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THE *MAKE TO LEARN* ELECTRIC MOTOR DESIGN SEQUENCE

Glen Bull[1], Joe Garofalo[1], Michael Littman[2], & Matthew Hoffman[3]
[1]*University of Virginia;* [2]*Princeton University;* [3]*National Museum of American History*

Make to Learn Invention Kits allow students to reconstruct working models of historic inventions. This design case describes the development of a series of *Make to Learn Electric Motor Invention Kits* that spans the time frame from development of the first patented electric motor in the United States to contemporary brushless motors. The design process is described and design decisions that led to the final sequence of electric motor kits are summarized.

Glen Bull is a professor of education in the Curry School of Education at the University of Virginia and director of the Curry School's Make to Learn Laboratory.

Joe Garofalo is an associate professor of mathematics education in the Curry School of Education at the University of Virginia and co-director of the Make to Learn Laboratory.

Michael Littman is a professor of engineering at Princeton University and principle investigator for the Joseph Henry Project at Princeton.

Matthew Hoffman is an educational specialist at the Smithsonian's National Museum of American History.

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INTRODUCTION

This design case describes the process through which a series of *Make to Learn Invention Kits* was developed that enable students to use school makerspaces to reconstruct historic inventions. Pivotal inventions now archived in the Smithsonian Institution—such as the telephone, the telegraph, and early electric motors—changed the course of history. The *Make to Learn* design team collaborated with Smithsonian curators to enable students to gain insight into the challenges experienced by the original inventors through reconstruction of these inventions.

This specific case describes the process through which a sequence of *Electric Motor Invention Kits* was developed. The factors that affected decisions made during the course of the design process, such as conceptual abstraction and mechanical complexity, are described. Although the factors discussed are specific to this particular sequence, they are also applicable to the design process used for the *Make to Learn* Telegraph and Telephone Invention Kits.

Overview

The goal of the project is for students to gain fluency in the process of invention and to understand related science concepts embodied in the inventions. *Make to Learn Invention Kits* have been developed for three types of motors in the electric motor sequence: (a) the Davenport Rotary motor, (b) the Charles Page Solenoid motor, and (c) a contemporary linear motor based on a 20th-century design.

The Davenport motor and the Charles Page motor have strong historical connections and associations. They provide a context for understanding the way in which the design of contemporary motors evolved. The historical sequence provides an empirical demonstration of how inventions can evolve as technology and knowledge progress. Invention and technology do not advance steadily; there are setbacks and misconceptions and dead ends, as well as progress.

The Electric Motor Invention Kit sequence demonstrates that much can be learned—both for the designers and for students—within what at first glance may appear to be a relatively simple landscape. The design of the sequence involved a process of discovery that was not dissimilar to the experience of the original inventors. It required an understanding of the scientific and engineering challenges that the inventors faced as well as modern-day pedagogical challenges faced in contemporary school settings.

Two factors that must be considered in a school setting are (a) ease of construction and (b) versatility. *Ease of construction* can be evaluated in terms of the number of class periods required for construction of a working model. *Versatility* refers to the extent to which students can successfully incorporate motors in mechanisms of their own design. These attributes, listed in Table 1, are described in greater detail for each type of motor:

Davenport Rotary Motor

The Davenport rotary motor (Patent No. 132; 1837) requires a commutator, a switching mechanism that reverses the flow of electrical current twice during each complete rotation of the motor. This motor is conceptually abstract and mechanically complex. Therefore, it is both difficult to understand and difficult to construct. Successful construction can be rewarding, however, since it paves the way for understanding of many other types of related switching mechanisms.

Charles Page Solenoid Motor

The Charles Page Solenoid motor (Patent No. 10,480; 1854) shuttles an armature back and forth between two solenoids. A flywheel connected to the armature operates a switching mechanism that alternately powers each of the solenoids as the armature moves back and forth. Students find this mechanism somewhat easier to understand and construct than the Davenport Rotary motor; they can reconstruct the Page motor in half the class periods required for the Davenport motor. However, the Page motor can be difficult to incorporate into other mechanisms and hence is less versatile than the Davenport motor.

Contemporary Linear Motor

The designs for contemporary linear motors were first developed and patented in the 1960s. This motor replaces the ferrous armature of the Charles Page solenoid motor with a rare earth magnet (an option that was not available to 19th-century inventors). The magnet eliminates the flywheel and switching mechanism of the Charles Page motor, greatly simplifying the design. The Contemporary Linear Motor Invention Kit is easy for students to construct, and it is also versatile and easy for them to incorporate into other mechanisms.

The description that follows outlines key decision points in the design process through which the Electric Motor Invention Kit sequence was developed.

KIT	PATENT	ELECTRIC MOTOR	EASY?	VERSATILE?
A.	1837	Davenport Rotary Motor	No	Yes
B.	1854	Charles Page Solenoid Motor	Yes	No
C.	1960	Contemporary Linear Motor	Yes	Yes

TABLE 1. The Make to Learn Electric Motor Sequence.

BACKGROUND

Makerspaces in schools offer new possibilities for teaching and learning. They provide access to technologies such as 3D printers and accompanying design software (Gershenfeld, 2005). In their current form, makerspaces are a relatively recent phenomenon made feasible by technological advances. Identification of effective uses of makerspaces in school settings will require exploration and experimentation. Among other uses, makerspaces provide prototyping and fabrication facilities that can enable students to reconstruct historical inventions and design their own inventions and innovations inspired by these historic mechanisms.

The Electric Motor Invention Kit sequence was developed through collaboration across the *Make to Learn* coalition. The core design team is anchored by the *Make to Learn Laboratory* in the Curry School of Education at the University of Virginia. The design team also includes the Smithsonian Institution, Princeton University, and Midlands Technical College in Columbia, South Carolina. Innovations are piloted in the *Laboratory School for Advanced Manufacturing* (Lab School). The Lab School is a partnership between the University of Virginia and nearby school districts in the city of Charlottesville and the county of Albemarle (Bull, Haj-Hariri, Atkins, & Moran, 2015).

Each *Make to Learn Invention Kit* includes resources: (a) a scanned 3D image of the invention digitized by the Smithsonian, (b) a CAD model of the invention, (c) animations that depict its operation, (d) related historical resources in the Smithsonian's collections such as patents and descriptions from inventors' notebooks, (e) instructional guides for teachers, (f) resources for students, (g) assessment items, and (h) accompanying professional development materials (Bull, Standish, Johnson, & Haj-Hariri, 2016).

Motivation for the *Make to Learn Invention Kit* Project

The motivation for development of historical reconstruction kits is two-fold.

- One motivation is to fulfill the mission of the Smithsonian's National Museum of American History by helping "people understand the past in order to make sense of the present and shape a more humane future" (Mission and History, n.d.).

Reconstruction of historic inventions provides a lens to understand the way in which the United States became the nation that it is today, and implications that this may have for the future.

- A second motivation is for students to understand the science and engineering principles that underlie transformational inventions.

  The pedagogical basis for this work is grounded in the framework for a Princeton course, *Engineering in the Modern World*, developed by David Billington and Michael Littman (Princeton University Course Offerings, 2015). The premise of the course is that foundational inventions such as the telephone, the telegraph, and 19th-century relays are transparent. For example, all of the parts in a 19th-century telegraph relay can be observed. Hence its operation is more accessible to learners than the black box of a modern-day solid state relay (Billington & Billington, 2013). An understanding of its basic design and function can scaffold understanding of more sophisticated concepts underlying modern technologies.

Roles of Key Participants

The design team participates in a standing planning and development meeting each week. The principal investigator at the Smithsonian, Carrie Kotcho, is the A. James Clark Director of Education & Outreach at the National Museum of American History. She provides coordination and oversight for collaborations with the curators of the electricity and physics collections, coordinates joint work with the Smithsonian Digitization Program Office's 3D lab, oversees dissemination of project materials on the Smithsonian 3D web site (http://3D.si.edu), provides coordination with the Smithsonian Enterprises office, and serves as a point of contact with other Smithsonian museums such as the National Air and Space Museum.

The principal investigator at Princeton, Michael Littman, is a professor of engineering and principal investigator of the Joseph Henry Apparatus Project. (Joseph Henry was a professor at Princeton who later served as the first secretary of the Smithsonian.) In that role, he provides expertise related to science and engineering education, with a particular emphasis on historical reconstruction of inventions, piloted in his course, *Engineering in the Modern World*.

The principal investigator at Midlands Technical College, Alan Grier, is the director of the Midlands Machine Tool and Mechatronics programs. In that role, he provides expertise on connections between historical inventions and modern day applications.

The principal investigator at the University of Virginia, Glen Bull, provides coordination with the Laboratory School for Advanced Manufacturing and other schools serving as test sites. Joe Garofalo co-directs the *Make to Learn Laboratory* at the University of Virginia. The lab develops prototypes of *Make to Learn Invention Kits*, develops accompanying K-12 instructional materials and assessment items, provides professional development, and conducts an annual K-12 Engineering Design Academy.

An advisory board includes representatives from the National Academy of Engineering, the Association for Science Teacher Education (ASTE), the Association of Mathematics Teacher Educators (AMTE), the International Technology and Engineering Education Association (ITEEA), the Association for Educational Communications and Technology (AECT), and the Society for Information Technology and Teacher Education (SITE), among others. Members of the advisory board review materials throughout the year as they are developed. They also participate in an annual advisory board meeting at the Smithsonian.

THE ELECTRIC MOTOR SEQUENCE

The final Electric Motor Invention Kit sequence is organized in terms of ease of construction, consisting of (a) the contemporary linear motor, (b) the Charles Page motor, and (c) the Davenport motor. When the project began, the design team was not aware of the attributes of these motors. Consequently the design for the contemporary linear motor was not developed until several years into the project. Its current design emerged from experience gained through development of previous prototypes and designs.

Kit A: Reconstruction of the Davenport Rotary Motor

The design team elected to begin the development process with the most historically significant motor in the sequence, the Davenport Rotary motor, which received the first U.S. patent awarded for invention of an electrical device.

It, therefore, plays an important role in the history of electromagnetic inventions. The design process initially consisted of the following phases:

Steps in Initial Design Sequence

1. Consultation with the Advisory Board
2. Development of a Reference Design
3. Pilot in the Schools

Advisory Board Consultation (Davenport Motor)

The project's advisory board initially met at the 2014 National Technology Leadership Summit (www.ntls.info). The members of the advisory board were assembled to develop recommendations for reconstruction of the Thomas Davenport rotary motor because of their expertise in STEM education. The planned activities consisted of the following:

- **MORNING:** Advisory board constructs a rotary motor.
- **AFTERNOON:** Advisory board adapts the design for use by middle school students.

This plan was founded on a significant misconception; the design team believed that the members of the advisory board would be able to successfully construct a motor. The members of the advisory board concurred with this belief. They were experts in STEM fields and leaders in the teacher educator associations representing science, mathematics, and engineering. Some members of the advisory board had contributed to development of electricity and magnetism standards that called for middle school students to construct an electric motor. They, therefore, had reason to believe that they would be able to perform this task themselves. The representative of an engineering association stated that the task should take less than an hour.

Despite this belief, none of the members of the advisory board were able to construct a working model of a rotary motor. At the end of the day, Michael Spector—past president of AECT and current editor of *Educational Technology, Research and Development*—summarized the result, commenting, "Today I learned two things: First, I was not able to make an electric motor. Second, I realized that I do not even understand how one works" (Spector, 2016).

Development of a Reference Design for the Rotary Motor

The second phase of the planned design process called for development of a *reference design*. In engineering, a reference design is a working model and associated specifications intended for others to copy. The reference design includes the essential elements of a design that others may enhance or modify when making a copy.

The Lab School teachers were given release time to allow them to work on this project. Selected teachers at one Lab School site were placed on 11-month contracts to allow them time to collaborate on the project. STEM teachers at the other site were given several weeks of release time. A summer engineering academy staffed by faculty and graduate students at the University of Virginia was held for the teachers and selected K-12 students in support of this effort. The teachers—like the advisory board members—were confident that they understood how an electric motor worked. They had taught the content in their science classes and believed that they could use this knowledge to build a working model of an electric motor.

This belief was challenged when they attempted to design and fabricate a motor. One teacher subsequently commented, "I didn't know that I didn't understand how an electric motor works. And if I didn't understand it, think how much less the students must have learned" (personal communication, June, 2014). The experience of the teachers paralleled the experience of the advisory board and resulted in an improved understanding of the complexity that the task represented.

After working for much of the summer, from June through August, one of six teachers did succeed in fabricating a working electric motor. Sparks and smoke streamed from the motor as it rotated, but it did work. The process proved useful in allowing the teacher to unpack key concepts involved in operation of the motor. The teachers did not, however, succeed in developing a reliable reference design that could be replicated and shared for use in makerspaces at other schools.

Decision Point 1. Initial efforts to develop a reference design for a rotary motor demonstrated that the task was more complex than originally envisioned. Therefore a decision was made to enlist the combined efforts of the *Make to Learn* coalition to create a working proof-of-concept model to serve as a reference design.

The Critical Contribution of Distributed Knowledge to Design Process

Many inventions are developed by a team of researchers. In a similar manner, reconstruction of these historic inventions also required knowledge distributed across a network of collaborators. Representative areas of expertise contributed by each collaborator outlined in Table 2 are organized by technological, pedagogical, and content knowledge (Mishra & Koehler, 2006).

The core design team met via videoconference each Monday afternoon. This process led to development of the prototype for a working model of a rotary motor (see

	TECHNOLOGICAL	PEDAGOGICAL	CONTENT
Smithsonian	Digitization of Artifacts	Museum Education	Historical Knowledge
Princeton	CAD Development	Engineering Design	Mechanical Engineering
Midlands	Mass Manufacturing	Applied Methods	Technical Knowledge
Curry School	Prototyping	K-12 Instructional Methods	STEM Education

TABLE 2. Distributed Knowledge Employed in Development of a Reference Design.

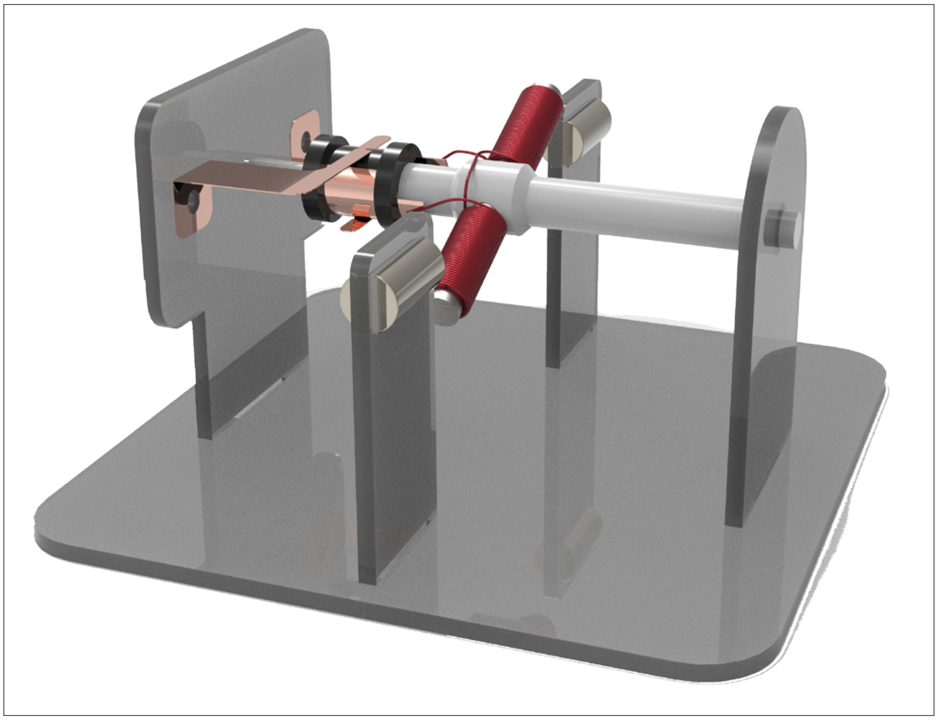

FIGURE 1. Prototype for a rotary motor—oblique view.

Figure 1). The prototype reference design worked well from a mechanical perspective. The Lab School teachers and their students were able to use the reference design to create their own working copies of a rotary motor. However, the switching mechanism (i.e., the commutator) proved to be challenging and difficult for students to understand and construct. The commutator was also the design element that presented the greatest difficulty to the original inventor, Thomas Davenport.

Piloting the Rotary Motor in a School Setting

This illustrates that the aspects that were difficult for the original inventors are also ones that are likely to prove challenging for students who attempt to retrace the inventors' footsteps. Students who study the historic record find these parallels to be reassuring. If iconic figures in history experienced these difficulties and were discouraged and frustrated at times, it is reasonable for a middle school student to experience the same difficulties. This knowledge can encourage students to persist rather than quitting after the first failure that they experience (Lin-Siegler & Ahn, 2016). This affirmation, in itself, was one of the more significant outcomes. Students encountered two difficulties faced by the original inventors:

1. *Conceptual Difficulties*. The students had difficulty understanding the principles underlying the commutator of a rotary motor.
2. *Mechanical Difficulties*. It was mechanically challenging for students to construct the mechanism of the commutator. There is a narrow tolerance in the mechanical dimensions that makes it challenging to construct a reliable commutator. Students were able to successfully replicate the reference design developed by the *Make to Learn* design team. However, like the Davenports, it took an extended period of time for students to achieve this success. Six class periods were required to complete the project even after revision and refinement.

Decision Point 2. The conceptual and mechanical difficulties that students experienced led to a decision to develop a reference design for a simpler version of an electric motor: the Charles Page solenoid motor.

Kit B: Reconstructing the Charles Page Motor

The Charles Page Electromagnetic Engine shuttles an armature back and forth between two sets of solenoids, one on the left and one on the right. A flywheel switches electrical current between the left and right solenoid to move the armature back and forth as the flywheel turns.

Because there is a discrete point at which the armature reverses direction, the mechanism is easier to observe and understand than a rotary motor. The switching mechanism for the Charles Page solenoid motor (see Figure 2) also requires less mechanical dexterity and fine motor skill to construct successfully.

Based on the experience gained through the development of a reference design for the rotary motor, the design sequence was revised as follows:

Steps in Revised Design Sequence

1. Development of a Reference Design
2. Pilot in the Lab School
3. Consultation with the Advisory Board

The revised process began with development of a reference design by the *Make to Learn* design team, which was followed by a pilot in the Lab School. This experience was used as the basis for consultation with the advisory board. Students from the Lab School served as mentors for members of the advisory board as they worked together to construct a motor.

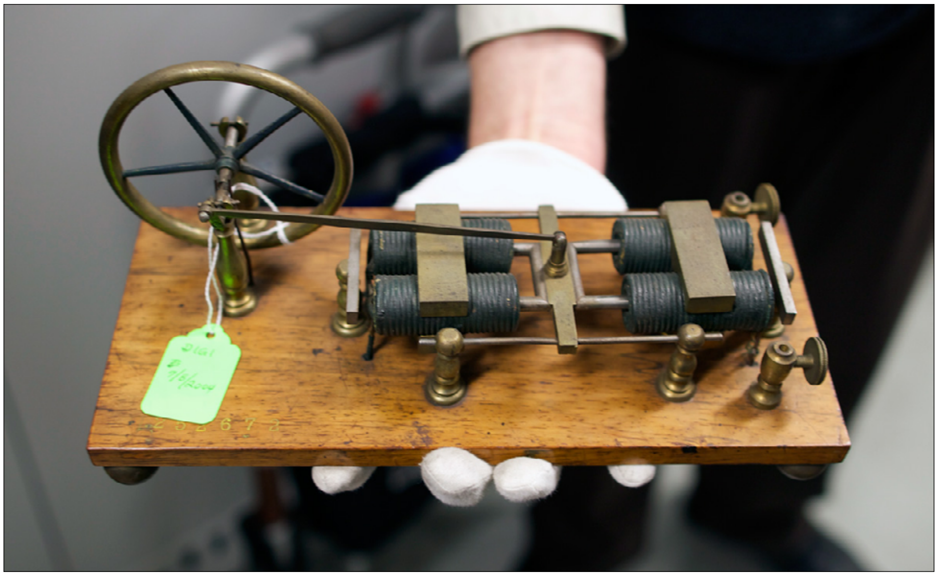

FIGURE 2. The Charles Page Motor (1854) from the National Museum of American History's Electricity Collection.

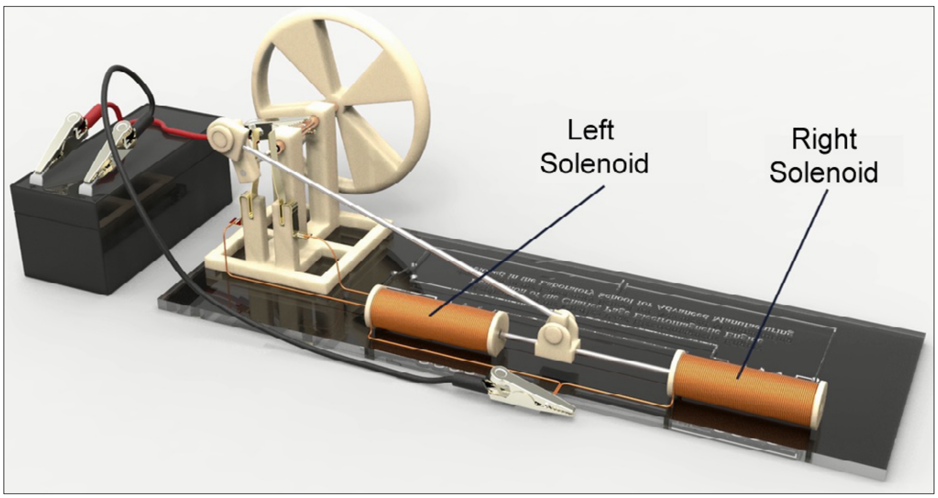

FIGURE 3. Reconstruction of the Charles Page motor.

Developing a Reference Design for the Charles Page Solenoid Motor

As was the case with the Davenport motor, a reference design for reconstruction of the Charles Page Solenoid motor was developed by the *Make to Learn* design team. The reference design simplified some aspects of the Charles Page motor in order to highlight key principles of operation.

For example, the original Charles Page motor has four solenoids (two on each side of the armature) while the reference design (see Figure 3) reduces this number to two solenoids.

Piloting the Charles Page Motor in a School Setting

Students in the Lab School were successful in reconstructing the Charles Page motor. The reference design provided a proof-of-concept example that enabled them to construct their own variations. The students developed three different variants of the solenoid motor. However, development of the student-designed variants required considerable time and adult support.

One goal of the project was to explore whether use of student-designed motors was more meaningful and engaging than use of a commercial demonstration unit. Science teachers at one Lab School site judged that student engagement and performance on teacher-made tests was enhanced by use of student-designed equipment. Science teachers at a second Lab School site did not work as closely with the engineering teacher. They elected not to use the student-designed motors in science classes at that site.

Advisory Board Consultation (2015)

For the 2015 meeting of the project advisory board, we arranged for six Lab School students to serve as mentors to the members of the advisory board. In contrast to the year before, the advisory board members were able to fabricate working reconstructions of the Charles Page motor. The board members approached the task with some trepidation given the difficulty encountered the year before. Several factors had changed:

1. *A Simpler Motor*. The design for the Charles Page solenoid motor was not as complex as the design required for the Davenport rotary motor.
2. *A Reference Design*. In contrast to the previous year, teams were provided with a prototype reference design.
3. *A Support Team*. Each advisory board team was supported by a middle school student who had successfully completed the design.

Advisory board members uniformly focused on the presence of a student mentor as the reason for their success. They found it helpful to talk directly with the students about their school experiences.

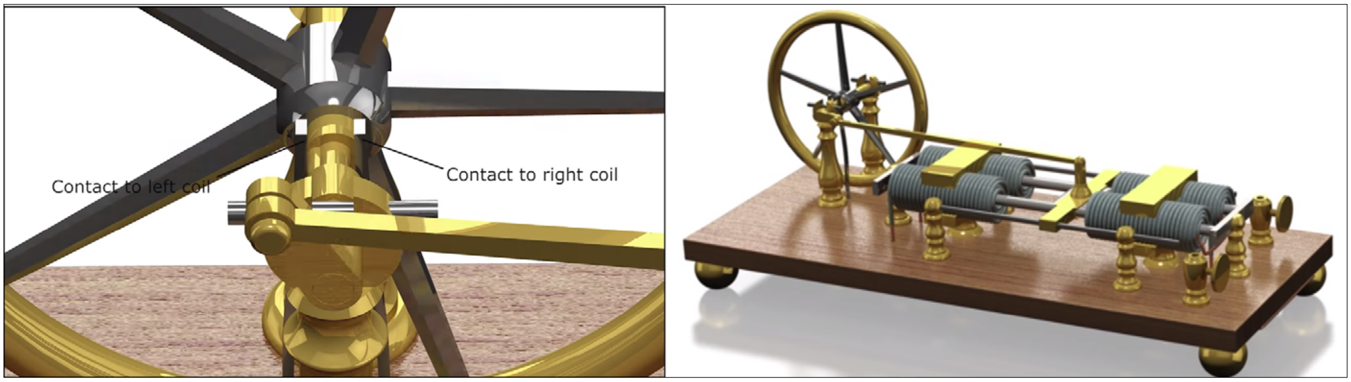

FIGURE 4. Charles Page motor animation: Switching contacts.

The *Charles Page Solenoid Motor Invention Kit* was a significant step forward. It was practical to implement in middle school engineering classes. The Lab School students successfully used the reference design to fabricate a working model. They achieved this result in less time than required for the rotary motor: three class periods for construction of the solenoid motor versus six class periods for construction of the rotary motor. From that perspective, the new design was a success.

However, the Charles Page reconstruction was not as useful in addressing another project goal. Fabrication of the motors was not an end goal in itself. Instead, the goal was to provide students with foundational knowledge that would allow them to incorporate their motors into mechanisms and designs that they invented. (Hence, the use of the term, *Invention Kit*.)

The flywheel and switching mechanism of the Charles Page motor present complexity that increases the difficulty of incorporating it into other mechanisms. A rotating contact (see Figure 4) on the axle of the flywheel in the Charles Page motor switches current between two solenoids. Each solenoid when energized draws the armature inward. The armature is connected to the flywheel via a crank. The crank rotates the flywheel. The flywheel stores rotational energy and smooths out the motion so that angular velocity is relatively constant in time.

Timing is critical to achieve this constancy. The point at which the solenoids deliver the greatest amount of power must be aligned with the point in the cycle at which the flywheel is most difficult to turn. These issues make it challenging to couple the motor to a second mechanism or device.

Decision Point 3. Because of the need for a design for a motor that was both easy to construct and that could easily be incorporated into other mechanisms, a decision was made to use the Charles Page reference design as the starting point for development of a third reference design for a motor that could achieve both goals. Reducing the time required for implementation was also a goal in this phase.

Kit C: A Contemporary Linear Motor

The goals for the third reference design were two-fold: (a) conceptually easy to understand and to construct, and (b) easy to incorporate into other mechanisms, thus encouraging student-designed inventions that incorporated the motor.

Developing a Reference Design for a Contemporary Linear Motor

Following the steps in the revised design sequence developed for Kit B, a third reference design was developed by the *Make to Learn* design team. The design was simplified by replacing the armature with a permanent magnet. The permanent magnet has a north and south pole, making it possible for two solenoids to be replaced with a single solenoid (see Figure 5).

An alternating current moves the magnet in one direction when the voltage is positive and in the opposite direction when the voltage is negative. The contemporary linear motor, therefore, is an alternating current (AC) motor. This eliminated the switching mechanism and flywheel of the Charles Page motor.

Piloting the Contemporary Linear Motor in a School Setting

In the pilot in the Lab School, this design allowed students to quickly and reliably construct a working motor. The design has fewer working parts, is easier to understand, and is easier to construct, thus advancing one of the project goals: It encouraged students to create their own innovations and inventions.

The third reference design allowed the linear motor to be constructed in a single class period in the middle school setting, as opposed to the six class periods required for construction of the rotary motor and three class periods required for construction of the solenoid motor. The time

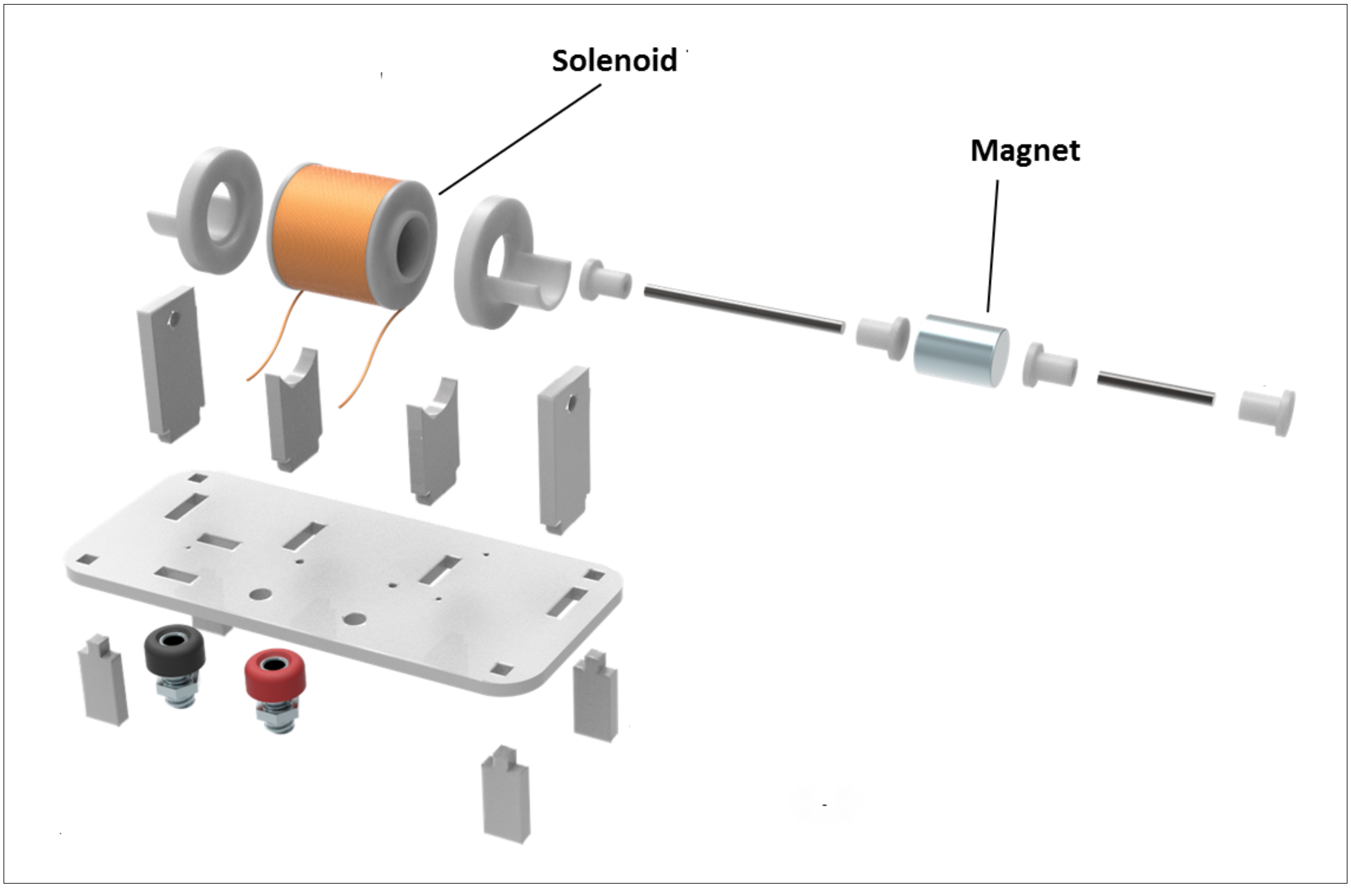

FIGURE 5. Contemporary linear motor (Exploded View).

recovered could then be used by students to design their own mechanisms that incorporated the linear motor (see Figure 6).

This strategy opened the door to exploration of related concepts such as mechanical linkages and interfaces as well as force and motion topics. Because the contemporary linear motor is an AC motor, it also provides a natural entry point to the topic of waveforms, including comparisons of ways in which 19th- and 20th-century inventors were able to produce and make use of alternating current. It therefore makes connections between foundational inventions developed in the 19th-century and the way in which the same mechanisms are designed today.

Advisory Board Consultation (2016)

The contemporary linear motor was introduced in the third annual meeting of the advisory board. The advisory board members were able to successfully collaborate with their student mentors to construct a linear motor. Each team also designed an animated figure controlled by the linear motor (see Figure 7).

The success experienced in the previous year's advisory board meeting also contributed to the successful outcome of the 2016 advisory board meeting. The advisory board members were now accustomed to collaborating with Lab School students, using them as advisors and informants. The task itself was also, by design, less complex. As a consequence, the teams of advisory board members and Lab School students successfully collaborated on design and fabrication of animated figures powered by the linear motor. For example, the linkage between the linear motor and the golfer in Figure 7 controls a putter that drives a ball into the hole.

Kit D: Solenoid Invention Kit

Students were successful in reconstructing all three motors, if constructed in a sequence of ascending difficulty: (a) the contemporary linear motor, (b) the Charles Page motor, and (c) the Davenport motor. In addition to successful reconstruction of each type of motor, our goal was for the students to understand the underlying principles of operation. Solenoids are at the heart of all three motors.

Decision Point 4. In order to help students gain knowledge that underlies the designs developed for all three motors, a decision was made to develop an introductory Solenoid Invention Kit.

Developing a Reference Design for a Solenoid Invention Kit

Following the steps in the revised design sequence developed for Kits B and C, a fourth reference design was developed in the *Make to Learn* Lab. A common solenoid that could be incorporated into several *Make to Learn Invention Kits* was developed, offering several advantages.

- Standardization on a common dimension for a solenoid used for reconstruction of a variety of inventions simplified the fabrication process and made it easier for teachers to maintain an inventory of parts for their classes.
- From a pedagogical perspective, use of a standard element that could be transferred from one invention to another made it more evident that a common underlying principle was involved.

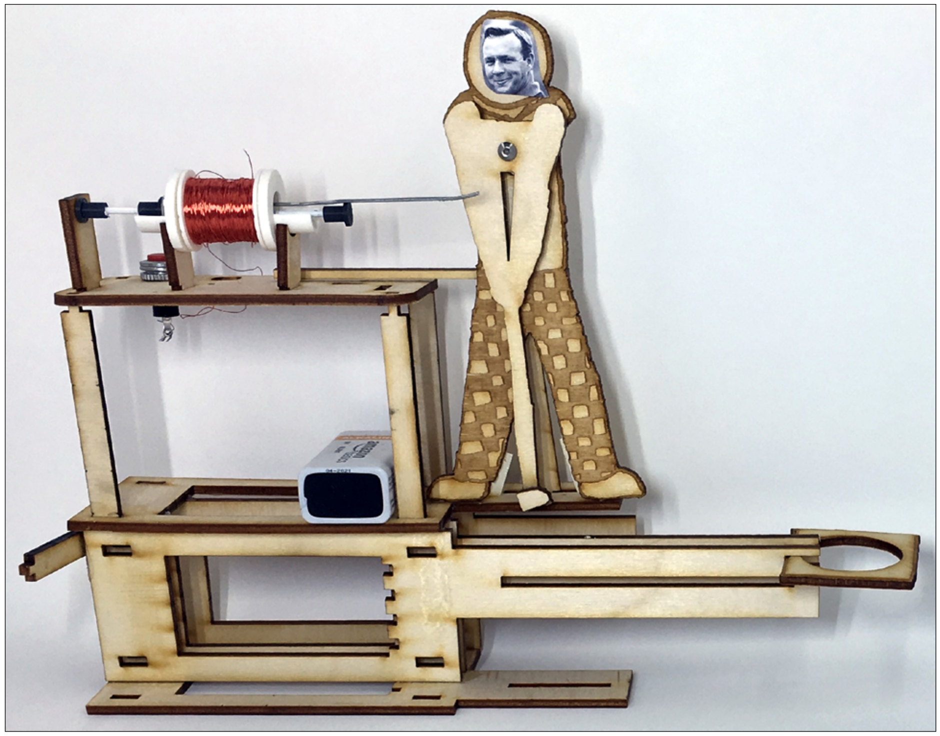

FIGURE 6. Linear motor incorporated into an animated figure.

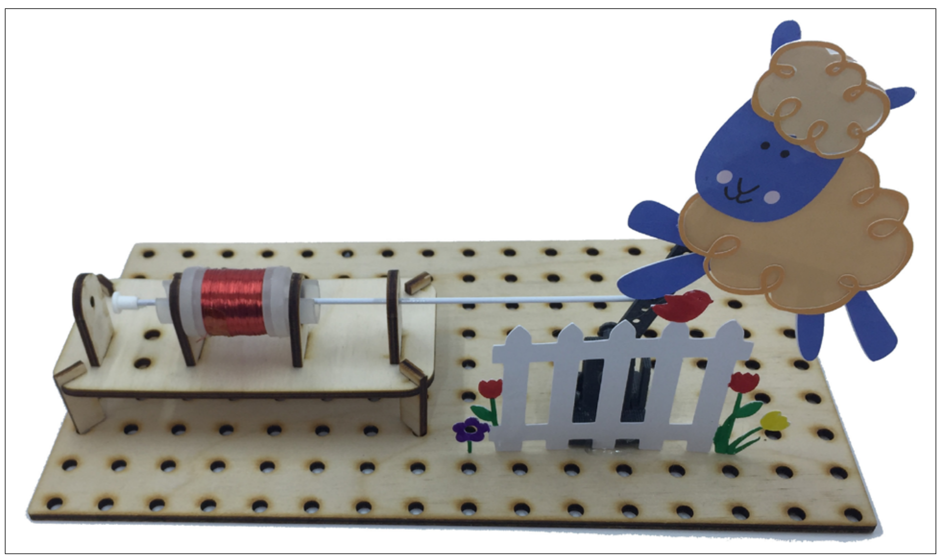

FIGURE 7. Mechanism constructed with a linear motor.

The base and solenoid bobbin developed for the contemporary linear motor was repurposed for design of the Solenoid Invention Kit. We initially used a neodymium magnet for the solenoids that was three-quarters of an inch in length and one-quarter inch in diameter. A class set of 20 neodymium magnets with these dimensions could be purchased for approximately $100. Through a process of refinement, we were able to successfully develop a useable solenoid with a magnet that was one-eighth of an inch in diameter. This adjustment reduced the cost of a class set of magnets by half. The change reduced the tolerances in achieving the power needed to drive the motor and required greater manual dexterity and care in assembling the motor. However, in pilot testing we found that middle school students were able to build working motors using a magnet with these dimensions.

The dimensions of the magnet—a cylinder that was three-quarters of an inch in length and one-eighth inch in diameter—determined the dimensions of the solenoid tube. This form factor, in turn, determined the dimensions of the base that was used to support the solenoid. On this basis, a common form factor was adopted for the base of the solenoid, the base of the contemporary linear motor, and the base of a parallel linear generator that was also developed to support the project.

Piloting the Solenoid Invention Kit in a School Setting

Student learning outcomes will be reported in depth in other publications. The preliminary findings suggest that the Solenoid Invention Kit can scaffold acquisition of foundational knowledge of science concepts. Formative assessment items were developed to evaluate student understanding. On a pre-test prior to pilot implementation in an eighth-grade class of 30 students, three-quarters of the students did not demonstrate an understanding of the relationship between electricity and magnetism. However, three-quarters of the students demonstrated a good understanding of the relationship between electricity and magnetism on a post-test after completion of the Invention Kit unit.

In an extension of the Solenoid Invention Kit, students were able to derive Ampere's Law to describe the relationship between an electrical current and the strength of the resulting magnetic field (Corum & Garofalo, 2017). Topics across a number of different disciplines are addressed through the Electric Motor Invention Kit sequence, including mathematics (direct and indirect proportions), science (electricity and magnetism), and engineering (the design process). In future implementations, systematic collection of data will permit more definitive descriptions of student learning outcomes that may result.

The Final Electric Motor Sequence

The activities described above were implemented by the *Make to Learn* team through a process of successive approximations over a period of years.

In the sequence developed to date (see Figure 8), the solenoid provides scaffolding for the contemporary linear motor. This linear motor, in turn, provides scaffolding for reconstruction of the Charles Page Solenoid motor. This motor provides scaffolding for the original Davenport rotary motor. The design process involved reverse engineering a sequence of mechanisms in which foundational concepts are introduced through relatively simple designs, providing scaffolding for the more complex ones that follow. The Solenoid Invention Kit serves as an introduction to this sequence, providing knowledge that is used in all the kits in the electric motor sequence: (a) the contemporary linear motor, (b) the Charles Page solenoid motor, and (c) the Thomas Davenport rotary motor.

DATE	EVENT
2013	Laboratory School for Advanced Manufacturing Established
2014	Davenport Rotary Motor Reconstructed
2015	Page Solenoid Motor Reconstructed
2016	Contemporary Linear Motor Kit Designed
2016	Solenoid Invention Kit Designed
2017	Stepper Motor Kit (under development)

TABLE 3. Electric Motor Sequence Timeline.

The following overview provides a summary of the intended use of each kit and a comparison with historical models.

Kit A. The Solenoid Invention Kit provides an introduction to electromagnetism. This *Invention Kit* recreates Ampere's work with electromagnetism and allows students to recreate a working actuator that they can incorporate into their own mechanisms and inventions. The solenoid in this kit differs from Ampere's solenoid chiefly in its use of plastic for the solenoid bobbin, a material that was not available to Ampere. The bobbin is also notched so that it can be fitted onto a spindle to allow it to be machine wound.

Kit B. The Linear Motor Invention Kit provides an introduction to electromagnetic motors. It simplifies the 19th-century designs by eliminating the commutator. This allows students to learn the basic concepts of electromagnetic motors without the conceptual complexity of commutators. A reconstruction of Joseph Henry's pole reversing switch is used to reverse the current to drive the contemporary linear motor. This design uses a neodymium magnet that was not available in the 19th century.

Kit C. The Charles Page Solenoid Engine. The historical solenoid motor invented by Charles Page uses two solenoids to move an iron armature back and forth. A flywheel rotates a cam to switch power between the two solenoids. This design builds on the knowledge gained through the *Linear Motor Invention Kit* while introducing the concept of automated switching mechanisms. This design uses two solenoids in place of the double solenoids (two on each side) used in the Charles Page patent model.

Kit D. The Davenport Rotary Motor. The historical rotary motor invented by Thomas Davenport uses a commutator to reverse the current every half turn. The commutator is conceptually complex and mechanically challenging. It builds on the concept of switching mechanisms introduced in the previous kit to scaffold this understanding. This design uses two permanent magnets in place of the four magnets used in the Davenport patent model.

Kit E. Stepper Motor. The Stepper Motor Invention Kit replaces the electromechanical commutator of the Davenport motor with a digital microcontroller that redirects the electrical current from one solenoid to the next to activate its magnetic field. This kit illustrates the way in which an electromechanical control mechanism can be replaced with a digital control mechanism. This kit introduces a relatively straightforward means of creating versatile motors that can be incorporated into many different student mechanisms and designs.

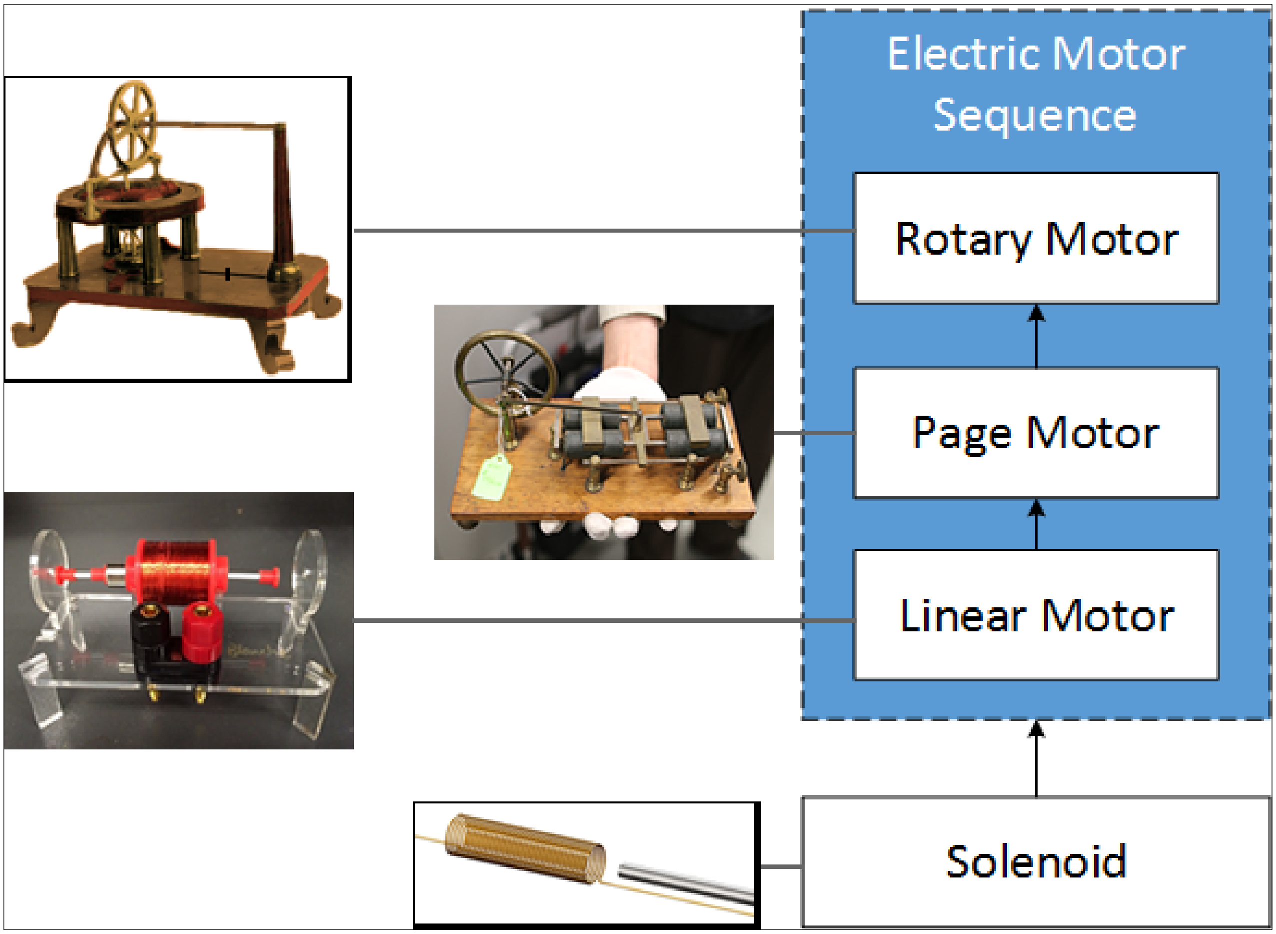

FIGURE 8. The electric motor instructional sequence.

The rotary motor is challenging to construct and can take many class periods to implement. The solenoid motor is easier to construct than the rotary motor, but the flywheel and switching mechanism make it challenging to incorporate into other mechanisms. The design for the contemporary linear motor is both easy to construct and facilitates incorporation into other mechanisms. In that sense, it combines the best characteristics of the preceding two designs. It serves as a gateway to other topics such as force and motion, mechanical linkages, and waveforms. It also provides a bridge to contemporary stepper motors and other mechanisms commonly employed in industrial automation.

REFLECTIONS ON THE DESIGN

By the end of the design process, all three groups—the advisory board, teachers, and students—were able to use reference designs to construct robust working models. The sequence enabled middle school teachers and students to construct models in order of increasing complexity. Moreover, they were able to design original mechanisms and innovations of their own design that incorporated the motors. Among the lessons learned from this process, three are of particular importance to the larger aspiration of designing effective instructional uses of makerspaces in a school setting.

1. Interdisciplinary Knowledge Was Required for Reconstruction of Historic Electric Motors

Advanced manufacturing technologies in schools, such as 3D printers, offer new opportunities for innovation. However, in this project, knowledge across multiple disciplines—including basic mechanical and electrical engineering—was required to take full advantage of these capabilities. Designing the electric motor sequence required knowledge of these disciplines in addition to knowledge of the content taught and the pedagogy.

The *Make to Learn* coalition provided access to distributed knowledge. Science educators, mathematics educators, mechanical engineers, electrical engineers, historians, and cultural anthropologists contributed their expertise. No single participant or institution represented on the *Make to Learn* Design Team possessed all of the knowledge required to design the *Make to Learn Invention Kits* that emerged through the design process. Hence a collaborative approach was required.

LEVEL	MECHANISM	TOPIC INTRODUCED	COMPLEXITY	TIME	VERSATILITY
Novice	Solenoid	Electromagnetism	Mechanically Simple	< 1 period	Moderate
Basic	Linear Motor	Electromagnetic Motors	Straightforward	1 period	High
Intermediate	Charles Page Motor	Switching Mechanisms	Modest Complexity	3 periods	Low
Advanced	Davenport Rotary Motor	Commutators	High Complexity	6 periods	High

TABLE 4. The Electric Motor Sequence in Order of Complexity.

2. Significant Time Was Required for Development of Reference Designs

The iterative design process that led to the Electric Motor Invention Kit sequence required four years because of the complex nature of the topic. The expert consultants on the design team initially over-estimated their own understanding of the inventions. As a result, the time and effort required to develop effective instructional activities were underestimated.

3. Effort by Experts to Construct an Electric Motor Was Useful in Identifying Gaps in Understanding

The major stakeholders—the design team, the advisory board, and the participating teachers—all overestimated their respective understanding of the principles underlying operation of electric motors This uniform result proved to be an instance of *The Illusion of Knowledge* (TIK)—a powerful but inaccurate *feeling of knowing* that results in the tendency to overestimate knowledge of a given domain (Rozenblit & Kiel, 2002).

A request for an explanation (or, in this case, a working model) can serve as an antidote to TIK (Sloman & Fernback, 2016). In this instance, it led to the realization that the task was more complex than originally envisioned. This realization produced useful reflection, which after several iterations led to development of robust Invention Kit activities that could be reliably replicated by middle school students.

CONCLUSION

The maker movement was inspired by a resurgence in personal creativity and fulfillment made possible by digital fabrication tools such as 3D printers. Schools are tasked with using these capabilities to ensure that students also meet specific instructional objectives.

Use of school makerspaces to reconstruct working models of historic electric motors provided one context for accomplishing these goals. Students were able to use the Electric Motor Invention Kits to design their own animated figures, fulfilling a key goal of the project—facilitating design of original student creations through reconstruction of historic inventions. The pilot Lab School activities were successfully incorporated into a Maker Education course for pre-service teachers at the University of Virginia, which may enable the next generation of teachers to use school makerspaces to greater advantage.

This process enabled teachers, students, and other collaborators to learn through a series of iterations to address a complex objective. A key principle demonstrated was that it was possible to learn through failure. As problems were encountered, they were addressed in the next design cycle. By this means, capacity for more complex and challenging projects was developed.

Students were able to learn science and engineering content through reconstruction of historical inventions. It addressed the objective of the Smithsonian's National Museum of American History by making its collections more accessible to individuals who are not able to visit the museums. The process also enabled students to gain insight into challenges that the original inventors faced, providing context for development of their own inventions and innovations.

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