preserved. One developer explained:

> The vision for this is not only [would] my students learn how the inventors came to invent these pivotal inventions in American History, but also that they would use the inventions to create innovations of their own. So, it could be something as simple as making the electric motor make this pop-up card work, or it could be something very complex like … that very elaborate 3D printed and die-cut thing where they have motors and actuators moving it. I think that's really the heart of it.

The teachers that implemented design challenges varied in the number and extent of the constraints that they included in the challenge. Brian described posing the challenge in the following way:

> I gave my kids a proposal and say, "Hey, you've just done a bunch of labs and you learned a bunch of science about how a solenoid works or how a linear motor can operate or what effect alternating current has on a solenoid." From there, let's say for the linear motor, I'll say, "I want you to build a device that creates back and forth motion at varying frequencies. And then I want you to do something with it."

This challenge was particularly open-ended; the primary constraint was that the students apply linear motion at varying frequencies. What the students did with the motion was up to them.

Pamela described how a challenge might be posed with greater constraints. She explained:

> So, in our class, we treat engineering as an open-ended design challenge. So, rather than saying, "All right. Now, we're gonna follow cookbook, step-by-step, these directions to make this," the engineering part is, "Okay. Your challenge is to turn your motor into a generator, and these are some resources. These are your materials. You have four days to do it." The engineering is the, "Okay. Here's your problem. Here are your materials and your constraints. Your solution is gonna look very different than somebody else's."

Students are more strictly constrained by the nature of the task, the materials they can use, and the amount of time they are given to work, but are still given autonomy to create unique designs.

Learning from Failure

The developers recommend that teachers require students to submit proposals before student begin work. In the Solenoid Invention Kit, the proposal is described in the following way:

> The first task students must complete for the Design Challenge is to submit a proposal that includes a design description, preliminary design sketches, and a plan for how the group will work towards a final product (roles, deadlines, etc.). This serves as a preliminary assessment for the instructor to see which groups need more support from the beginning. Proposals should not represent a perfect plan that will automatically work. Rather, teachers should allow students to authentically run with their ideas, even if they fail. If students are way off the mark on their proposal, the teacher should facilitate their conversation towards more feasible designs. (Laboratory School for Advanced Manufacturing, 2017a)

Such proposals are important in that they encourage students to think through the task and chart a course forward. However, they are rarely perfect, which developers describe as an important aspect of the process. Brian described how he approaches student proposals:

> [In their proposal], if they have what they think is back and forth motion, but they've incorrectly applied or their design is going to be horrible and not work, I'll still approve them. I want them to figure out that that's a misapplication of the science. There is probably going to be more learning in that situation than if they get it right off the bat.

Brian and others explained that there is more value in the students discovering their mistakes on their own than in being told by the teacher that their designs will not work. He explained that he generally approves plan unless they do not address the criteria of the challenge.

> The way I framed it in the past is, "I want you to dive into the deep end and sort of into the unknown, but I want to make sure you're diving into the right body of water." If, for the linear motor, I say, "Build a device that creates back and forth motion," and they're doing something that has nothing to do with back and forth motion – let's say it's rotational motion or something completely opposite or nothing related. I'll say, "No, let's go back to the requirements and the way it's stated. We want back and forth motion."

In this way, the teacher is ensuring that they can succeed with the challenge, but not that they will succeed. As a developer put it, “I think it's really important that they succeed in this, not that they succeed at first, but that they can succeed.”

Coaching Students through Failure

As one developer explained, some teachers can find it challenging to allow students to fail. Teachers, by nature or conditioning, do not like to see their students struggle. Nonetheless, initial failure is common with the Invention Kits.

> I think there are a lot of teachers too that don’t know how or that have difficulty handling their kids not succeeding the first time out in a class. Quite honestly, the first time I think some teachers pull some of these particular units together; there was no one that succeeded first time around.

Teachers described an impulse to step in with solutions, which needed to be resisted.

One developer explained that this impulse can be particularly difficult to resist early on, when students are not yet acclimated to working through their own problems.

> I've seen this time and time again with the Invention Kits. A child or student will get very frustrated when a teacher doesn't answer. "Why aren't you doing your job? This is your job. You're a horrible teacher." So the type of teacher that can't deal with frustration or isn't comfortable with tension at the beginning of the implementation of these kits is not gonna be a teacher that's gonna be comfortable enacting [them].

As this passage illustrates, working in an environment where initial failure is tolerated, and even encouraged, takes some getting used to for both teachers and students.

While allowing students to fail is part of the process, Brian pointed out that he is still responsible for helping them process those failures. In order to do that, he explained that it was important to try to be present for failures or to otherwise make sure that students communicate their failures to him. When these failures are missed, opportunities for learning can be lost. He stated:

> There's been a couple of instances this year where I've come to a kid [or] a group, and they've got some ideas and they're trying to make it work, and then the next day I see that they're doing something different, and I'll say, "Well, what happened?" And they'll be like, "Oh, it didn't work." And, knowing the science or whatever, it could've worked. So, that's a critical piece - making sure you're present and you can process and help them to understand, "Why is it not working? Have you isolated all the different elements to see what's not working? Is it a

> misapplication of the science … or is it more of a technical thing where you haven't connected something correctly or whatever?"

By processing failures with students, he can intervene if the students cannot identify or misidentify why their designs fail before they prematurely "scrap" otherwise viable plans.

Balancing Challenge and Frustration

Teachers and developers explained that allowing students to work through obstacles takes patience and strategic intervention. One developer recalled a conversation he had with one of the core teachers:

> What he has told me is that he's constantly assessing where everyone's at. Not just where they are with the progression of the Invention Kit, but also are they being challenged enough or are they being challenged too much. He kind of uses the spectrum of boredom to frustration. So, if you're on the frustration side, you're being over-reached too much and eventually you'll be frustrated and less likely to persist. And then, if you're too bored or you're not being challenged enough, you're also gonna be more likely to be, quit and lose that autonomy. So, I think he tries to push them a little bit, not necessarily right in the middle, but a little bit biased towards the frustration side.

As this developer described it, maintaining student engagement depended upon finding a balance between challenge and frustration.

Maintaining such a balance requires the teacher to continually assess his or her students to determine their needs. Sometimes, students lack requisite content knowledge. Brian shared that one of his core strategies for addressing gaps in content understanding (and thereby addressing frustration) is “just-in-time” teaching, which he employs with small groups.

> Just in time teaching is a hot buzzword, and it's a good one. I'm not going to teach you anything until I know you are ready for it, but you've struggled enough that you've been resourceful and it make sense at this point.

When students confront obstacles, they develop an authentic desire for the content knowledge and an immediate application. This “need to know” makes them much more receptive to the content.

Allotting Time

Allowing students to make mistakes and correct them does take time. As the developers explain in the Solenoid Invention Kit Unit Plan:

> Failure is an important part of the engineering design process. Therefore, it is important to allocate appropriate class time to allow students to brainstorm multiple solutions, design an optimal solution, and revise their strategy/design as they progress through the engineering and fabrication process.

One developer described providing ample time as, not only important, but crucial to success.

> You need to have the time built in to allow the students to say, “Hey, okay. This didn’t work. What can we do to make it work?” Or what are your ideas about what – that takes time. A lot of teachers don’t wanna allow that time and I think that is the major thing that makes it not work in a classroom.

In other words, if students do not have time to make mistakes and iterate, a core aspect of the Invention Kit experience will be missed.

Requiring Students to Think for Themselves

Developers and teachers reported that one of the most powerful aspects of the Invent phase is that students are required to think for themselves. The design challenges do not come with clear directions for how to create a successful design. Brian explained that students were initially struck by this responsibility but ultimately benefited.

> So, the crux of the real learning and why I think this is a great program is that they're not following any instructions. They're used to following instructions because, in design assignments, I gave them some instructions. In the labs, they're following instructions. And you maybe even heard Lauren [a student] say this – she said, "This is hard." I'm like, "Yeah, it is hard. That's good, though." It's this moment where they're like, "Whoa. I'm going to really need to do my own thinking on this. I have to do genuine research to figure this out." That's where I think our kids win, by having this program. They're forced to think and apply in ways we don't often ask kids to do.

The comment from his student, Lauren, illustrates an additional benefit – not only was she being forced to think for herself, she was also aware of that fact and was willing to rise to the challenge.

Journaling

One strategy that teachers use to stimulate this kind of meta-cognition is journaling. Most teachers required their students to keep some form of journal or log. Brian described how journaling was an important part of his students' weekly routine.

> Every Friday, we do what's called a milestone…. The milestone is a paragraph response – synthesizing their response to several questions. The first question

> would be like, "How did your project progress this week?" The second is, "What obstacles did you face? How did you overcome them? What did you learn? Are you ahead of, on, or behind schedule? They kind of summarize their week.

This journal served two purposes. First, it forced his students to consciously and purposefully reflect on their mistakes and what they learned from them – another example of meta-cognition. Second, it helped him monitor his students' progress and identify where they might need guidance. He added that another benefit for students was that the journal allowed students to consider their own progress over time and feel a sense of accomplishment.

Teacher and Peer Feedback

Design challenges culminate with feedback from the teacher and others. Developers recommend teachers use a rubric to assess student projects, and they have provided an exemplar developed by one of the core teachers that other teachers can use or adapt. This rubric can be used to rate students on criteria such as planning, craftsmanship, documentation, optimization, time management, as well as whether or not the design works as intended. All teachers used a rubric of some kind to provide feedback for students.

The developers also suggest that teachers provide opportunities for students to present their designs to their peers or others. They explain this presentation could be done in a variety of formats, including a gallery walk, a traditional presentation, or using a "Shark Tank" format. The latter is based upon a popular reality-television show where aspiring entrepreneurs "pitch" their ideas to a panel of would-be investors, who then ask questions and decide whether or not to finance their idea. In the classroom version, students pitch their ideas to a panel that may consist of teachers, community members, or their peers. At one implementation site using this format, the panel selected winners, though this is not considered necessary.

All teachers provided students with opportunities to share their work in some form. Richard explained that he liked to have his students present their work to school visitors, but that he did not require all students to do so. Brian stated that he initially had his students present their work using the “Shark Tank” format, but that he since moved away from this requirement, opting to have his students share their designs using an online portfolio tool called SeeSaw. He explained the flexible pacing of his classroom made student presentations difficult to schedule.

> I'm finding it's difficult to do that [arrange presentations] – the course is self-paced, so when one group finishes a project another group has two or three more weeks. I'm finding more and more that my high flyers are going to do great work, do it fast, and do it high quality and there's no point in me slowing them down. I can keep coming up with more and more things for them to do, because the sequence is so great and the technology is readily available. I can move them forward. But in the past, we've done that as a way to make sure they can answer questions and answer more traditional test-based questions in an oral format. They worked okay. Now, when they're submitting their projects, they do that same sort of thing, but it's in their portfolio so they can move on.

Brian explained that, since groups rarely finished their designs at the same time, there was never a good time to stop for whole-group presentations. However, he felt that it was still important for students to be able to review each other’s designs and provide feedback. The SeeSaw application, which allows students to submit videos, images, and text descriptions of their designs, also includes a commenting tool, which students use to provide feedback to one another. Students can access one another's work on their Chromebooks or on a large monitor at the front of the screen. He explained that "Periodically, you'll see kids go to the monitor [at the front of the room] and going through kids' [SeeSaw] portfolios to either get ideas or see how they designed a piece. Used in this way, the students' portfolios became resources for ideas and know-how that other students could access at any time.

Invent Subcomponents

On the IC Map, the Invent phase includes four subcomponents. Each subcomponent contains a number of dimensions. Both are listed in Table 12. A sampling of key findings that contributed to the development of these subcomponents and dimensions follows.

Table 12
Overview of the Invent Component – Subcomponent Statements and Dimensions

Subcomponent Statement	The Big Idea	Dimensions
10. Implement Design Challenges	Students apply content knowledge in a way that is personally meaningful.	• Design Brief • Student Choice • Proposal • Idea Generation
11. Help Students Learn from Failure	Failure is an important part of the learning process.	• Autonomy • Time • Resources • Support and Instruction
12. Emphasize Engineering Design Processes	Teachers can use the Invent phase to teach more formal aspects of engineering design.	• Processes • Terminology • Culture

13. Provide Opportunities for Students to Share Their Designs and Receive Feedback	Presenting a public product adds authenticity and provides opportunities for feedback.	• Authentic Audience • Feedback and Assessment

Table 13.1
IC Map Subcomponent 10

<table>
<tr><td colspan="4">Invent - Applying and Extending New Understandings</td></tr>
<tr><td colspan="4">10. Implement Design Challenges</td></tr>
<tr><td colspan="4">The Big Idea: Students apply content knowledge in a way that is personally meaningful.</td></tr>
<tr><td colspan="4">Dimensions: Design Brief, Student Choice, Proposal, Idea Generation</td></tr>
<tr><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr>
<td>• The teacher tasks students with a design challenge that requires them to practically apply content knowledge and skills gained during previous Invention Kit activities. He or she uses a detailed design brief to outline any design criteria and constraints.
• The challenge is broad enough to allow students to exercise choice and pursue ideas that are personally meaningful. He or she demonstrates respect for student ideas.
• Teacher requires student to submit a detailed proposal that includes a design description, preliminary design sketches, and a plan for how the group will work towards a final product (roles, deadlines, etc.).
• The teacher helps students develop strategies for brainstorming ideas. For example, he or she may encourage them to research existing applications.</td>
<td>• The teacher tasks students with a design challenge that requires them to practically apply content knowledge and skills gained during previous Invention Kit activities.
• The challenge is broad enough to allow students to exercise some choice and pursue ideas that are personally meaningful. He or she demonstrates respect for student ideas.
• Teacher requires student to submit a rough outline of their plan.
• The teacher brainstorms ideas with the students.</td>
<td>• The teacher tasks students with a design challenge that requires them to practically apply content knowledge and skills gained during previous Invention Kit activities.
• The challenge is narrow and limits students' abilities to choose personally meaningful topics. The teacher may require students to choose from a pre-established set of options.
• The teacher may require students to articulate their choice of design but does not require them to submit a plan.</td>
<td>• The teacher provides a prepared design which students follow step-by-step. No student planning or designing is involved.</td>
</tr>
</table>

Table 13.2
IC Map Subcomponent 11

Invent - Applying and Extending New Understandings			
11. Help Students Learn from Failure			
Big Idea: Failure is an important part of the learning process.			
Dimensions: Autonomy, Time, Resources, Reflection, Support and Instruction			
A	B	C	D
• The teacher gives students the autonomy to authentically pursue their ideas, even if he or she thinks their designs will fail. • The teacher treats failures as opportunities to learn. Therefore, students are given ample time to try out different design configurations. • Within the constraints of the design challenge, the teacher provides avenues to a variety of resources that students can use to try different approaches to their designs. • The teacher requires students to regularly reflect on obstacles and document their learning through journaling or similar methods. • The teacher attempts to be present for failures and always debriefs with students to help students process those failures. • The teacher coaches students how to find solutions when they are stuck. He or she monitors students' reactions, seeking a balance between challenge and frustration. He or she evaluates what information students need to arrive at a solution themselves and utilizes "just-in-time" direct instruction when needed.	• The teacher provides limited autonomy for students to pursue their ideas. If the teacher thinks their designs will fail, he or she recommends changes. • Teacher provides limited time for students to try out different design configurations. • The students have limited access to resources that they can use to try different approaches to their designs. • The teacher requires students to occasionally reflect on obstacles and document their learning through journaling or similar methods. • The teacher attempts to be present for failures and usually debriefs with students to help students process those failures. • When students are stuck, the teacher provides them solutions.	• The teacher limits students' opportunities to learn from failure by providing limited autonomy, time, and resources. • When students do fail, they are not required to reflect on their mistakes. • The teacher rarely debriefs with students to help them process failures. • When students are stuck, the teacher does little to help them.	• The teacher does not allow students to fail.

Table 13.3
IC Map Subcomponent 12

<table>
<tr><td colspan="4">**Invent - Applying and Extending New Understandings**</td></tr>
<tr><td colspan="4">**12. Emphasize Engineering Design Processes**</td></tr>
<tr><td colspan="4">The Big Idea: Teachers can use the Invent phase to teach more formal aspects of engineering design.</td></tr>
<tr><td colspan="4">Dimensions: Processes, Terminology, Culture</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td></td></tr>
<tr><td>● The teacher actively teaches engineering design processes and strategies. The teacher utilizes one or more models of the process and requires students to articulate how their own design processes reflect and shift among the different stages.
● The teacher uses engineering design terminology with students and expects that students also use these terms and concepts accurately. When discussing designs with students, he or she asks them to address criteria and constraints. Students are taught to use terms such as solutions, prototypes, and iterations.
● By utilizing engineering design processes and terminology, the teacher continually seeks to make engineering design part of the classroom culture and invites students to view themselves as engineers.</td><td>● The teacher mentions engineering design processes, but does not require students to apply the processes to their own work.
● The teacher uses some engineering design terminology with students but does not require students to use it.
● The teacher makes limited efforts to instill a culture of engineering design in his or her classroom.</td><td>● The teacher does not address engineering design processes.
● The teacher does not use engineering design terminology.</td><td></td></tr>
</table>

Table 13.4
IC Map Subcomponent 13

Invent - Applying and Extending New Understandings			
13. Provide Opportunities for Sharing and Feedback			
The Big Idea: Students receive feedback from the teacher and others.			
Dimensions: Teacher Rubrics, Student Sharing, Providing and Receiving Peer Feedback			
A	B	C	
• The teacher utilizes a rubric to guide and assess student designs. The rubric is detailed enough to provide specific feedback for improvements. • The teacher regularly requires students to share their designs with an authentic audience (e.g. presentations, gallery walks, online portfolios). • Students regularly answer questions about their designs and receive feedback from peers. Students ask questions and provide feedback to others.	• The teacher utilizes a rubric, but it is vague and does not address the specific criteria and constraints of the particular challenge at hand • The teacher sometimes requires students to share their designs with an authentic audience (e.g. presentations, gallery walks, online portfolios). • Students sometimes answer questions about their designs and receive feedback from peers. Students sometimes ask questions and provide feedback to others.	• If a rubric is used, it provides little useful information (e.g. the design works or does not work). • The teacher does not require students to share their designs. • Student have few opportunities to give or receive peer feedback.	

The Connect Component

Unlike the Make, Explore, and Invent components, the Connect component does not have a corresponding step or phase. In this study, the Connect component includes the broader themes and values that provide context and cohesion for the Invention Kits. As such, its placement as the fourth component is not meant to indicate that it only follows the first three. On the contrary, elements of the Connect component are meant to be interwoven throughout the Invention Kit activities.

Key Findings

Broader Goal

In a document describing the Invention Kits, the developers explain that the goal of the project is to fulfill a larger mission. They write:

> The goal of the project is to fulfill the mission of the Smithsonian's National Museum of American History by "help[ing] people understand the past in order to make sense of the present and shape a more humane future." To that end, Invention Kits are designed to allow students to understand the process of invention and innovation from a historic perspective while allowing students to become inventors themselves. (Bull et al., 2017)

This passage suggests that the Invention Kits can help students understand the current state of innovation by examining innovations throughout history. It also suggests that the Invention Kits permit students to participate in the process of innovation, perhaps setting the state to impact the future.

One teacher/developer described how the Smithsonian's mission statement inspired the current, three-step framework for the Invention Kits.

> We realized that past inventions [were] a way to understand the current things because everything in present day is so mass-manufactured that they can't interact with it, they can't use it. You go into the past, you make it, now they understand present. Now, what can they invent using what they learned? It's almost a three-step process.

In other words, by studying an historic invention, students go into the past. By recreating and exploring the invention, students understand the present. And by using the invention as a stepping off point for their own inventions, they consider future possibilities.

Inventions are Connected

One of the core themes of the Invention Kits is that inventions are connected. Students encounter this theme in two ways: first, by directly studying the history of the inventions; and, second, by following the Invention Kit sequence itself, which is designed to help them experience the connectedness of the inventions, as they recreate inventions that were built upon one another chronologically and conceptually. This idea of both studying and experiencing these connections is evident in the Teachers' Guide for the Solenoid Invention Kit:

> A solenoid is a coil of conductive wire that generates a magnetic field when electric current flows through it. This discovery made many other inventions possible, including the telegraph, the telephone, electric motors, radio, television, computers, and smart phones. Because the solenoid contains the foundational scientific principles that led to so many other inventions, we selected it as the first invention in the Make-to-Learn Invention Kit series. Students will discover,

> explore, and interact with these principles while following in the footsteps of these early inventors. (Laboratory School for Advanced Manufacturing, 2017b)

First, the intent is for students to trace the path of the solenoid to understand how it has been used in subsequent inventions up to and including modern day devices. Next, students will experience the connectedness by first creating their own solenoids, then using them to build historical devices that depend on them, such as the linear motor and generator.

Teachers explained that a core strategy for engaging students in conversations about the connectedness of inventions was to help students consider the impacts of these inventions on their modern-day lives. Richard explained that, "[For] each of these Kits, I think kids have to understand, "Wow, what we're about to do is really something that changed the world." He then described how he introduced his telegraph unit by asking students to consider what their lives would be like without digital communication.

> How I start the telegraph unit is "Hey, how would you guys like to live without Instant Message?" Really, I introduced the telegraph as, "How mind boggling is it that there was a time without instant communication?" … If you wanted this feedback right now, how many months would it take you for this to go back and forth, right, by letter and all that? It'd be a nightmare." So, there's an immediate appreciation. The generator, holy mackerel, the telephone, all these are just – it is mind boggling. So, I think kids do get that immediate "Oh, my gosh…. Where would my life be right now without X invention?" It scares them, I think.

Considering things in this light helps students appreciate the impacts that certain inventions have had on society and their own lives. Brian described a similar approach:

> If you're teaching anything, there needs to be a through line. I'm trying to create that through line almost always. We're studying inventions from 1820, but they are impacting us today. That sounds very good, but it doesn't always play out that way and I probably don't do a great job of it, but I'm trying to get them – their filter is now. Their world filter and learning filter is now. What we're learning has to be connected in keeping that filter in mind. And the real-world connection to this historical invention is a critical aspect of it.

Brian explained that it was crucial to help students trace the connections from one invention to another up to the present day because it added relevance for the students, which was a necessary part of student engagement.

Nonetheless, one teacher explained that some connections are less evident to students than others, which prompted further discussion.

> Sometimes a kid might say, "Well, we don't use a linear motor…." [So, I would ask,] "Without the linear motor, would we have the rotary motor? …What you invent doesn't have to innovate the next thing, but it might provide knowledge for the next thing, which is just as important. It's no less important to create something that immediately changes something.

In this way, the teacher impressed upon students that some inventions are no longer immediately recognizable in modern technologies, but that they were no less important.

Such conversations may contribute to a broader understanding of the nature of innovation. One developer explained:

> That's the whole mentality that we're trying to communicate to teachers and students. Is that this is how all inventions were made, they're not just made of thin

> air. You take the things that people have developed and you combine them in ways, in different configurations, and then you've invented something that didn't exist before.

All inventions in some way build upon previous discoveries and/or inventions. Studying these connections helps students understand how innovation truly occurs.

Empathizing with Inventors

As stated above, one reason for "following in the footsteps of these inventors" is to reinforce the connectedness of inventions. Another goal is to reenact history in such a way that students can experience discovery and innovation first hand. One teacher explained that fostering these experiences was key part of implementing the Invention Kits.

> An Invention Kit should immerse the kid in the experience of inventing an object. I see it happen time and time again – one of the most amazing things that a kid ever said to me was, "Wow, I really feel like Bell and Morse." They understand exactly as much as I understand about electricity and this. It's true, they always think of inventors as these mystical people that knew everything. In reality, they're people that know very little and are looking to learn more and more. It happens that the 1800's has about the same knowledge as our current eighth graders do, so they can grow up in the 1800's. They live the experience, in a way, of these innovators.

As this passage relates, some of the inventors included in the Invention Kits had little understanding of the scientific principles they were investigating and were uncertain what their experiments would reveal. Richard found that, when students learned this, they were surprised and empowered.

A developer described a similar experience when he and a colleague adapted the Solenoid Invention Kit to teach Ampere's Law:

> When those kids derived Ampere's Law, independently, different groups of kids said to us, "That's really cool." And we got "cool" from different groups of middle school kids, and even high school kids, and even college kids. It's interesting that they all use the term, "cool," when we had solenoids that were heating up as they put power through. And what they thought was cool about it was that they came up with a law that a scientist came up with. As one kid said, "We figured out something that a scientist figured out and we're seventh graders."

While recreating history, the students derived a formula that they previously believed only a scientist could have accomplished. In this way, the students experienced science firsthand and felt a sense of pride and accomplishment.

Brian explained that he tries to draw students' attention to the reenactment of history by dramatizing the students' findings.

> When they do Lab Three … and the first time they see that compass move. I don't know if you saw me trying to dramatize that and be like, "Whoa, how cool is this? … This discovery fundamentally changed our world. You just reenacted Hans Oersted in 1820." I tell the battery story and the compass moving.

In this exchange, the teacher sought to appeal to the students' natural sense of curiosity and wonder, while simultaneously underscoring the historical impact of the discovery.

In addition to recreating moments of discovery and accomplishment, the Invention Kits are also designed “to allow students to experience and understand challenges that early inventors faced” (Bull et al., 2017). By studying history, as they endeavor to build working models of historical artifacts, students are able to appreciate that early inventors were also experienced challenges and frustrations not unlike their own. In a recent article, the developers described the psychological impact this appreciation

> Students who study the historic record often find these parallels to be reassuring. If iconic figures in history experienced these difficulties and were discouraged and frustrated at times, it is not unreasonable that a middle school student might experience the same difficulties. This knowledge can enable students to persist rather than quitting after the first failure that they experience. (Bull & Garofalo, 2017)

In this way, students come to realize that frustration is a normal, and purposeful, part of the experience.

Implementation Challenges

Teachers implementing the Invention Kits conceded that the historical element was difficult to capture and sustain. One teacher explained that the length of the units was a complicating factor.

> That's probably been the hardest thing, honestly. The narrative fits really well, but it's so long-term. Some of these curriculum units – the solenoid invention kit takes two to five weeks, depending on what they do, what their project looks like, and

> how they self-pace. So, they get the first part of the narrative and then we move on to the next part of the narrative. And there is a long-time lapse between them.

In other words, the length of the Invention Kits made it difficult to preserve the narrative thread throughout an Invention Kit and from one Kit to the next. As this teacher went on to explain, “I see the narrative piece mostly as a hindsight kind of thing. We tie it in, but there are so many gaps. It's hard to keep that real and on their forefront every day.” While he intersperses the history of the inventions whenever he can, he believes that the history can also be used to at the end of the school year to as a tool for reflection and empowerment.

> At the end of the course, we can say … "Hey, let's look through our portfolios. Let's look back at all we've learned this year. Let's tie all this together and say, 'We've followed in the footsteps our inventors did in 1820 and 1832 and 1854.' This is the story of invention in our nation, and actually, you guys know more science than these guys did. They were just kind of fooling around and playing around and took a little bit of what the previous guy did and made it a little bit further." Hopefully, that's a way to empower them and say, "Hey, you guys have learned a lot. Now, based on what you do know, go ahead and extend it and sign up for my eighth-grade [engineering] course."

This conversation was intended to prompt students to reassume a larger perspective and recognize that the work they completed fits into a historical narrative that extends to the present day. It was also used as an invitation to pursue engineering the following year.

An eighth-grade teacher explained that it was difficult to address the historical component because it does not fit well with the eight-grade curriculum, which made it difficult to justify devoting much time to it.

> I understand that there is a historical basis, but it is seventh-grade history curriculum, and it's hard for me to actually integrate that piece as an eighth-grade science teacher with 160 students. I wish that I had more time to do that. It's difficult. I knew that at one of the schools, they've changed the way they're doing physical science. They've moved it to seventh grade. So, they might actually have a better alignment of their history curriculum. So, if you could work with another teacher and blend those two things in, that would be easier for me to work with.

In this teacher's case, a crowded science curriculum left little time to address the history of the inventions. However, she saw cross-curricular collaborations among teachers as a potential solution. She also believed that it would be helpful if the Invention Kits included short mini-lessons or videos that addressed the historical components. Currently, these materials have not been developed.

A third teacher said she had not yet addressed the historical aspects of the Invention Kits because she was implementing the Kits for the first time and had not yet been trained on those elements.

> The only thing that I have really ever been told about the kits is that they're based on historical models and we use those models as a basis for teaching electricity. But, this is my first year with the program. I didn't do any of the stuff [teacher workshops] over the summer. The only training I've had is reading those websites and asking [a colleague] some questions as we go along.

This teacher suggested that the website, by itself, lacked adequate materials to address the historical aspects of the inventions. She believed these strategies could perhaps be learned during a teacher workshop.

Maker Culture

The terms "making" and "maker" were frequently cited in interviews and was found throughout the Invention Kit documentation. For example, the home page of the Make-to-Learn website states that the site was "established to advance maker education." In the website's preface, the developers write:

> The maker movement is advancing a grassroots renaissance in creativity and innovation. Fueled by ready access to personal fabrication systems, community makerspaces are springing up around the world. Makerspaces provide individuals with access to prototyping tools that facilitate innovation and invention. (FabNet Invention System, 2016)

This passage describes a contemporary of version of making, which has arisen alongside the proliferation and increasing affordability of technologies such as 3D printers and microcomputers. However, the developers point out the values behind the maker movement – creativity and an innovative spirit – have always been part of American culture.

> Making is not a new phenomenon. A collaboration with the National Museum of American History has traced the roots of making to the beginnings of the nation. In fact, making is an important element of the nation's character that played a key role in its current prosperity. (FabNet Invention System, 2016)

The developers hope that, as students engage with the Invention Kit activities to learn scientific concepts and develop skills in engineering and engineering design, they will also tap into and foster the creative values that undergird the nation's character. As one developer put it, "It's trying to find the balance of hands-on, conceptual knowledge [and] skills. And then, trying to build in some of these values that come with this maker culture, and this innovation creative values."

Like the historical aspects of the Invention Kits, the developers envision elements of making being visible throughout the Invention Kits. The focus on technological and mechanical competencies throughout the Invention Kits is meant to fulfill this vision regarding maker skills. In an ideal implementation, opportunities for creativity are similarly dispersed. Brian encouraged students to be creative during the Make phase, as they created their own versions of the artifacts. He stated that he also felt that there were elements of making and creativity in his approach to Invent phase, in which his students developed unique, and often whimsical, extensions for the artifacts.

Several developers explained that they were concerned that, as more teachers adopt the Invention Kits, some may not choose to emphasize creativity.

> I hope they [new teachers] don't basically squash creativity. I hope they don't get so focused on, "All right, well, did you build your kit, and does your kit look? Just like what's in the picture? Well, if your kit doesn't look like what's on the picture, then you did it wrong." I hope they don't get so focused on replication that they miss out on that.

This developer, and others, predicted that opportunities to nurture creativity would be lost if teachers took away or diminished students' freedom to invent. As one developer put it, "You're stopping short if you don't have that final invention component where you're actually having them dig down and try to reach and make something unique with it that didn't exist before."

Connect Subcomponents

On the IC Map, the Connect phase includes two subcomponents. Each subcomponent contains a number of dimensions. Both are listed in Table 14. A sampling of key findings that contributed to the development of these subcomponents and dimensions follows.

Table 14
Overview of the Connect Component – Subcomponent Statements and Dimensions

Subcomponent Statement	The Big Idea	Dimensions
14. Use Historical Themes to Illustrate the Nature of Invention and Innovation	Students learn concepts of innovation and change.	• "Inventions are Connected" • "Invention as a Systemic Process" • Relating to self
15. Promote Values that Connect to a Contemporary Culture of Invention and Making	Students are encouraged to become makers and inventors themselves.	• Creativity and Problem Solving • Self-empowerment • Communities of Making

Table 15.1
IC Map Subcomponent 14

Connect – Understanding Invention and Innovation			
14. Use Historical Themes to Illustrate the Nature of Invention and Innovation			
The Big Idea: Students learn concepts of innovation and change.			
Dimensions: “Inventions are Connected,” “Invention is a Systemic Process,” Relating to Self			
A	B	C	
• The teacher implements activities in which students actively identify, research, and report on discoveries and inventions that paved the way for the target invention. Students perform similar tasks related to the subsequent inventions and innovations that were made possible by the targeted invention. • The teacher assign tasks that require students to identify and explore understand the broader systems that arise from and support innovations (e.g. the development of the telegraph led to the telegraph system, which also connected to an electrical system). • The teacher assigns tasks that require students to explore the personal stories of inventors. The teacher helps students understand that historical inventors were similarly perplexed by their observations of the natural world and often struggled to bring their ideas to fruition.	• The teacher tells students about the discoveries and inventions that paved the way for the target invention and the subsequent inventions and innovations that were made possible by the targeted invention. • The teacher tells students about the broader systems that arise from and support innovations (e.g. the development of the telegraph led to the telegraph system, which also connected to an electrical system). • The teacher tells students that historical inventors were similarly perplexed by their observations of the natural world and often struggled to bring their ideas to fruition	• Historical themes are not included.	

Table 15.2
IC Map Subcomponent 15

Connect – Understanding Invention and Innovation			
15. Promote Values that Connect to a Contemporary Culture of Invention and Making			
The Big Idea: Students are encouraged to become makers and inventors themselves.			
Dimensions: Creativity and Problem-Solving, Self-Empowerment, Communities of Making			
A	B	C	
• The teacher regularly showcases examples of student creativity and inventiveness. He or she publicly praises students for making sense of complex problems and overcoming adversity. • The teacher regularly encourages students to learn new skills for designing and making. He or she directs students to resources (e.g. online, books, local businesses) where they can further explore their interests and gain new skills. He or she visibly praises students that extend their new skills to other areas, inside and outside of school. • The teacher regularly encourages students to share their works with one another and to freely share and accept constructive feedback. He or she encourages students to teach one another new skills and techniques. The teacher may even encourage students to share their skills and designs to broader communities of making, locally and online.	• The teacher occasionally showcases examples of student creativity and inventiveness. He or she publicly praises students for making sense of complex problems and overcoming adversity. • The teacher occasionally encourages students to learn new skills for designing and making. He or she directs students to resources (e.g. online, books, local businesses) where they can further explore their interests and gain new skills. He or she visibly praises students that extend their new skills to other areas, inside and outside of school. • The teacher occasionally encourages students to share their works with one another and to freely share and accept constructive feedback. He or she encourages students to teach one another new skills and techniques. The teacher may even encourage students to share their skills and designs to broader communities of making, locally and online.	• While these values may be present, the teacher does not emphasize them or connect them to Maker Culture.	

Summary

In this chapter, data collected during the Innovation Configuration Mapping process is organized under four primary headings – Make, Explore, Invent, and Connect. These headings correspond to the four core components that are documented in the Innovation Configuration Map. The section entitled "Make" contains data relating to the reconstruction of historical artifacts and the development of the skills and competencies for computer-assisted design, computer-aided manufacturing, and making and constructing by hand.

The section entitled "Explore" contains data relating to the use of historical artifacts to explore scientific principles. These activities are designed to let students engage naturally with content and construct their own knowledge. Developers and teachers described how the sequence of the activities help scaffold learning and how the devices themselves possess a certain transparency that makes the underlying scientific principles accessible to students. Teachers described strategies for facilitating inquiry and managing workflows and student collaboration. Teachers also described how they used these activities to bridge to the next phase, Invent.

The section entitled "Invent" contains data relating to student designs and inventions. During a core Invention Kit activity, students are challenged to extend the historical artifacts by incorporating the underlying principles and mechanisms in a design of their own that accomplishes a personally-meaningful task. In this section, teachers and developers describe strategies for helping students learn from failure and think for themselves, as well as strategies for facilitating the engineering design process.

The final section, “Connect,” contains data relating to overarching themes of the Invention Kits, such as the idea that inventions and innovations build upon one another. Teachers reported that these are valuable lessons but that it was challenging to keep these themes at the forefront of students’ thinking during the Invention Kit activities. The “Connect” section also includes data regarding how teachers reinforce values and practices relating to the Maker Movement.

CHAPTER 5

Discussion

In recent years, there has been an increased demand for engineering-focused, STEM education resources that are integrative and prepare students to apply STEM content, skills, and practices as they are used in the real world (National Academy of Engineering & National Research Council, 2014). The Make-to-Learn Invention Kits are a series of innovative learning modules designed to address this demand. The Invention Kits combine science, engineering, and advanced technologies for design and manufacturing in the context of invention and innovation throughout American history. They include hands-on learning activities and are well-suited for inquiry- and project-based classrooms. These characteristics make the Invention Kits appealing to teachers, schools, and districts seeking to provide meaningful STEM learning opportunities for their students.

Nonetheless, some would-be adopters of the Invention Kits will likely find them difficult to implement for the same reasons. Many teachers lack training and experience with engineering education and inquiry-based teaching approaches (Committee on K-12 Engineering Education, 2009). Lacking sufficient background, these teachers may have difficulty visualizing what an effective implementation of the Invention Kits looks like. Hall and Hord (2013) state that a lack of a clear understanding and visualization of an education innovation often leads to modifications that diminish its effectiveness or the outright rejection of the innovation.

To address this issue, Hall and Hord (2013) developed a strategy called Innovation Configuration Mapping. Innovation Configuration (IC) Mapping is designed to help would-be adopters visualize an innovation by outlining an innovation's essential components and detailing various ways of implementing them. IC Maps help would-be adopters understand the innovation, thereby increasing its adoption and effective implementation.

This study focused on developing an IC Map for the Make-to-Learn Invention Kits. To this end, I sought to answer the following research questions:

1. What are the critical components of the Make-to-Learn Invention Kits from the perspectives of the developers and facilitators?
2. How do Invention Kit developers and facilitators describe their visions for how the components should be implemented?
3. In practice, how do teachers adapt the Invention Kits to their context? What components of the kits do teachers choose to implement or emphasize? Do the teachers add new components to the Invention Kits? If so, what are these additions?

Developing the IC Map was an iterative process that involved interviewing the developers to document their visions for the Invention Kits as well as interviewing and observing teachers that are currently piloting the kits. Several cycles of qualitative data analysis were used to sort the data into major themes and categories which were included on the IC Map. The IC Map went through several revisions, based upon feedback from the developers, teachers, and dissertation committee members. This chapter begins with a summary of the major findings as they relate to the literature followed by their implications for practice. The chapter concludes with reflections on the process of

Innovation Configuration Mapping, limitations of the study, and directions for future research.

Overview of the Map

The IC Map is divided into four top-level components entitled Make, Explore, Invent, and Connect. These components represent major tasks that students and teachers engage in during the Invention Kits. The first three components are generally completed sequentially. The final component, Connect, is done throughout.

In organizing the IC Map, I attempted to mirror the structure of the Invention Kits themselves as much as possible. An Invention Kit is large and complex, being comprised of several overlapping phases, each of which contains many unique tasks and considerations. As much as possible, I wanted to chunk the information on the map so that the reader can more easily crosswalk the map, the Invention Kit materials, and the particular activities that one may be leading or observing in a classroom at any given time. For the same reason, I borrowed two of the titles directly from the Invention Kits. For instance, “Make” and “Invent” are used as headings for activities on the Make-to-Learn site. “Explore” and “Connect” are not used as titles in the Invention Kit materials, but the terms are used frequently within the context of their corresponding activities. In devising this structure, I considered alternatives. For example, I might have attempted to create a simplified map that combined the four components and assumed a more holistic, top-level perspective. This approach might have reduced the number of pages necessary. However, the map would have carried considerably less information, including details and descriptions that might help the would-be adopter visualize implementations of the Invention Kits. Rogers (2003) describes complexity as “the degree to which an innovation is perceived as difficult to understand and use" (p. 16). In attempting to reduce the complexity of the Invention Kits, I determined that the best approach was to be concise, but through. I did not want to risk oversimplifying the kits and giving potential adopters an incomplete picture of the considerations that go into implementing them. In its current form, the IC Map is intended to simply and clearly communicate how the Invention Kits are used at each stage of the process, which may help teachers better understand the kits and the various ways they can be used.

The Make Component

The Make component includes activities surrounding the reconstruction of an historical invention. The reconstruction of an historical artifact serves as an authentic task through which students can learn and practice basic technological and mechanical competencies such as CAD, 3D printing, and soldering. This task has evolved since the earliest versions of the Invention Kits, which accounts for significant differences in the ways teachers approach this component. The original intention was for students to study 3D models of the historical inventions, then "re-envision" them, with each student or group of students creating a unique design. The complexity of this task later led to the development of tested designs that teachers and students can download and fabricate. This latter approach saves time and ensures that everyone has a working model.

Both approaches were observed in practice and are supported by the developers. However, the two approaches represent fundamentally different tasks: re-envisioning the inventions with unique designs is open-ended; building the inventions from established designs is more constrained. Developers expressed some concern that the latter approach could conflict with the goal of the project to foster creativity and invention, especially if students perceive it a “model-making” or “painting by numbers.” Nonetheless, some teachers preferred this approach because it simplified things and allowed them to get to the science-focused activities in the Explore phase more quickly. Others chose this approach because they lacked adequate equipment (e.g. 3D printers or laser cutters) to feasibly have all students fabricate their own artifacts. These teachers were likely to pre-fabricate parts from the established designs themselves – the students’ only task then was to put the parts together.

In supporting these varied approaches, the developers acknowledged that teachers desire options that make it easier to adapt the Invention Kits to meet their own objectives and constraints. This study suggests that science teachers may prefer to spend less time on the Make component because the science standards are more explicitly addressed during the Explore phase. Meanwhile, teachers of engineering may be more likely to allow students to develop their own versions because it allows students to practice engineering design. Providing the option for teachers to choose their approach makes sense from an innovation diffusion perspective. Roger (2003) explains that such flexibility to “re-invent” an innovation leads to “faster adoption rates and higher degrees of sustainability” (p. 183). Providing options broadens the appeal of the kits by making them seem more compatible with the teachers’ current practices (Rogers, 2003), but may lead teachers to use the kits is ways that are less than ideal, particularly if they become rote exercises in model-making. The IC Map may be particularly useful in this regard. While teachers may be encouraged to adapt the Invention Kits in any manner that makes sense to them, the IC Map can help the developers convey their original vision and rationale, so that teachers can more easily consider any trade-offs that their re-inventions may involve.

The extent to which teachers focused on technological and mechanical competencies largely depended upon which approach they adopted to recreating the historical artifacts. Those who had students fabricate the pre-established designs or pre-fabricated the parts themselves, devoted less time to the development of technological and mechanical competencies compared with those who had their students develop their own designs. However, even among those teachers that did emphasize technological and mechanical competencies, there were variations in their approaches. One teacher devoted considerable class time to activities that taught students CAD and similar skills in advance of creating their artifacts. Another teacher provided only short overviews of the various skills, which he felt was enough to get students started toward learning the skills themselves.

The Explore Component

The Explore component includes activities that students perform to learn scientific principles relating to the artifact. For the most part, these “Lab Activities” take the form of experiments, where students learn about phenomena (such as electromagnetism) by testing different variables. Developers reported that the Lab Activities are designed to help students construct their own knowledge of scientific principles that underlie the inventions. The Invention Kits include a number of features that are designed to facilitate knowledge construction. First, the Lab Activities are sequenced to scaffold conceptual understanding from the ground up. Students start with very basic ideas and build upon them as they move through the Lab Activities. Because each Lab Activity builds upon the previous activity and sets up the next, the developers recommended that teachers implement them in order, though they imagined that the particulars of the Lab Activities could be adapted in a variety of ways. The most important thing to preserve is the conceptual progression. Most of the teachers in this study followed the intended progression of Lab Activities relatively closely. Teachers were more likely to add materials to supplement the Lab Activities than to skip over them.

Next, the Invention Kits are designed to facilitate knowledge construction by allowing students to engage naturally in scientific inquiry. This requires teachers to provide students with adequate time, flexibility, and some measure of autonomy to make observations, test hypotheses, and draw conclusions. The goal is for students to develop deep understanding of scientific principles, but this arrangement also allows them to learn scientific practices – a key feature of STEM curricula (National Research Council, 2012). In practice, it can be difficult to give students the time, flexibility, and autonomy they may need. Several of the teachers in this study were constrained by short class periods and crowded curricula, particularly the regular science teachers. In addition, teachers reported that some students struggled with autonomy. It may be that these students had few prior experiences with this kind of learning.

While the Invention Kits are intended to be student-centered, teachers still serve very active and important roles as facilitators. Teachers need to ask thought-provoking questions and challenge students to articulate and justify their reasoning. One of the teachers' objectives is to help students uncover and correct their own misconceptions about the natural world. This is not done by telling students how things work, but by orchestrating opportunities for them to discover how things work themselves. The teacher's role as a facilitator during the Explore phase (and throughout the Invention Kit) is consistent with practices associated with project-based learning, a pedagogical approach cited by several developers as an important influence on the design of the Invention Kits. All of the teachers observed in this study embraced this role. Nonetheless, some teachers felt that limited time, crowded classrooms, and various technical challenges associated with the Lab Activities left them with fewer opportunities to engage with students in this way as they would have liked.

Student collaboration is another feature of the Invention Kits that requires teacher facilitation. Also rooted in constructivism and found in project-based learning, the premise is that knowledge construction is aided when students discuss their ideas with peers. Students can challenge each other's thinking and collaboratively develop and test hypotheses. As a facilitator, rather than the sole source of knowledge, the teacher forces students to work together to find solutions to their problems. In this way, the students become more self-reliant. The teachers in this study generally arranged students in groups ranging in size from two to five students. Students rarely worked alone on Lab Activities. Teachers reported that students occasionally are unaccustomed to true collaboration and self-reliance, and that these skills need to be worked on. Such considerations are common in project-based learning environments – so much so, that, in a study of project-based learning classroom management practices, Mergendoller and Thomas (2000) listed "Managing Student Groups" and "Establishing a Culture that Stresses Student Self-Management" as two of their seven main themes.

A more mundane, but equally important, part of implementing the Invention Kits relates to managing materials and workflows. This study found that inadequate resources or difficulty accessing those resources could significantly disrupt students as they attempted to complete the Lab Activities, leading to downtime and frustration. Teachers reported that preparing for the Lab Activities requires a significant amount of time and planning. Most had devised strategies for sorting and distributing materials as quickly as possible, such as using small plastic bins or Ziploc bags. These strategies were generally developed through trial-and-error as teachers saw needs for them. Similarly, teachers found ways to arrange their classrooms that put tools and materials within easy reach of their students.

While a key objective of the Lab Activities is to help students construct scientific knowledge, the Lab activities are also intended to lay the groundwork for their own inventions. Teachers explained that having conversations with students about the real-life applications of the inventions and the scientific principles behind them helped in this regard. From there, it was easier to ask the students to consider what they would like to do with the invention.

The Invent Component

Teachers implement the Invent component when they require their students to extend the historical artifact to create their own unique designs. This task is designed as a culmination of all previous Invention Kit activities and is, arguably, the Invention Kits' most defining feature. It requires students to correctly apply the invention's underlying scientific principles and provides additional opportunities to practice skills related to engineering and engineering design. The developers recommend that teachers introduce the Invent phase to students through an open-ended design challenge. A key requirement of this phase is that the students have the autonomy and flexibility to create something that is personally meaningful to them. This means that the students' designs could take many forms. The rationale is that, when applying targeted skills and content to something that matters to them, students appropriate the knowledge. Here, the developers are influenced by constructionism, an extension of constructivism, which stresses that when students create their own learning objects, they become more engaged and find the underlying content more accessible (Papert & Harel, 1991). To borrow from Resnick et al. (2000), when a student creates his or her own device, that device becomes all the more transparent to that student, meaning that the student gains a more intimate understanding of the various parts and how they work individually and collectively.

Teachers that implemented design challenges generally required their students to submit proposals prior to building to demonstrate that they had engaged in planning and were poised to meet the challenge criteria. Nonetheless, both developers and teachers emphasized that the purpose of these proposals was not to ensure that students succeeded the first time. In contrast, they stressed that working through initial failures was an essential part of the learning experience. Allowing students to learn from their mistakes required teachers to provide students time for troubleshooting and revisions. It also required that teachers resist the urge to step in too soon to "fix" the students' problems. Nonetheless, the teachers in this study described coaching students that needed help, sometimes guiding them to a resource and at other times providing "just-in-time" instruction. In determining when and how much coaching was needed, teachers described trying to strike a balance between challenging the students and pushing them to frustration. The goal was to help the students think for themselves, but letting certain students struggle for too long could lead to disengagement. A final, and very important, part of learning from failure is student reflection. The teachers in this study described how they prompted students to continually reflect on the obstacles they faced and what they learned from them. Generally, students were asked to reflect informally in conversations with their peers and the teacher and more formally by writing in journals or logs.

While principles of engineering design are woven throughout the Invention Kits, in the Invent phase, students experience the engineering design process in its entirety. In this study, teachers sought to make this process explicit to students. Most had adopted models of the engineering design process that depicted its stages in various ways, but all contained the same core sequence laid out by Groves, Abts, and Goldberg (2014). In their sequence, students 1) identify a challenge and specify the requirements; 2) imagine a set of possible solutions and select the most promising; 3) define the solution using scientific knowledge, mathematical techniques, and technological tools and evaluate prototypes; 4) report findings and conclude whether their design meets the challenge; and 5) reflect on the process and recommend iterations or implementation. Teachers in this study often required students to identify where they were in the engineering design process using these kinds of terms and concepts. One of the overarching goals was to immerse them in the experience and help them identify themselves as engineers.

The Invent phase often concludes with students sharing their designs and giving and receiving feedback. This is an important aspect of the experience that is a common to several of the core influences of the Invention Kits. A share component is often included in descriptions of the engineering design process, as it is by Groves, Abts, and Goldberg (2014) above. Similarly, project-based learning also usually includes the presentation of a product or artifact (J. S. Krajcik et al., 1994). Finally, maker culture, which is addressed later in this chapter, also stresses the importance of sharing one's creations. For the Invention Kits, student presentations could take a variety of forms, from traditional, front-of-the-classroom presentations to student showcases or gallery walks. What was most important was that students have opportunities demonstrate their skills, give and receive feedback, and inspire their classmates. While peer feedback was generally informal, teachers often used rubrics to more formally evaluate the students' designs and presentations.

The Connect Component

The Connect component includes the themes and values that provide broader context and purpose for the Invention Kits. Unlike the previous components, the Connect component is not tied to a particular phase or group of activities. Instead, students should be engaged in aspects of the Connect component throughout the Invention Kit experience.

One of the core goals of the project is to "allow students to understand the process of invention and innovation from a historical perspective while allowing students to become inventors themselves" (Bull et al., 2017). This goal involves elucidating connections among historical inventions and tracing those connections all the way to the modern day. Furthermore, in tracing these connections with their students, teachers should help students understand that the paths of innovation will continue on into the future and that they can help shape those paths. To describe this idea, several developers alluded to the mission statement of the Smithsonian's National Museum of American History, which is to "help people understand the past in order to make sense of the present and shape a more human future" (Smithsonian National Museum of American History, 2017).

The sequence among Invention Kits themselves is designed to reveal connections among inventions and roughly parallels their chronological development. Each Invention Kit contains historical information that provides students the context for the invention's development. This information explicitly states how the inventor's work connected to and built upon the work of others. Collectively, these vignettes form an historical narrative that ties the Invention Kits together. At the same time, the connections among the inventions are implicitly reinforced when students carry artifacts from one Invention Kit to the next (e.g. the solenoid is used in all three current Invention Kits).

Teachers reported that, while it was helpful to view the connections among inventions through the lens of history, those connections became most powerful when the narrative was extended to the modern day. For students, the historical inventions took on added relevance when they were able to uncover how yesterday's inventions made possible the technologies they take for granted today. As one teacher explained, students view the world through their modern-day filters, so it is critical for the teacher to establish a "through line" from the historical invention to the modern day. When students can see these modern-day connections, they are much more likely to be engaged.

Another source of motivation embedded in the Invention Kits is revealed when students learn about the challenges that historical inventors faced and then experience some of those same challenges while creating their own designs. One teacher explained that these experiences helped his students appreciate that inventors were not “mystical people that knew everything” – that they too overcame challenges. This teacher felt that, when his students overcame their own challenges, they remembered these lessons and felt, in some way, like inventors themselves. These self-perceptions, he suggested, helped students persevere and added weight and a sense of pride to their accomplishments.

While both developers and teachers described the historical elements as important parts of the Invention Kits, teachers felt that they could be doing more to leverage these aspects. Some felt that they did not have enough time to fully explore the history of the inventions. Others felt that they needed additional materials to adequately cover these topics, such as videos or other resources. Some teachers felt that they needed more guidance along these lines, perhaps in the form of professional development. In their current forms, it is true the Invention Kits contain historical information but lack specific activities to address these topics. This lack of instructional materials led one teacher to describe the historical components of the Invention Kits as “the esoteric icing on the cake.” By this, she suggested that the original teachers at the pilot sites may understand the value of the historical components, but that newer teachers may not may not.

A final part of the Connect component is the connection to the maker movement. The Invention Kits are designed to tap into this “grassroots renaissance in creativity and innovation” that has coincided with the proliferation of affordable advanced manufacturing technologies (such as 3D printers) and accessible micro-processing devices like Arduino (FabNet Invention System, 2016). Over time, participants in this “movement” – mostly amateur inventors, tinkerers, and crafters – have embraced certain cultural norms and values. Among these are creativity and problem-solving, a do-it-yourself attitude that compels one to learn new skills and techniques, and a willingness to share one's creations and know-how with others (Hatch, 2013).

With schools beginning to establish their own makerspaces, the developers described a need to provide models for how these spaces can be used to target specific curricular objectives. At the same time, the developers seek to reinforce the aforementioned maker values. Creativity is encouraged as students develop unique designs with a personal flair. Problem-solving skills are essential when students try to get their designs to work. Learning new tools and techniques is a core objective in all phases, particularly the Make and Invent phases. Finally, students are encouraged to their creations and know-how at the conclusion of the Invent phase.

Implications for Practice

By definition, an innovation is "an idea, practice, or object that is perceived as new by an individual or other unit of adoption" (Rogers, 1993, p. 12). Occasionally, innovations are complex, meaning that what is regarded as a single innovation is actually a collection of coordinated, mutually-reinforcing innovations (Ellsworth, 2000). This study underscores that the Make-to-Learn Invention Kits are a complex innovation; certainly, there are many things in the kits that some teachers will perceive as new. The complexity of this innovation bears numerous implications.

Teaching/facilitating multiple subjects

First, there are implications that relate to pedagogical content knowledge. The Invention Kits fit into the genre of integrated STEM because, at the most basic level, they accommodate the teaching of two or more STEM subjects concurrently. The current

Invention Kits focus on three of the four subjects – science, technology, and engineering. This does not mean that all teachers will use the Invention Kits to teach all three subjects in equal measure. Instead, many teachers that adopt the Invention Kits will do so as teachers of isolated subjects, and will, therefore, choose to focus primarily on the subject matter for which they are responsible. For example, the teachers in this study were either engineering or science teachers. For the most part, the engineering teachers spent more time on the engineering aspects of the kits, while the science teachers spent more time on the scientific explorations. Such prioritizations are to be expected. However, regardless of whether the teacher chose to emphasize one subject over the others, all of the teachers were teaching the other subjects to some degree. The interdisciplinary nature of the activities demanded such. This means that teachers that adopt the Invention Kits will need to have some at least some measure of knowledge and skill teaching each of the subjects. For the teachers in this study, implementing the Invention Kits required some teaching of subjects for which they were not formally trained. As long as it remains uncommon for teachers to be trained in more than one subject, most future adopters of the Invention Kits will also face this challenge. This means that teachers that wish to implement all aspects of the Invention Kits well will need to develop deep understandings of new content matter as well as learn new pedagogical strategies for teaching that content. One developer explained that, in his observations of Invention Kit implementations, when things did not go well, it was often because a science teacher did not understand the engineering concepts embedded in the kits, or an engineering teacher did not fully understand the science. In other cases, it may have been that the teachers knew the content but did not know how to effectively teach it. The Invention Kit materials do not (and cannot) convey all the pedagogical content knowledge that teachers will need to implement the activities. Teachers that adopt these kits will need to take stock of the pedagogical content knowledge they possess for each subject and take the initiative to fill in any gaps. As a start, teachers should ask themselves how comfortable they are facilitating the engineering design process, how comfortable they are at facilitating scientific inquiry, and how comfortable they are at introducing and supporting new technologies.

Adopting learner-centered approaches

Teaching a new content area, in itself, requires innovation, but some teachers will also need to learn and practice new approaches for classroom management, many of them relating to project-based learning. First and foremost, they will need to adopt a student-centered approach. As several developers and teachers explained, students engaged in the Invention Kits should not be allowed to view the teacher as the "keeper of all knowledge." Rather, teachers should serve as facilitators, providing guidance and prompting when necessary, but otherwise putting the students in charge of their own learning (Thomas, 2000). For many teachers, this is not easy; for some, it conflicts with the teacher-centered approaches they have grown accustomed to (Capraro et al., 2013), plus there is a balance between providing students too much or too little support (Blumenfeld et al., 1991).

Teachers will also need to develop strategies for managing a complex classroom environment (Blumenfeld et al., 1991). If utilizing a student-centered approach with flexible pacing, it is possible that groups of students will be engaged in very different activities at the same time. Some might be using the computers to work on CAD files, others might be working through Lab Activities, and still others might be printing parts or putting them together. Each of these tasks (and many others) has its own requirements, considerations, and potential roadblocks. As much as possible, the teacher will need to anticipate these things and proactively take steps to establish organizational schemes and workflows to mitigate what can easily become a rather chaotic environment. Unfortunately, there is no single collection of strategies that will work for all teachers. Most strategies are context-dependent and will vary depending on one's students, classroom configuration, tool set, etc.

Leveraging first-hand experience

Being able to anticipate problems and ensure a relatively smooth implementation requires first-hand experience. Assuming the perspective of a student, teachers should build the artifacts and complete the Lab Activities themselves before implementing them with their classes. As several participants explained, doing so helps the teacher reveal areas where students might struggle. Each artifact has nuances that can make the difference between a device that works or does not work. Some of the Lab Activities also have nuances that can cause them to fail or lead to misconceptions. At the same time, going through the activities helps the teacher confirm that he himself has a sound grasp on the related concepts that the students are about to learn. Many teachers are surprised to learn that they do not understand the scientific concepts as well as they thought (National Academy of Engineering & National Research Council, 2014). Additionally, by going through the activities, the teacher can ensure that he or she has the required materials and tools. He or she can also visualize strategies to get those resources to students in an efficient and timely manner. Finally, only through first-hand experience will a teacher learn how to troubleshoot his or her own set of tools and devices.

Teacher attitudes and dispositions

When implementing the student-centered, inquiry-based, project-based approaches at the center of the Invention Kits, it is difficult to anticipate everything that one might encounter. This is especially true when teachers are implementing them for the first time. For that reason, developers and teachers suggested that one's attitude can be just as important than one's preparation. Participants cited numerous examples during the course of this study. One example was cited above – teachers should view themselves as facilitators rather than "keepers of knowledge." This attitude is summed up in the classic "guide by the side" versus "sage on the stage" expression. Similarly, teachers should seek to be non-controlling – autonomy is an important component of the Invention Kits. Next, teachers should not assume that things will always work the first time. This is where it is important to remember that students (and teachers) can learn from failure. Also, when teaching new subjects and content, one might not become aware of his or her lack of certain content knowledge until it is exposed by students in the course of an interaction. In this case, it is important for the teacher to model to the students that he or she is willing to learn alongside them. In reference to the previous two examples, one teacher described the need to be "comfortable with being uncomfortable." As she suggested, teachers should accept (and, if possible, embrace) that they will encounter the unexpected. This is not to say that students and teachers will not experience frustrations – nearly all participants in some way described needing to be able to cope with students that become discouraged or even angry when things are not working as planned. When describing his attitude to coping with such challenges, one teacher stated, “You’d better have a sense of humor.” In any case, attitudes matter, and teachers will need to bring their own personalities, styles, and intangibles to bear when implementing the Invention Kits.

Implications for Ongoing Development and Adoption

Preserving the vision of the Invention Kits

Currently, all of the sites piloting the Invention Kits have at least some connection to the developers. In most cases, they have personally met with the developers and had conversations about the vision and goals for the project. In many cases, they have attended meetings or workshops to walk them through the Invention Kit activities and help get them up and running with the technologies. Most are able to access in-person or virtual support from the development team when they run into problems. For all of these reasons, nearly all of the teachers using the Invention Kits have had rich exposure to what the innovation is intended to look like in practice. In the future, this is likely to change. In fact, one can already see evidence that some newcomers have had less exposure to the original vision that others. Recall that one teacher stated that she was not addressing the historical component because she had not been trained on it, while another teacher referred to it as the “esoteric icing on the cake.” This suggests that this component may not readily be adopted if teachers do not feel that they have enough information to act on it, especially as the innovation moves further away from the core group. And the historical component is not the only feature that teachers may choose to deemphasize or drop. Recall that one developer was concerned that students may lose opportunities to be creative if the kits become exercises in model-making. This is not to say that the

Invention Kits lose all merit if those components are not adopted. As previously stated, there may be legitimate reasons for not implementing those components. Nonetheless, the developers will want to ensure that the importance of those components are adequately communicated and supported. Then, if teachers choose to drop certain aspects of the Invention Kits, the developers can be more certain that the teachers did so for deliberate reasons, not because they lacked sufficient information or misunderstood the component. The Innovation Configuration Map drafted during this study may help teachers understand the individual parts of the Invention Kits and how they fit together, but it will not be enough by itself. Teachers will also need professional development that targets the "how" and the "why" of each component. The "how" should include tips for how to facilitate specific activities as well as broader strategies for managing inquiry- and project-based classrooms. The "why" should include training on core concepts. Being able to visualize the Invention Kits is vital, but teachers also need to have knowledge of the principles behind the kits, which can help them determine what changes they should consider (or should avoid) to preserve the pedagogical integrity of the units (Rogers, 2003). For the Invention Kits, this principles knowledge should include the core ideas relating to constructionism and project-based learning.

Contextual Factors

As the implications above demonstrate, social and contextual factors have a tremendous impact on the manner in which the Invention Kits are implemented. In this study, the Invention Kits are presented as avenues to integrative STEM learning experiences that are fundamentally different from more traditional, siloed approaches to the STEM subjects. However, the Invention Kits, by themselves, do not change anything. Rather, impact of Invention Kits in a given classroom largely depends on the teacher, the students, and a host of environmental and cultural considerations. In other words, teachers and administrators should not view the Invention Kits as a turn-key solution to STEM integration. In many cases, integrating STEM through the Invention Kits – or any similar engineering-focused lessons or curricula – will need to be accompanied by broader changes in how teachers teach, how students learn, and how classrooms and schools are structured. This study has focused on teacher behaviors, but the data suggest that many external factors that may be outside the control of teachers, including rigid class schedules, crowed rolls, cramped curricula, and state assessments, often work against teachers. For the most part, the engineering teachers that were implementing the Invention Kits in ways that most closely mirrored the vision of the developers possessed a great deal of flexibility to establish inquiry-based classroom structures and were not overly-constrained by state-mandated curricula and assessments. On the whole, the science teachers implementing the kits had less flexibility in these areas. In either case, the data suggest that successful implementation begins with the vision of the teacher, but does not end there. His or her efforts will need to be supported by other stakeholders, including building-level and district-level administrators, who may be needed to help teachers devise creative strategies for balancing workloads and schedules in order to give teachers and their students more time and flexibility to immerse themselves in the Invention Kits.

Subtle changes can make a big difference

Many of the implementation variations that were observed during this study were the direct result of one or more of the external factors mentioned above. For example, the decision to provide students with pre-built artifacts was made because teachers felt that they did not have enough time to allow students to make their own, given the crowded curriculum for which they were responsible. However, this study suggests that such changes, however subtle, can significantly alter the nature of the activities. In this study, the Invention Kits are presented as an innovative approach STEM. However, it is clear that certain changes diminish the innovative nature of the Invention Kits – perhaps to the extent that the kits conform to and reinforce the status quo. For example, one could argue that a group of students that go through the Solenoid Invention Kit Lab Activities, without then appropriating the science to develop their own inventions, have not truly experienced electromagnetism in a way that significantly departs from the way electromagnetism has been taught for years. As previously mentioned, some teachers felt compelled to make these changes based upon external factors. In other cases, it may be that decisions to selectively implement parts of the Invention Kits in traditional ways were the result of the natural proclivity of teachers to work within their comfort zones. In either case, an à la carte approach to implementing the Invention Kit activities, while sometimes unavoidable and entirely the prerogative of the teacher, may significantly alter the effects of the Invention Kits.

Building on experience

Hall and Hord (2013) describe the “Levels of Use” that teachers move through as they gain experience and confidence with an educational innovation. Initially, teachers often seek to mechanically follow procedures in order to establish basic competence. Only later do they develop the confidence and deep understanding of the innovation to make refinements and branch out. Two of the teachers interviewed had been involved in the project since the first Invention Kit was developed during the 2013-2014 school year. A third teacher had two years of experience implementing the kits. The remaining teachers were implementing the kits for the first time. This study suggests that the progression described by Hall and Hord is relevant in the context of the Invention Kits. Because of the diverse challenges of implementing this complex innovation, the teachers implementing the Invention Kits for first time devoted a large portion of their energies to the logistics of implementing the kits. Meanwhile, the more experienced implementers had developed strategies for dealing with the more mundane aspects of implementation, allowing them to focus more attention on student learning. However, even the most experienced implementers were still relatively new to the Invention Kits, and it is reasonable to expect that these teachers will continue to refine and improve their approaches. As such, teachers that choose to adopt the Invention Kits – and the administrators that support them – should anticipate that several cycles of implementation may be necessary to develop a sense of comfort and competence.

Evolution of the Invention Kits

As described in the discussion of the Make component, the Invention Kit developers are sensitive to the needs and constraints of the pilot teachers and have made a number of revisions to the Invention Kits to provide options to accommodate those needs – the development of ready-to-print artifact designs is an example. These accommodations underscore that the Invention Kits continue to evolve based on two-way communication between the developers and the pilot teachers. They are not the products of a linear model in which the developers pass on finished products to the teachers, which the teachers merely apply. In many respects, the Invention Kits are being shaped by the teachers that are implementing them, whose decisions, in turn, are shaped by social, cultural, and political factors that impact their jobs as teachers. In this way, the evolution of the Invention Kits can be viewed through the lens of the social construction of technology (SCOT). The theory of social construction of technology rejects notions of technological determinism in which technologies develop independently of society – or, in this case, teachers and other stakeholders (Johnson, 2005, p. 1792). Pinch and Bijker (1984) describe a multi-directional model of development in which various stakeholders (called relevant social groups) interact with an innovation and alter its shape until the innovation reaches a state of stabilization that in some way satisfies a need or problem for each group. One can discern such dynamics at play in the development of the Invention Kits. Each relevant social group in the Make-to-Learn Invention Kits project brings its own set of needs and beliefs into mix. As the data suggest, the problems that science teachers are trying to solve with the Invention Kits are not necessarily the same as those of engineering teachers. At the same time, the developers are attempting to craft the Invention Kits to meet the needs of both science and engineering teachers, while at the same time adhering to their own pedagogical philosophies and visions for the project. These various (and occasionally conflicting) interests have influenced various iterations of the kits and spur variations in implementation. As an innovation, the Invention Kits have not yet stabilized. And such stabilization may not occur for some time, since the Invention Kits have not yet been broadly disseminated and different relevant social groups (art teachers, for example) are just now beginning to experiment with the kits and join the conversation.

Limitations

One limitation of this study was its small sample size. Since the Invention Kits are still in the pilot phase, there was a limited number of sites available to include. All of the sites that were chosen were relatively close by (all within the state of Virginia). The sample could have been expanded slightly if would have been feasible to arrange visits to the pilot sites in Texas or South Carolina. Nonetheless, the small sample size limited the number of implementation variations that could be observed.

Another limitation of the study related to its short duration and limited access to the participants. Observations and interviews were completed over the span of two months, which meant that I was only able to observe each teacher implement one Invention Kit. With more time, I might have been able to observe the teachers implement the entire sequence of Invention Kits. A longitudinal study, conducted over the course of a school year, or even across multiple school years, might have revealed additional changes to the Invention Kits as the teachers' approaches evolved over time. Additional time would have also permitted me to more thoroughly field test drafts of the IC Map.

The number of classroom visitations I was able to make was also limited by the significant amount of travel involved in visiting each site, as well as the fact that the teachers in the sample were implementing the kits at the same time. Perhaps with some creative scheduling and a team of researchers, it would have been possible to spend more time in a single classroom. This might have facilitated a more ethnographic approach, which could have more thoroughly documented the culture of creativity and invention that some of the teachers had established. At the same time, a team of researchers with varied perspectives might have discerned a greater number of variations and provided different insights. Hall and Hord (2013) suggest that the process of Innovation Configuration Mapping is best accomplished by a small team this reason. Nonetheless, as a sole researcher, I tried to account for my limited perspective by communicating with the developers and other academics for member checking and consultation as often as possible and at each stage of the process. For example, I met with developers or teachers to review each successive draft of the Innovation Configuration Map. Meanwhile, I arranged for one of my dissertation committee co-chairs to perform an external audit of my data and analysis. On several other occasions, I met informally with my dissertation committee co-chairs for similar purposes.

Another limitation was that all of the study sites were receiving assistance from facilitators connected with the project. The extent of this assistance varied, from frequent on-site assistance to periodic phone consultations. Nonetheless, the sample did not include sites that were implementing the Invention Kits without any intervention because these sites did not yet exist. The absence of any kind of intervention by the development team almost certainly would have contributed to variations that were not observed in this sample.

A final limitation was that the Invention Kits themselves were not fully developed. While the core components may not change as the kits mature, new or revised activities might change the look of the Invention Kits. For example, at the time of this study, the developers had created few resources for the historical component. Had I been able to delay the study until more activities were available, it might have been easier to document the Connect component with more specificity and depth.

Suggestions for Future Research

Because the Invention Kits will continue to undergo changes, it will be necessary to revise the Innovation Configuration Map developed during this study. A common practice is to clearly mark each IC Map with the term "draft" to indicate that new adaptations of the innovation will continue to emerge as time passes (Hall & Hord, 2013). This practice seems particularly appropriate in the context of the Invention Kits. As the Invention Kits mature and are adopted by a broader and more diverse set of users, future researcher could expand upon the work begun in this study in several areas.

A future researcher might begin by establishing fidelity lines. On an IC Map, fidelity lines are used to indicate ranges of variations that might be considered "ideal," "acceptable," and "unacceptable" (Hall & Hord, 2013, p. 63). It is worth restating that the purpose of developing IC Maps is not to suggest that there is a right or wrong way to implement an innovation. Implementation variations are inevitable (Hall & Hord, 2013). Most teachers will choose to adapt and implement the Invention Kits in whatever ways they feel most comfortable, and there are many legitimate reasons for making changes. Nonetheless, some ways of implementing the kits are closer to the vision of the developers than others and not all changes are equal. This study suggests some adjustments probably have little impact on the integrity of the design. These variations would fall into the "ideal" or "acceptable" ranges. Others changes may fundamentally conflict with the pedagogical philosophies underlying the Invention Kits. These variations would likely be labeled as "unacceptable." Fidelity lines can shift for each component (Hall & Hord, 2013). This feature would be useful in a future version of the IC Map to indicate that not all "D" variations are necessarily undesirable or at odds with the spirit of the Invention Kits. Nonetheless, Hall and Hord (2013) stress that a decision to add fidelity lines should not be made until after the map has undergone significant vetting and revisions. They state, “The insertion of fidelity lines should not be arbitrary or capricious. The rationale should be strong, and, hopefully, empirical data should support their placement” (p. 63). As more teachers begin using the Invention Kits, thereby opening up additional opportunities for revising and testing the Map, the data may support the addition of these lines.

Next, a future study might explore the reasons that adopters make changes. This study focused primarily on documenting what changes teachers made, not necessarily why they made those changes. Nonetheless, this study suggests several broad reasons one might make changes: (1) a teacher might make changes based upon the types of students she is teaching; (2) she might adapt the Invention Kits based on her primary content focus (e.g. they science, technology, or engineering); (3) the teacher might make changes to suit the materials and tools she has (or does not have) access to; and (4) she might make changes to suit her pedagogical style. There may be other reasons that one would make changes. Fully understanding these reasons might help developers build in accommodations for these teachers that preserve the core components of the Invention Kits. Hall and Hord’s (2013) Stages of Concern and Levels of Use constructs, also part of the Concerns-Based Adoption Model, might be useful to this end.

Finally, a future study might explore more thoroughly how different user groups adapt the Invention Kits. Such a study could be rooted in literature relating to the Social Construction of Technology (SCOT). SCOT researchers posit that different social groups interpret innovations in different ways and thereby help shape the innovation (Pinch &

Bijker, 1984). In this study, I focused on the two social groups that the developers originally had in mind when creating the Invention Kits – secondary science teachers and secondary engineering teachers. While I did not differentiate between the two groups on the Map, this study suggested that some of the observed variations were due to differences between the two groups' goals and objectives. As more science teachers and engineering teachers adopt the Invention Kits, a larger sample will be available to explore how the two social groups interpret (and adapt) the Invention Kits differently. At the same time, other social groups may adopt the Invention Kits in sufficient numbers to explore how they might interpret the kits. One developer, who is also a mathematics professor, already provided a glimpse of how mathematics teachers might modify the Invention Kits when he and a colleague adapted the Solenoid Invention Kit to teach Ampere's Law. In this case, the students did not create a physical artifact, but instead devised a mathematical formula. More recently, an elementary art teacher has begun adapt the Invention Kits, undoubtedly in ways that emphasize creativity and artistic skills. At the time of this study, these social groups were not sufficiently involved or in large enough numbers to consider including them in the study. However, this will likely change in the future, revealing an entirely different set of implementation variations.

Conclusion

In this study, I focused on identifying the essential components of the Make-to-Learn Invention Kits. I also set out to describe the developers' vision for how each of the components should be implemented. Finally, I attempted to document how teachers adapted each component in practice. The results of the study pointed to four overlapping, but distinct, core components of the Invention Kit: (1) reconstructing a working historical artifact, (2) exploring scientific principles using the artifact, (3) extending the artifact and the scientific principles to a unique creation, and (4) viewing the invention through the lens of history and connecting the experiences to modern-day cultures of innovation. The goal was to collect and report this data using a process called Innovation Configuration Mapping, which is intended to help would-be adopters and other stakeholder visualize what an educational innovation looks like in use.

Innovation Configuration Mapping proved to be an effective methodology for this study. The IC Map developed during this process underscores the complexity of the Invention Kits, which include numerous social, pedagogical, and technological considerations. Some of the components that emerged during this study were either unwritten, briefly mentioned, or merely implied in the lesson themselves. These include some of broader values and assumptions that undergird the lessons. At the same time, the IC Mapping process allowed me to document the ground-level intricacies of putting these values into practice. In doing this, I was able to convey that these intricacies change from context to context and that there may be more than one acceptable way to approach various components of the Invention Kits.

The resulting map should not be considered a finished product. As the Invention Kits evolve and newer users adopt them, revisions to the Map will be necessary. Nonetheless, it is my hope that teachers with only a basic introduction to the Invention Kits may read the IC Map and develop a clear, practical sense of what actually goes into the Kits and how the activities might fit into their own classrooms.

REFERENCES

Ackermann, E. (2001). Piaget's Constructivism, Papert's Constructionism: What's the difference?, Geneva.

Barron, B., & Darling-Hammond, L. (2008). Teaching for Meaningful Learning: A Review of Research on Inquiry-Based and Cooperative Learning. Book Excerpt. George Lucas Educational Foundation.

Barron, B. J. S., Schwartz, D. L., Vye, N. J., Moore, A., Petrosino, A., Zech, L., . . . Vanderbilt, T. G. a. (1998). Doing with Understanding: Lessons from Research on Problem- and Project-Based Learning. The Journal of the Learning Sciences, 7(3/4), 271-311.

Blumenfeld, P. C., Soloway, E., Marx, R. W., Krajcik, J. S., Guzdial, M., & Palincsar, A. (1991). Motivating Project-Based Learning: Sustaining the Doing, Supporting the Learning. Educational Psychologist, 26(3/4), 369-398.

Brennan, K. (2015). Beyond Technocentrism. Constructivist Foundations, 10(3), 289 - 296.

Brophy, S., Klein, S., Portsmore, M., & Rogers, C. (2008). Advancing Engineering Education in P-12 Classrooms. Journal of Engineering Education, 97(3), 369-387.

Buck Institute for Education. (2016). What is Project Based Learning (PBL)? Retrieved from https://www.bie.org/about/what_pbl

Bull, G., & Garofalo, J. (2017). Developing the FabNet Electric Motor Invention Kit Sequence.

Bull, G., Garofalo, J., Standish, N., Littman, M., Corum, K., & Hoffman, M. (2017). FabNet Invention Kits.

Bull, G., Haj-Hariri, H., Atkins, R., & Moran, P. (2015). An educational framework for digital manufacturing in schools2(2). Retrieved from doi:10.1089/3dp.2015.0009

Bull, G., Littman, M., & Hoffman, M. (2015). An Age of Discovery.

Capon, N., & Kuhn, D. (2004). What's so Good about Problem-Based Learning? Cognition and Instruction, 22(1), 61-79.

Capraro, R. M., Capraro, M. M., & Morgan, J. R. (2013). STEM Project-Based Learning : An Integrated Science, Technology, Engineering, and Mathematics (STEM) Approach (Vol. 1;2nd;). Dordrecht: SensePublishers.

Committee on K-12 Engineering Education. (2009). Engineering in K-12 education: understanding the status and improving the prospects (G. P. Linda Katehi, and Michael Feder Ed.). Washington, D.C. :: National Academies Press.

Cook, N. D., & Weaver, G. C. (2015). Teachers' Implementation of Project-Based Learning: Lessons from the Research Goes to School Program. The electronic journal of science education, 19(6), 1.

Creswell, J. W. (2013). Qualitative inquiry and research design : choosing among five approaches (3rd ed. ed.). Los Angeles :: SAGE Publications.

Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the Challenges of Inquiry-Based Learning through Technology and Curriculum Design. The Journal of the Learning Sciences, 8(3/4), 391-450.

Ellsworth, J. B. (2000). Surviving change : a survey of educational change models. Syracuse, N.Y. :: Clearinghouse on Information & Technology, Syracuse University.

FabNet Invention System. (2016). Make to Learn. Retrieved from http://www.maketolearn.org/

Fishman, B., Penuel, W. R., Allen, A.-R., Cheng, B. H., & Sabelli, N. (2003). Design-Based Research: An Emerging Paradigm for Educational Inquiry. Educational Researcher, 32(1), 5-8.

Groves, J., Abts, L., & Goldberg, G. (2014). Using an Engineering Design Process Portfolio Scoring Rubric to Structure Online High School Engineering Education. Paper presented at the 2014 ASEE.

Hall, G. E. (2010). Technology's Achilles Heel: Achieving High-Quality Implementation. Journal of Research on Technology in Education, 42(3), 231-253.

Hall, G. E. (2013). Evaluating Change Processes: Assessing Extent of Implementation (Constructs, Methods and Implications). Journal of Educational Administration, 51(3), 264-289.

Hall, G. E., & George, A. A. (2000). The Use of Innovation Configuration Maps in Assessing Implementation: The Bridge Between Development and Student Outcomes.

Hall, G. E., & Hord, S. M. (2013). Implementing change : patterns, principles, and potholes (4th ed. ed.). Boston :: Pearson.

Hall, G. E., Wallace, R. C. J., & Dosset, W. A. (1973). A Developmental Conceptualization of the Adoption Process Within Educational Institutions. University of Texas, Austin.

Hatch, M. (2013). The Maker Movement Manifesto: Rules for Innovation in the New World of Crafters, Hackers, and Tinkerers. New York: McGraw-Hill Education.

Heck, S., et al. (1981). Measuring innovation configurations : procedures and applications. In S. Heck (Ed.). Austin :: The University of Texas.

Heil, D. R., Pearson, G., & Burger, S. E. (2013). Understanding Integrated STEM: Report on a National Study. Paper presented at the 120th ASEE Annual Conference and Exposition, Atlanta, GA.

Hord, S. M., Stiegelbauer, S. M., Hall, G. E., & George, A. A. (2006). Measuring Implementation is Schools: Innovation Configurations: SEDL.

Horsley, D. L., & Loucks-Horsley, S. (1998). CBAM Brings Order to the Tornado of Change. Journal of Staff Development, 19(4), 17.

Johnson, D. G. (2005). Social Construction of Technology. In C. Mitcham (Ed.), Encyclopedia of Science, Technology, and Ethics (pp. 1791-1795). Detroit: Macmillan Reference USA.

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. International Journal of STEM Education, 3(1), 1-11. doi:10.1186/s40594-016-0046-z

Krajcik, J., Blumenfeld, P. C., Marx, R. W., Bass, K. M., Fredricks, J., & Soloway, E. (1998). Inquiry in Project-Based Science Classrooms: Initial Attempts by Middle School Students. The Journal of the Learning Sciences, 7(3/4), 313-350.

Krajcik, J. S., Blumenfeld, P. C., Marx, R. W., & Soloway, E. (1994). A Collaborative Model for Helping Middle Grade Science Teachers Learn Project-Based Instruction. The Elementary School Journal, 94(5), 483-497.

Laboratory School for Advanced Manufacturing. (2017a). Solenoid Invention Kit Design Challenge. Retrieved from http://www.maketolearn.org/inventions-kits/solenoid/guide/

Laboratory School for Advanced Manufacturing. (2017b). Solenoid Invention Kit Unit Plan. Retrieved from http://www.maketolearn.org/inventions-kits/solenoid/guide/

Ladewski, B. G., Krajcik, J. S., & Harvey, C. L. (1994). A Middle Grade Science Teacher's Emerging Understanding of Project-Based Instruction. The Elementary School Journal, 94(5), 499-515.

Martinez, S., & Stager, G. (2013). Invent to Learn: Making, Tinkering, and Engineering in the Classroom. Torrance, CA: Constructing Modern Knowledge Press.

Marx, R. W., Blumenfeld, P. C., Krajcik, J. S., Blunk, M., Crawford, B., Kelly, B., & Meyer, K. M. (1994). Enacting Project-Based Science: Experiences of Four Middle Grade Teachers. The Elementary School Journal, 94(5), 517-538.

Maxwell, J. A. (2013). Qualitative Research Design: An Interactive Approach (Vol. 3rd). Los Angeles: Sage.

Mergendoller, J. R., Maxwell, N. L., & Bellisimo, Y. (2006). The Effectiveness of Problem-Based Instruction: A Comparative Study of Instructional Methods and Student Characteristics. Interdisciplinary Journal of Problem-based Learning, 2(1).

Mergendoller, J. R., & Thomas, J. W. (2000). Managing project based learning: Principles from the Field. Paper presented at the Annual Meeting of the American Educational Research Association, New Orleans.

Merriam, S. B., & Tisdell, E. J. (2016). Qualitative research: A guide to design and implementation (Vol. 4th). San Francisco: Jossey-Bass.

Mioduser, D., & Betzer, N. (2008). The contribution of Project-based-learning to high-achievers’ acquisition of technological knowledge and skills. International Journal of Technology & Design Education, 18(1), 59-77. doi:10.1007/s10798-006-9010-4

Moore, T. J., Glancy, A. W., Tank, K. M., Kersten, J. A., Smith, K. A., & Stohlmann, M. S. (2014). A Framework for Quality K-12 Engineering Education: Research and Development. Journal of pre-college engineering education research, 4(1), 1-13. doi:10.7771/2157-9288.1069

National Academy of Engineering. (2016). NAE Grand Challenges for Engineering. Retrieved from http://www.engineeringchallenges.org/challenges.aspx

National Academy of Engineering, & National Research Council. (2014). STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research. Washington, DC: The National Academies Press.

National Research Council. (2010). Standards for K-12 Engineering Education? [electronic resource]. Washington :: National Academies Press.

National Research Council. (2012). A framework for K-12 science education: practices, crosscutting concepts, and core ideas. Washington, D.C. :: The National Academies Press.

NGSS Lead States. (2013). Next Generation Science Standards: For States, By States. Washington, DC: The National Academies Press.

Noss, R., & Clayson, J. (2015). Reconstructing Constructionism. Constructivist Foundations, 10(3), 285 - 288.

Papert, S. (1984). New Theories for New Learnings. School Psychology Review, 13, 422 - 428.

Papert, S. (2005). Teaching Children Thinking. Contemporary Issues in Technology and Teacher Education (CITE Journal), 5(3-4), 353 - 365.

Papert, S., & Harel, I. (1991). Constructionism: Ablex Publishing Corporation.

Patton, M. Q. (2015). Qualitative research & evaluation methods: Integrating theory and practice (Vol. 4th). Thousand Oaks, CA: Sage Publications.

Penuel, W. R., Fishman, B. J., Haugan Cheng, B., & Sabelli, N. (2011). Organizing Research and Development at the Intersection of Learning, Implementation, and Design. Educational Researcher, 40(7), 331-337. doi:10.3102/0013189x11421826

Pinch, T. J., & Bijker, W. E. (1984). The Social Construction of Facts and Artefacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other. Social Studies of Science, 14(3), 399-441.

Resnick, M., Berg, R., & Eisenberg, M. (2000). Beyond Black Boxes: Bringing Transparency and Aesthetics Back to Scientific Investigation. The Journal of the Learning Sciences, 9(1), 7 - 30.

Roehrig, G. H., Moore, T. J., Wang, H.-H., & Park, M. S. (2012). Is Adding the E Enough? Investigating the Impact of K-12 Engineering Standards on the Implementation of STEM Integration. School Science and Mathematics, 112(1), 31-44. doi:10.1111/j.1949-8594.2011.00112.x

Rogers, E. M. (2003). Diffusion of innovations (5th ed., Free Press trade pbk. ed. ed.). New York :: Free Press.

Russell, J. L., Jackson, K., Krumm, A. E., & Frank, K. A. (2013). Theories and Research Methodologies for Design-Based Implementation Research: Examples from Four Cases Yearbook of the National Society for the Study of Education (Vol. 112, pp. 157-191): Teachers College, Columbia University.

Saldaña, J. (2009). The coding manual for qualitative researchers. Thousand Oaks, Calif;London;: Sage.

Sanders, M. (2008). STEM, STEM Education, STEMmania. Technology Teacher, 68(4), 20-26.

Smith, K. A., Sheppard, S. D., Johnson, D. W., & Johnson, R. T. (2005). Pedagogies of Engagement: Classroom-Based Practices. Journal of Engineering Education, 94(1), 87-101.

Smithsonian Institution. (2015). American Innovations in an Age of Discovery. Retrieved from http://3d.si.edu/invention

Smithsonian National Museum of American History. (2017). National Museum of American History. Retrieved from http://americanhistory.si.edu/

Spradley, J. P. (1980). Participant Observation. New York: Holt, Rinehart, and Winston.

Stager, G. (2005). Papertian Constructionism and the Design of Productive Contexts for Learning. Paper presented at the EuroLogo X, Warsaw, Poland.

The White House. (2016). Educate to Innovate. Retrieved from https://www.whitehouse.gov/issues/education/k-12/educate-innovate

Thomas, J. W. (2000). A review of research on project-based learning.

U.S. Department of Education. (2015, 11/10/15). Race to the Top Fund. Retrieved from http://www2.ed.gov/programs/racetothetop/index.html

Wells, J. G. (2016). PIRPOSAL Model Of Integrative STEM Education: Conceptual And Pedagogical Framework For Classroom Implementation. Technology & Engineering Teacher, 75(6), 12-19.

Wells, J. G., & Ernst, J. (2012/2015). Integrative STEM Education. Retrieved from http://www.soe.vt.edu/istemed/

APPENDICES

Appendix A

Teacher Preliminary Questionnaire/Interview Protocol

1. Would you please describe your background as it relates to your current position as a STEM teacher/integrator?
    a. What formal educational experiences/training have you had?
    b. What informal educational experiences/training have you had?
    c. Do you have any personal or professional experiences in STEM fields outside of education?
2. Describe your approach to STEM curricula.
    a. What is your role in the classroom?
    b. What are your students' roles?
    c. How do you organize your classroom?
3. Would you describe some of the STEM activities that you've done with your students?
4. Describe your experience and comfort level facilitating engineering design?
5. Describe your experience and comfort level with project-based learning?
    a. Can you describe for me a project-based learning experience that has worked well for you?
    b. Can you describe a project-based learning experience that was a struggle to implement?

Appendix B

Invention Kit Developer Interview Protocol

1. Would you describe for me the Make-to-Learn Invention Kit series?
   a. Describe the focus of the Invention Kits.
   b. What are its most important characteristics?
   c. Describe for me an Invention Kit.
   d. What are the core influences of the Invention Kits? Describe where those influences are evident in the design.
2. What would I see in a classroom where the Make-to-Learn Invention Kits are in use?
   a. What do teachers do?
   b. What do students do?
   c. How do teachers and students interact?
   d. How do students interact?
   e. What does the classroom look like?
   f. Would you walk me through implementation of one of the Invention Kits?
3. What do you consider the most essential components of the Invention Kits?
   a. Tell me more about [name of components].
   b. Describe what [name of component] looks like when it is implemented the way you like it to be.
   c. What are some other ways [name of component] might be implemented?
   d. Can you give me a version of [name of component] that would be unacceptable to you?
   e. Of the components that you have described, which should teachers consider their highest priorities when beginning to implement the Invention Kits?
4. What kinds of how-to knowledge do teachers and others need to be successful with this Invention Kits?
   a. What kinds of information do teachers need to use this Invention Kits well?
   b. What do teachers need to know beforehand, or what do they need to learn?
5. What kinds of principles do teachers and others need to understand to be successful with this Invention Kits?
   a. What are the underlying big ideas that are useful to know and understand?
   b. What are some examples of how understanding these big ideas might impact the implementation of the Invention Kits?

Notes:

- "A key part of IC Mapping is the orientation that is taken. The focus is on developing pictures of the operational forms of the innovation, not statements of its philosophy or a listing of its implementation requirements" (Hall & Hord, 2013, p. 70).

Appendix C

Teacher/Facilitator Interview Protocol

1. Would you describe for me the Make-to-Learn Invention Kit series?
    a. Describe the focus of the Invention Kits.
    b. What are its most important characteristics?
    c. Describe for me an Invention Kit.
2. What would I see in your classroom when you are implementing the Make-to-Learn Invention Kits?
    d. What would you be doing?
    e. What would your students be doing?
    f. How do you and your students interact?
    g. How do your students interact?
    h. What does the classroom look like?
    i. Would you walk me through the activities that make up an Invention Kit?

3. What do you consider the most essential components of the Invention Kits?
    j. Tell me more about [name of components].
    k. Describe what [name of component] looks like when things go according to plan. you like it to be.
    l. Describe what [name of component] looks like when things don't go as planned.
    m. What are your highest priorities when implementing the Invention Kits?
    n. Describe any changes or adaptations you've made to the Make-to-Learn Invention Kits?
5. What kinds of how-to knowledge do you need to be successful with these Invention Kits?
    a. What kind of information do you need to use this Invention Kits well?
    b. What do you need to know beforehand, or what do you need to learn?
6. What kinds of principles do you need to understand to be successful with this Invention Kits?
    a. What are the underlying big ideas that are useful to know and understand?
    b. What are some examples of how understanding these big ideas has impacted your use of the Invention Kits?

Appendix D

IC Map for Self-Assessment Survey

1. Is the IC Map organized in a way that easy to read and understand?

2. Is the language used in the IC Map adequately descriptive, concise, and free of jargon?

3. Is the tone of the IC Map appropriate? In other words, is the tone of the IC Map constructive rather than critical?

4. Does the IC Map allow you to accurately convey your implementation of the Invention Kits?

Appendix E

Participants

Invention Kit Development Team			
Developer 1	Professor, Instructional Technology	Curry School of Education	University of Virginia
Developer 2	Professor, Instructional Technology and Mathematics Education	Curry School of Education	University of Virginia
Developer 3*	Professor, Department of Mechanical and Aerospace Engineering		Princeton University
Developer 4	Graduate Student, Instructional Technology	K-12 Engineering Design Lab	University of Virginia
Developer 5	Graduate Student, Instructional Technology	K-12 Engineering Design Lab	University of Virginia
Collaborator/Pilot Site Coordinator 1	Professor, Department of Middle, Secondary & Mathematics Education		James Madison University
Collaborator/Pilot Site Coordinator 2	Professor, Department of Learning Technologies	College of Information	University of North-Texas
Classroom Teachers			
Erica Q.	Grade 8 - Mechatronics	Seifert Middle School	Adkins County Public Schools
Brenda F.	Grade 8 – Physical Science	Seifert Middle School	Adkins County Public Schools
Brian N.	Grades 7 and 8 – Engineering	Brandeis Middle School	Chester City Public Schools
Pamela Y.	Grade 8 – STEM	Mountain Top Middle School	Huntsville City Public Schools
Christine I.	Grade 8 - STEM	Thomas Paine Middle School	Huntsville City Public Schools
Jack E.	Grade 8 - STEM	Thomas Paine Middle School	Huntsville City Public Schools
Dylan T.	Grade 8 – STEM	Thomas Paine Middle School	Huntsville City Public Schools
Facilitators			
Richard N.	K-8 STEM Coordinator		Adkins County Public Schools

Note. Developer 3 was not interviewed for this study.

Appendix F

Observation Protocol – Pilot Study

Guiding Questions for Observation:

- What does the STEM curriculum look like in practice?
    - What are the components of the lessons/activities? How is the class period structured?
    - What content is being addressed?
    - What skills are being addressed (academic, social, technical, etc.)?

- What are teachers and students doing during the lessons?
    - What strategies are the teachers utilizing?
    - What strategies are the students utilizing?
    - What routines are in place?

- What are the interactions?
    - Between teachers and students?
    - Among students?
    - What expectations (for performance or behavior) are shared? How are they communicated?

- What does the classroom look like (including configuration and resources)?
    - How does the physical environment facilitate/impede the activities?
    - How does the teacher utilize the environment?
    - How do the students utilize the environment?

Specific Observation Look-Fors:

- How do the students show their thinking? Are they using journals? Are they generating any other artifacts?
- What kinds of questions do the teachers ask the students?
- What kinds of questions do the students ask the teachers?
- How do the students talk about their work?
- How do the teachers assist struggling students?
- How do the students organize their workspaces? How do they store their work?
- What are the routines relating to tools and technology?

Appendix G

Interview Protocol – Pilot Study

Broad questions:

- Describe what is it like to teach in this environment?
- What are the essential elements to make this kind of curriculum work?
- Imagine you have a new challenge or task to present to the students. Can you lead me through how you go about doing that?
- If I were to watch you facilitate these activities, what would I hat kind of scaffolding do you provide?
- How do you intervene when students are struggling?
- What do you know now that you wish you would have known when you started?

Specific questions:

- How do you manage accountability? Grades?
- What expectations for behavior, performance, and safety do you have in place? How do you communicate those expectations? What are the consequences for not adhering to those expectations?
- Describe the classroom workflows and workspaces.
- How do you manage pacing and timelines for project completion?
- Do you align your curriculum with other classes? If so, how?

Appendix H

Innovation Configuration Map for the Make-to-Learn Invention Kits

<table>
<tr><td colspan="4">Make – Reconstructing Tools and Mechanisms</td></tr>
<tr><td colspan="4">1. Have Students Construct Tools and Artifacts for Learning</td></tr>
<tr><td colspan="4">The Big Idea: Students benefit by building their own artifacts.</td></tr>
<tr><td colspan="4">Dimensions: Student Participation, Tools and Materials</td></tr>
<tr><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr>
<td>● All students participate in constructing the tool (e.g. continuity tester) and/or artifact (e.g. linear motor) they will be using.
● The teacher provides all the tools and materials needed to successfully construct the tool and/or artifact.</td>
<td>● All students participate in constructing some portion of the tool and/or artifact that they will be using.
● The teacher provides all the tools and materials needed to successfully construct the tool and/or artifact.</td>
<td>● The teacher allows only some of the students to participate in constructing the tool and/or artifact that they will be using.
and/or
● The teacher does not provide sufficient tools and materials to successfully construct the tool and/or artifact.</td>
<td>● Students do not construct the tool and/or artifact that they will be using. Tools and/or artifacts are pre-built.</td>
</tr>
</table>

Make – Reconstructing Tools and Mechanisms			
2. Build Competencies for Modern Design and Manufacturing Technologies			
The Big Idea: Students develop high-tech skills.			
Dimensions: Computer-Assisted Design (CAD), Computer-Aided Manufacturing (CAM), Themes			
A	B	C	D
● Students use CAD software for exploring and modifying existing designs (e.g. historical devices) or for creating their own designs. ● Students use CAM technologies such as 3D printers, laser cutters, or digital die cutters to fabricate their own designs. ● The teacher leads explorations about how CAD and CAM technologies impact modern invention and innovation. The teacher shares examples from the news, magazines, and other media. Students discuss how the rising accessibility of these tools has made it easier for ordinary Americans to invent and innovate.	● Students use CAD software for exploring existing designs (e.g. historical devices) but not for making modifications or creating their own designs. ● Students use CAM technologies such as 3D printers, laser cutters, or digital die cutters to fabricate designs that are provided to them. ● The teacher leads explorations about how CAD and CAM technologies impact modern invention and innovation. The teacher shares examples from the news, magazines, and other media.	● Students are exposed to CAD software (e.g. teacher demonstration or isolated student activity) but do not have opportunities for exploring and modifying existing designs or creating their own designs. ● Students are exposed to CAM technologies (e.g. teacher demonstrations, videos, photos, or articles), but they do not have opportunities to use the technologies.	● Students are not exposed to CAD software. ● Students are not exposed to CAM technologies.

<table>
<tr><td colspan="4">Make – Reconstructing Tools and Mechanisms</td></tr>
<tr><td colspan="4">3. Build Competencies for Constructing by Hand</td></tr>
<tr><td colspan="4">The Big Idea: Students develop low-tech skills and a “can-do” spirit.</td></tr>
<tr><td colspan="4">Dimensions: Hand Tools, Methods, Materials, Support</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td></td></tr>
<tr>
<td>● Students regularly use tools and methods for assembling designs created using CAM technologies or for building entirely by hand. The teacher provides instruction on methods that relate to safely measuring, cutting, shaping, adhering, fastening, etc. Tools include saws, utility knives, soldering irons, etc.
● Students regularly build using a variety of materials. These may include plastics, woods, metals, and paper. They have opportunities to learn and practice special techniques that are used to work with various materials. They are able to consider the suitability of a material for a given purpose and consider trade-offs among them.
● The teacher uses a variety of strategies to help students extend their know-how. The teacher guides students to outside sources such as Instructables or YouTube. He or she regularly asks students who have mastered a skill to teach their peers.</td>
<td>● Students occasionally use tools and methods for assembling designs created using CAM technologies or for building entirely by hand.
● Students occasionally build using a variety of materials. These may include plastics, woods, metals, and paper. They have opportunities to learn and practice special techniques that are used to work with various materials.
● The teacher sometimes uses a variety of strategies to help students extend their know-how. The teacher may occasionally point students to outside sources or ask students who have mastered a skill to teach their peers.</td>
<td>● Students rarely or never use tools and methods for assembling designs created using CAM technologies or for building entirely by hand.
● Students rarely or never build using a variety of materials.
● The teacher is the sole source for know-how.</td>
<td></td>
</tr>
</table>

<table>
<tr><td colspan="4">Explore – Exploring Science through Lab Activities</td></tr>
<tr><td colspan="4">4. Leverage the Lab Sequence to Scaffold Learning</td></tr>
<tr><td colspan="4">The Big Idea: The Lab Activities are deliberately sequenced to build conceptual understanding.</td></tr>
<tr><td colspan="4">Dimensions: Lab Activities, Documentation of Student Thinking, Formative Assessment, Multiple Representations</td></tr>
<tr><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr>
<td>● The teacher implements all the Lab Activities in order. Any modifications or substitutions preserve all aspects of the conceptual learning progression.
● The teacher requires students to address the essential and guiding questions in each Lab Activity and document their observations using the Lab Handouts or similar materials.
● The teacher frequently interacts with students, while they are engaged in the activities, to ensure they are having success. He or she poses thought-provoking questions that require students to articulate their thinking regarding the essential questions and make connections among the Lab Activities.
● The teacher utilizes multiple representations (videos, computer simulations, hands-on or digital manipulatives, etc.) from the Invention Kits and elsewhere (e.g. YouTube) to further illustrate essential concepts as needed. The teachers helps students connect them to the Lab Activities.</td>
<td>● The teacher implements most the Lab Activities in order. Any modifications or substitutions preserve most aspects of the conceptual learning progression.
● The teacher requires students to address the essential and guiding questions in each Lab Activity and document their observations using the Lab Handouts or similar materials.
● The teacher occasionally checks in with students to ensure they have successfully completed the lab activities. He or she occasionally poses questions to assess their thinking and prompt connections.</td>
<td>● The teacher implements only some the Lab Activities. Not all concepts are addressed.
or
● The teacher implements all of the Lab Activities but implements them out of order. The learning progression is significantly altered.
● The teacher asks students to address essential and guiding questions but does not require students to document their observations.</td>
<td>● The teacher implements few or none of the Lab Activities.</td>
</tr>
</table>

Explore – Exploring Science through Lab Activities

5. Let Students Engage Naturally with the Content

The Big Idea: Students engage in scientific inquiry to construct knowledge.

Dimensions: Autonomy, Time, Flexibility

A	B	C	
● The teacher gives students the autonomy to work through the Lab Activities on their own and take ownership of the process. ● The teacher provides ample time for students to engage in scientific inquiry in a hands-on fashion – observe, hypothesize, investigate, draw conclusions, make discoveries, etc. ● Students have the flexibility to extend the activities pursue additional connections.	● The teacher gives students some autonomy to work through the Lab Activities on their own. ● The teacher provides a moderate amount of time for students to engage in scientific inquiry in a hands-on fashion – observe, hypothesize, investigate, draw conclusions, make discoveries, etc. ● The pacing of the Labs or other teacher-imposed constraints do not provide flexibility for student to pursue additional connections.	● The teacher exerts total control over the Lab Activities. Students do not have the autonomy to work through the activities on their own. ● The Lab Activities are rushed – students do not have time to engage in scientific inquiry.	

Explore – Exploring Science through Lab Activities			
6. Use the Tool or Artifact to Actively Facilitate Deep Understanding of Scientific Principles			
The Big Idea: Teachers actively facilitate knowledge construction.			
Dimensions: Asking Questions, Addressing Misconceptions			
A	B	C	
● The teacher asks thought-provoking questions that probe for deep understanding of how scientific principles govern the functionality of the tools and/or mechanisms. The teacher requires students to justify their thinking (e.g. "What type of electrical current is at play? How do you know that?). ● When students demonstrate misconceptions, he or she asks thought-provoking questions that help students reveal those misconceptions themselves (e.g. "Can you prove that?")	● The teacher asks students to explain what they observed, but does not require them to justify their thinking. Questions can be answered by regurgitating definitions (e.g. "Why is this an example of alternating current?"). ● When students demonstrate misconceptions, he or she asks students to perform additional actions that will reveal those misconceptions (e.g. "Try this.").	● The teacher asks few questions that facilitate learning or reveal misconceptions. ● When students demonstrate misconceptions, he or she corrects their misconceptions by telling them what is actually happening.	

Explore – Exploring Science through Lab Activities			
7. Facilitate Collaboration			
The Big Idea: Students benefit from discussing their ideas with peers.			
Dimensions: Size, Interactions, Self-Reliance			
A	B	C	D
● The teacher organizes students in pairs or in small groups. ● The teacher requires students discuss their observations with one another. The students pose questions and help test each other's ideas. ● When problems arise, they work together to find solutions, only seeking teacher assistance when necessary. When approached by students for help, the teacher generally avoids giving students the answer. Instead, he or she coaches them how to find their own answers.	● The teacher organizes students in pairs or in small groups. ● The teacher requires students discuss their observations with one another. ● When problems arise, they sometimes work together to find solutions but often seek teacher assistance.	● The teacher organizes students in large groups (over 5). ● The students have limited opportunities to discuss their observations with one another. ● When problems arise, they are unable to work together and seek teacher assistance.	● The teacher does not use collaborative grouping. The Lab Activities are done as teacher-led, whole-class activities.

Explore – Exploring Science through Lab Activities

8. Manage Materials and Workflows

The Big Idea: Teachers create and manage a classroom environment that is conducive to exploring the artifact.

Dimensions: Materials, Organization, Workflows

A	B	C	
● The teacher provides ample supplies of all the materials necessary for students to have successful Lab Activity experiences. ● The teacher organizes tools and materials so that can be distributed by the teacher or retrieved by students easily. ● Workflows are established that allows students to work productively. The teacher ensures that students understand the tasks at hand. Students understand procedures for getting materials they need. The teacher ensures that the students make steady progress throughout the activities.	● The teacher provides adequate supplies of most of the materials necessary for students to have successful Lab Activity experiences. Materials substituted or omitted only minimally impact the Lab Activity experiences. ● The teacher organizes tools and materials so that can be distributed by the teacher or retrieved by students somewhat easily. ● Workflows are established that allows students to work productively.	● The teacher does not provide the necessary materials for students to have successful lab activity experiences. ● A lack of organization or clear workflows results in significant downtime and disruptions. Opportunities for learning are substantially impacted.	

Explore – Exploring Science through Lab Activities			
9. Establish the Purpose and Utility of the Tool or Mechanism			
The Big Idea: Teachers establish relevance and set the stage for invention.			
Dimensions: Use, Real-World Applications, Extensions			
A	B	C	D
● The teacher ensures that students can use the tool or artifact properly. ● The teacher helps students understand the purpose and utility of the tool or artifact. He or she provides examples of real-world applications and invites students to research other applications. He or she helps students appreciate that many innovations are built upon basic ideas. ● The teacher poses open-ended questions that prompt students to consider novel uses of the tool or mechanism (e.g. “What could you use this for?”). If the object is an ancillary mechanism (e.g. a continuity tester), the teacher guides students to understand how such devices support and facilitate the process of invention.	● The teacher ensures that students can use the tool or artifact properly. ● The teacher helps students understand the purpose and utility of the tool or artifact. He or she provides examples of real-world applications and invites students to research other applications. He or she helps students appreciate that many innovations are built upon basic ideas.	● The teacher ensures that students can use the tool or artifact properly but does not help students understand how it is used in the real-world.	● The teacher neither ensures that students can use the tool or artifact properly nor helps students understand how it is used in the real-world.

Invent - Applying and Extending New Understandings			
10. Implement Design Challenges			
The Big Idea: Students apply content knowledge in a way that is personally meaningful.			
Dimensions: Design Brief, Student Choice, Proposal, Idea Generation			
A	B	C	D
● The teacher tasks students with a design challenge that requires them to practically apply content knowledge and skills gained during previous Invention Kit activities. He or she uses a detailed design brief to outline any design criteria and constraints. ● The challenge is broad enough to allow students to exercise choice and pursue ideas that are personally meaningful. He or she demonstrates respect for student ideas. ● Teacher requires student to submit a detailed proposal that includes a design description, preliminary design sketches, and a plan for how the group will work towards a final product (roles, deadlines, etc.). ● The teacher helps students develop strategies for brainstorming ideas. For example, he or she may encourage them to research existing applications.	● The teacher tasks students with a design challenge that requires them to practically apply content knowledge and skills gained during previous Invention Kit activities. ● The challenge is broad enough to allow students to exercise some choice and pursue ideas that are personally meaningful. He or she demonstrates respect for student ideas. ● Teacher requires student to submit a rough outline of their plan. ● The teacher brainstorms ideas with the students.	● The teacher tasks students with a design challenge that requires them to practically apply content knowledge and skills gained during previous Invention Kit activities. ● The challenge is narrow and limits students' abilities to choose personally meaningful topics. The teacher may require students to choose from a pre-established set of options. ● The teacher may require students to articulate their choice of design but does not require them to submit a plan.	● The teacher provides a prepared design which students follow step-by-step. No student planning or designing is involved.

Invent - Applying and Extending New Understandings

11. Help Students Learn from Failure

Big Idea: Failure is an important part of the learning process.

Dimensions: Autonomy, Time, Resources, Reflection, Support and Instruction

A	B	C	D
● The teacher gives students the autonomy to authentically pursue their ideas, even if he or she thinks their designs will fail. ● The teacher treats failures as opportunities to learn. Therefore, students are given ample time to try out different design configurations. ● Within the constraints of the design challenge, the teacher provides avenues to a variety of resources that students can use to try different approaches to their designs. ● The teacher requires students to regularly reflect on obstacles and document their learning through journaling or similar methods. ● The teacher attempts to be present for failures and always debriefs with students to help students process those failures. ● The teacher coaches students how to find solutions when they are stuck. He or she monitors students' reactions, seeking a balance between challenge and frustration. He or she evaluates what information students need to arrive at a solution themselves and utilizes "just-in-time" direct instruction when needed.	● The teacher provides limited autonomy for students to pursue their ideas. If the teacher thinks their designs will fail, he or she recommends changes. ● Teacher provides limited time for students to try out different design configurations. ● The students have limited access to resources that they can use to try different approaches to their designs. ● The teacher requires students to occasionally reflect on obstacles and document their learning through journaling or similar methods. ● The teacher attempts to be present for failures and usually debriefs with students to help students process those failures. ● When students are stuck, the teacher provides them solutions.	● The teacher limits students' opportunities to learn from failure by providing limited autonomy, time, and resources. ● When students do fail, they are not required to reflect on their mistakes. ● The teacher rarely debriefs with students to help them process failures. ● When students are stuck, the teacher does little to help them.	● The teacher does not allow students to fail.

<table>
<tr><td colspan="4">Invent - Applying and Extending New Understandings</td></tr>
<tr><td colspan="4">12. Emphasize Engineering Design Processes</td></tr>
<tr><td colspan="4">The Big Idea: Teachers can use the Invent phase to teach more formal aspects of engineering design.</td></tr>
<tr><td colspan="4">Dimensions: Processes, Terminology, Culture</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td></td></tr>
<tr><td>● The teacher actively teaches engineering design processes and strategies. The teacher utilizes one or more models of the process and requires students to articulate how their own design processes reflect and shift among the different stages.
● The teacher uses engineering design terminology with students and expects that students also use these terms and concepts accurately. When discussing designs with students, he or she asks them to address criteria and constraints. Students are taught to use terms such as solutions, prototypes, and iterations.
● By utilizing engineering design processes and terminology, the teacher continually seeks to make engineering design part of the classroom culture and invites students to view themselves as engineers.</td><td>● The teacher mentions engineering design processes, but does not require students to apply the processes to their own work.
● The teacher uses some engineering design terminology with students but does not require students to use it.
● The teacher makes limited efforts to instill a culture of engineering design in his or her classroom.</td><td>● The teacher does not address engineering design processes.
● The teacher does not use engineering design terminology.</td><td></td></tr>
</table>

Invent - Applying and Extending New Understandings			
13. Provide Opportunities for Sharing and Feedback			
The Big Idea: Students receive feedback from the teacher and others.			
Dimensions: Teacher Rubrics, Student Sharing, Providing and Receiving Peer Feedback			
A	B	C	
● The teacher utilizes a rubric to guide and assess student designs. The rubric is detailed enough to provide specific feedback for improvements. ● The teacher regularly requires students to share their designs with an authentic audience (e.g. presentations, gallery walks, online portfolios). ● Students regularly answer questions about their designs and receive feedback from peers. Students ask questions and provide feedback to others.	● The teacher utilizes a rubric, but it is vague and does not address the specific criteria and constraints of the particular challenge at hand ● The teacher sometimes requires students to share their designs with an authentic audience (e.g. presentations, gallery walks, online portfolios). ● Students sometimes answer questions about their designs and receive feedback from peers. Students sometimes ask questions and provide feedback to others.	● If a rubric is used, it provides little useful information (e.g. the design works or does not work). ● The teacher does not require students to share their designs. ● Student have few opportunities to give or receive peer feedback.	

Connect – Understanding Invention and Innovation

14. Use Historical Themes to Illustrate the Nature of Invention and Innovation

The Big Idea: Students learn concepts of innovation and change.

Dimensions: “Inventions are Connected,” “Invention is a Systemic Process,” Relating to Self

A	B	C	
● The teacher implements activities in which students actively identify, research, and report on discoveries and inventions that paved the way for the target invention. Students perform similar tasks related to the subsequent inventions and innovations that were made possible by the targeted invention. ● The teacher assign tasks that require students to identify and explore understand the broader systems that arise from and support innovations (e.g. the development of the telegraph led to the telegraph system, which also connected to an electrical system). ● The teacher assigns tasks that require students to explore the personal stories of inventors. The teacher helps students understand that historical inventors were similarly perplexed by their observations of the natural world and often struggled to bring their ideas to fruition.	● The teacher tells students about the discoveries and inventions that paved the way for the target invention and the subsequent inventions and innovations that were made possible by the targeted invention. ● The teacher tells students about the broader systems that arise from and support innovations (e.g. the development of the telegraph led to the telegraph system, which also connected to an electrical system). ● The teacher tells students that historical inventors were similarly perplexed by their observations of the natural world and often struggled to bring their ideas to fruition	● Historical themes are not included.	

<table>
<tr><td colspan="4">Connect – Understanding Invention and Innovation</td></tr>
<tr><td colspan="4">15. Promote Values that Connect to a Contemporary Culture of Invention and Making</td></tr>
<tr><td colspan="4">The Big Idea: Students are encouraged to become makers and inventors themselves.</td></tr>
<tr><td colspan="4">Dimensions: Creativity and Problem-Solving, Self-Empowerment, Communities of Making</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td></td></tr>
<tr><td>● The teacher regularly showcases examples of student creativity and inventiveness. He or she publicly praises students for making sense of complex problems and overcoming adversity.
● The teacher regularly encourages students to learn new skills for designing and making. He or she directs students to resources (e.g. online, books, local businesses) where they can further explore their interests and gain new skills. He or she visibly praises students that extend their new skills to other areas, inside and outside of school.
● The teacher regularly encourages students to share their works with one another and to freely share and accept constructive feedback. He or she encourages students to teach one another new skills and techniques. The teacher may even encourage students to share their skills and designs to broader communities of making, locally and online.</td><td>● The teacher occasionally showcases examples of student creativity and inventiveness. He or she publicly praises students for making sense of complex problems and overcoming adversity.
● The teacher occasionally encourages students to learn new skills for designing and making. He or she directs students to resources (e.g. online, books, local businesses) where they can further explore their interests and gain new skills. He or she visibly praises students that extend their new skills to other areas, inside and outside of school.
● The teacher occasionally encourages students to share their works with one another and to freely share and accept constructive feedback. He or she encourages students to teach one another new skills and techniques. The teacher may even encourage students to share their skills and designs to broader communities of making, locally and online.</td><td>● While these values may be present, the teacher does not emphasize them or connect them to Maker Culture.</td><td></td></tr>
</table>