FabNet Invention Kits: Outcomes and Implementation

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APPROVAL OF THE DISSERTATION

This dissertation, FabNet Invention Kits: Outcomes and Implementation, 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.

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Dedication

To Dad, who instilled in me a love for learning
To Mum, who always believed I could
To Heather, Conrad, and Griffin, whose love and support made it possible

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FabNet Invention Kits: Outcomes and Implementation

Overview and Conceptual Links

The focus of this dissertation is the outcomes and implementation of the FabNet Invention Kits, a series of science and engineering modules which encourage hands-on teaching and learning. Teachers use project-based learning pedagogy while students build tangible representations of a seminal historical invention. The first two manuscripts explore the learning outcomes of the speaker invention kit and the solenoid invention kit respectively. The third manuscript describes the implementation of the Invention Kits by two middle school teachers.

Improving K–12 education in science, technology, engineering, and mathematics (STEM) subjects has been generally agreed upon need for several years (National Research Council, 2009). The U.S. Department of Education, the National Science Board, and the National Academies Groups are among the agencies calling for improvement and change (Livingston, 2008; NSB, 2007; NAS, NAE, & IOM, 2011). Generally, the goal is to improve STEM education programs so that future generations are more qualified for employment in the rapidly growing technology fields.

The U.S. National Assessment of Education Progress reports roughly 75% of U.S. eighth graders are not proficient in mathematics or science when they complete eighth grade (President’s Council of Advisors on Science and Technology (PCAST), 2010). Employers report job applicants lack needed skills in these subject areas to succeed in the work place. STEM education is seen as a key component to overcoming the challenges facing this nation in an increasingly interconnected and competitive world (National Governors' Association, 2007). The general consensus is that an improvement in K–12 STEM education will help meet these needs.

The skills acquired in STEM content areas during the middle school years lay the foundation for a successful career in the STEM as many STEM occupations require competencies in science, mathematics, technology, and problem solving workforce (Woolley, Strutchens, Gilbert, & Martin, 2010). Middle school is a crucial stage in student development as these students prepare for a rapidly changing future (George, Stevenson, Thomason, & Beane, 1992). Without the proper scaffolding, more advanced study is impossible.

Concrete and authentic experiences can help ground a student's understanding of abstract concepts (Hayer & Papert, 1991). Research indicates technology-based and hands-on instruction improves learning science concepts, and can be more effective than traditional methods (Ekmekci & Gulacar, 2014). Facilitating students' learning through hands-on projects can make abstract concepts more tangible. It can also engage students in a way traditional whole-class lectures or simply reading out of a textbook may not. Using hands-on methods may allow students to engage with the content in their own way, which can be more conducive to diverse groups of students (Hayer & Papert, 1991).

Laboratory School

All three manuscripts report on studies conducted in the Laboratory School for Advanced Manufacturing (Lab School). In 2013, the University of Virginia's Curry

School of Education and School of Engineering and Applied Science collaborated with the Charlottesville City Public Schools and the Albemarle County Public Schools to construct and run a lab school (Bull, Haj-Hariri & Nelson, 2014). Buford Middle School and Sutherland Middle School constructed model facilities for integration of emergent technologies into the K-12 curriculum. In addition, the K-12 Fabrication Laboratory was established to support this effort in the Curry School of Education at the University of Virginia. The goal of the Lab School is to identify and develop effective educational practices for use of advanced manufacturing technologies in K-12 schools (Bull, Haj-Hariri, Atkins, & Moran, 2015).

The Lab School explores integration of hands-on learning and advanced manufacturing technologies into the current middle school curriculum. Advanced manufacturing technologies offer students the opportunity to learn content through the experience of seeing their ideas realized in form of physical artifacts (Bull & Groves, 2009; Chiu, Bull, Berry, & Kjellstrom, 2012).

FabNet Invention Kits

The Lab School collaborated with the National Museum of American History and Princeton University to tell the story of America’s history through the lens of transformational inventions which span the nation’s history from 1800 through 1960. These inventions include the electric motor, the telegraph, the telephone, and the radio. FabNet Invention Kits are open source, digital resource packages which include 3D models of the inventions from the Smithsonian collections, instructional guides, historical primary and secondary sources, and support materials for teachers and students.

FabNet Invention Kits utilize project-based learning (PBL) as a pedagogical framework. In PBL, and the Invention Kits, projects are the catalyst around which learning is centered. Using driving questions and real life problems, complex projects challenge students to problem solve for solutions. This is done through scientific inquiry, peer collaboration, and individual and group research. Over a period of time, students design, prototype, test, and refine products that meet project guidelines. (Thomas, Mergendoller, & Michaelson, 1999).

Project-based Learning

Project-based learning is a student-centered pedagogy that uses projects to drive student learning (Mergendoller, Maxwell, & Bellisimo, 2006). Researchers have purported project-based learning to be more effective in improving problem solving skills and critical thinking than traditional teaching methods (Mergendoller, Maxwell, & Bellisimo, 2006; ChanLin, 2008). Frequently utilized to enhance student learning in medical disciplines, PBL is now being implemented in elementary and secondary classrooms (Holm, 2011).

Project-based learning encourages students to learn through contextual and practical projects. By situating learning within a real-world problem, PBL projects engage students in problem solving practices similar to what professionals do in industry. Lectures, whole-class discussions, and seatwork are mostly absent in PBL with students working autonomously or in small groups (Mergendoller & Thomas, 2000).

Students participating in PBL classes have demonstrated positive gains in important areas. These gains include higher scores on content assessments as compared to students in traditional classrooms (Mioduser & Betzer, 2003). Students also demonstrated an ability to transfer knowledge gained in a PBL environment to other tasks (Boaler, 1997). Problem solving, critical thinking, and peer collaboration are skills which students engaged in PBL have demonstrated significant gains (Mergendoller, Maxwell, & Bellisimo, 2006; ChanLin, 2008). Further, students' engagement (Brush & Saye, 2008), creative thinking (Doppelt, 2009), investigative skills (Baumgartner & Zabin, 2008), and learning confidence (Tretten & Zachariou, 1995) have all been shown to improve within a PBL environment. These positive gains make PBL an attractive methodology for teachers to enact in their classrooms.

Technological, Pedagogical, Content Knowledge (TPACK)

Learning environments that utilize methods such as PBL can be challenging for teachers to implement. They can feel overwhelmed by the scope of the projects and by the time-consuming nature of the units (Marx, Blumenfeld, Krajcik, & Soloway, 1997). Learning and incorporating new pedagogy, classroom management, and technology is difficult and assessing PBL units in an authentic manner can be challenging (Doppelt, 2009).

An added challenge comes from the FabNet Invention Kits, which while utilizing the PBL framework, offer many opportunities to interact with advanced manufacturing technologies such as 3D printers, 2D die-cutters, and laser cutters in the classroom. The rapid development of low cost, easy to use digital fabricators has allowed schools to adopt these advanced manufacturing machines in many classrooms (Bull & Groves, 2009). Digital fabrication is being used to promote higher order thinking and problem solving skills in middle school students by allowing students to conceptualize an idea and then realize the idea in a physical form (Bull & Groves, 2009).

One of the more challenging skills a teacher must have in this diverse and technologically advanced educational society is the ability to properly and effectively implement technology into the classroom (Mishra & Koehler, 2006). Many teachers are unaware of how to effectively integrate technology into their curriculum because they did not experience effective integration as students (Niess, 2011). As evident from the insufficient and inconsistent instances of technology integration in K-12 schools, these methods are creating unsatisfactory results (Harris, Mishra, & Koehler, 2009).

The TPACK framework is a way of thinking that allows a teacher to integrate technology and effective teaching strategies to enhance student learning (Niess, van Zee, & Gillow-Wiles, 2011; Shavelson, Ruiz-Primo, Li, & Ayala, 2003). The TPACK framework offers the science teacher a new way of thinking about technology integration, one that directs focus towards the convergence of content knowledge, pedagogical knowledge, and technological knowledge to find a better way of teaching than the current practices associated with technology integration.

Manuscript 1

A quasi-experimental study was conducted to investigate the learning outcomes of middle school science students participating in a hands-on unit investigating the properties of sound and waves. This study, conducted in three different sections of a physical science course explored the learning outcomes across sections and by gender using a pre- and post-test. Findings are consistent with prior research indicating that hands-on projects may reduce the achievement gap among students in science subjects (Cantrell et al., 2006). Fortus, Dershimer, Marx, Krajcik, and Mamlok-Naaman (2004) found significant gains in students who engaged in design-based learning in science classrooms. Similar to findings from previous research (Fortus et al., 2004) these students constructed scientific knowledge through hands-on activities that encouraged them to problem solve and demonstrate their knowledge gains.

Manuscript 2

Building on the findings reported in manuscript one, the FabNet Invention Kits were developed and refined. Manuscript two reports on the learning outcomes of middle school students participating in a class using the Solenoid Invention Kit. Through the collection and analyzation of pre- and post-test data accompanied by direct observations and interviews, conceptual changes have been documented. Results show a marked changed in the student's understanding of electricity and magnetism and demonstrate the possible value of hands-on project-based learning modules to address electricity and magnetism.

Findings from this study are consistent with previous research indicating that authentic, technology-based and hands-on instruction help student's understanding of abstract concepts (Hayer & Papert, 1991; Ekmekci & Gulacar, 2014). The findings are also consistent with Mergendoller, Maxwell, and Bellisimo (2006) and ChanLin (2008) who found significant gains in students who engaged in project-based learning in science classrooms.

Manuscript 3

Using case study methodology, manuscript three provides a descriptive report of two teachers as they implement a project-based learning environment in their classrooms using the FabNet Invention Kits. Themes emerging from this study include organizing and facilitating small group collaboration and learning, classroom management, time management, technology utilization, and classroom safety.

Both teachers demonstrated strategies crucial to implementing this type of learning environment using the Invention Kits while at the same time demonstrating the possibilities this type of environment has to positively impact the students participating. This study provides some insight into what is required of a teacher who wishes to use these types of activities in their own classroom.

This study documents the successes and challenges these two teachers faced and will benefit teachers who are practicing PBL now and teachers who will be practicing PBL in the future. This study will also inform school leaders on the challenges faced and support needed by teachers who are implementing this pedagogical strategy.

References

Baumgartner, E., & Zabin, C. (2008). A case study of project-based instruction in the ninth grade: A semester-long study of intertidal biodiversity. *Environmental Educational Research, 14*(2), 97-114.

Boaler, J. (1997). *Experiencing school mathematics: Teaching styles, sex, and settings.* Buckingham, UK: Open University Press.

Brush, T., & Saye, J. (2008). The effects of multimedia-supported problem-based inquiry on student engagement, empathy, and assumptions about history. *The Interdisciplinary Journal of Problem-based Learning, 2*(1), 21-56.

Bull, G., & Groves, J. (2009). The democratization of production. *Learning & Leading with Technology, 37*(3), 36-37.

Bull, G., Haj-Hariri, H., & Nelson, A. (2014). The lab in the classroom: 3D printers in schools. *Make, 41*, 24-25.

Bull, G., Haj-Hariri, H., Atkins, R., & Moran, P. (2015). An educational framework for digital manufacturing in schools. *3D Printing and Additive Manufacturing, 2*(2), 42-49.

Cantrell, P., Pekcan, G., Itani, A., & Velasquez-Bryant, N. (2006). The effects of engineering modules on student learning in middle school science classrooms. *Journal of Engineering Education, 95*(4) 301–309.

ChanLin, L. J. (2008). Technology integration applied to project-based learning in science. *Innovations in Education and Teaching International,45*(1), 55-65.

Chiu, J. L., Bull, G., Berry III, R. Q., & Kjellstrom, W. R. (2013). Teaching engineering design with digital fabrication: Imagining, creating, and refining ideas. In C. Mouza & N. Lavigne (Eds.), *Emerging Technologies for the Classroom* (pp. 47-62). New York, NY: Springer-Verlag.

Doppelt, Y. (March, 2009). Assessing creative thinking in design-based learning. *International Journal of Technology Design in Education, 19*(1), 55–65.

Ekmekci, A., & Gulacar, O. (2015). A case study for comparing the effectiveness of a computer simulation and a hands-on activity on learning electric circuits. *Journal of Mathematics, Science & Technology Education, 11*(5), 765-775.

Fortus, D., Dershimer, R.C., Marx, R.W., Krajcik, J., & Mamlok-Naaman, R. (2004). Design-based science (DBS) and student learning. *Journal of Research in Science Teaching, 41*(10), 1081-1110.

George, P., Stevenson, C., Thomason, J., & Beane, J. (1992). *The middle school and beyond*. Alexandria, VA: Association for Supervision and Curriculum Development

Harris, J., Mishra, P., & Koehler, M. (2009). Teachers' technological pedagogical content knowledge and learning activity types: Curriculum-based technology integration reframed. *Journal of Research on Technology in Education, 41*(4), 393-416.

Hayer, I., & Papert, S. (1991). *Constructionism: Research reports and essays, 1985-1990*. New York, NY: Ablex Publishing.

Holm, M. (2011). Project-based instruction: A review of the literature on effectiveness in prekindergarten through 12th grade classrooms. *Rivier Academic Journal, 7*(2), 1-13.

Livingston, A. (2008). *The Condition of Education 2008 in Brief (NCES 2008-032).* Washington DC: National Center for Education Statistics.

Marx, R. W., Blumenfeld, P. C., Krajcik, J. S., & Soloway, E. (1997). Enacting project-based science: Challenges for practice and policy. *Elementary School Journal, 97*, 341-358.

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, 1*(2), 5.

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

Mioduser, D., & Betzer, N. (2003). The contribution of project-based learning to high-achievers' acquisition of technological knowledge and skills. *International Journal of Technology and Design Education, 18*, 59-77.

Mishra, P., & Koehler, M. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *The Teachers College Record, 108*(6), 1017-1054.

National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. (2011). *Rising above the gathering storm revisited: Rapidly approaching category 5.* Condensed version. Washington, DC: The National Academies Press.

National Governors Association. (2007). *Innovation America: A final report*. Washington, DC: Author.

National Science Board. (2007). *National action plan for addressing the critical needs of the U.S. science, technology, engineering, and mathematics education system*. Arlington, VA: National Science Foundation.

Niess, M. L. (2011). Investigating TPACK: Knowledge growth in teaching with technology. *Journal of Educational Computing Research, 44*(3), 299-317.

Niess, M., van Zee, E., Gillow-Wiles, H., & Staus, N. (2011, March). Advancing K-8 teachers' STEM education for teaching interdisciplinary science and mathematics teaching with technologies. Presented at *Society for Information Technology & Teacher Education International Conference*, Nashville, TN.

President's Council of Advisors on Science and Technology (PCAST). (2010). *Prepare and inspire: K-12 education in science, technology, engineering, and math (stem) for America's future.* Washington, DC: Executive Office of the President.

Shavelson, R., Ruiz-Primo, A., Li, M., & Ayala, C. (2003). *Evaluating new approaches to assessing learning* (CSE Report 604). Los Angeles, CA: University of California, National Center for Research on Evaluation.

Thomas, J. W., Mergendoller, J. R., & Michaelson, A. (1999). Project based learning for middle school teachers. *Middle School Journal, 36*(2), 28-31.

Tretten, R. & Zachariou, P. (1995). *Learning about project-based learning: Assessment of project-based learning in Tinkertech schools*. San Rafael, CA: The Autodesk Foundation.

Woolley, M.E., Strutchens, M.E., Gilbert, M.C., & Martin, W.G. (2010). Mathematics success of black middle school students: Direct and indirect effects of teacher expectations and reform practices, *The Negro Educational Review, 61*, 41-60.

Manuscript 1

The Effects of an Engineering Design Module on Student Learning in a Middle School Science Classroom

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Abstract

Eighth grade students often experience difficulty with abstract concepts such as those taught in physical science courses. In order to determine the effect of an engineering design module, advanced manufacturing machines were employed including 2D and 3D fabricators to create artifacts from computer-aided designs. Students completed a *Waves and Sound Assessment* prior to participating in the digital fabrication activities, and again after the hands-on activities. This study also reports the differences found in learning outcomes between genders. Major findings for the 13 males and 8 females were that both males ($p < .01$) and females ($p < .01$) scores improved significantly over the course of the two-week-long unit on waves and sound. Large effect sizes for the open-ended questions and multiple-choice questions were found in both males ($d = .83$) and females ($d = 1.48$). There were no significant differences in scores between sexes at either the pre-test or the post-test time period for the open-ended or multiple-choice questions. Findings indicate advanced manufacturing activities were effective for both boys and girls in fostering gains in science content knowledge related to waves and sound concepts.

Introduction

The need to improve K–12 education in science, technology, engineering, and mathematics (STEM) subjects has been generally agreed upon for several years (National Research Council (NRC), 2009). Groups and agencies calling for improvements and changes include the U.S. Department of Education, the National Science Board, and the National Academies (Livingston, 2008; NSB, 2007; NAS, NAE, 2011). Generally, the goal is to improve STEM education programs so that future generations are more qualified for employment in the rapidly growing technology fields.

The U.S. National Assessment of Education Progress reports roughly 75% of U.S. eighth graders are not proficient in mathematics or science when they complete eighth-grade (President's Council of Advisors on Science and Technology (PCAST), 2010). Employers report job applicants lack needed skills in these subject areas to succeed in the work place (National Governors' Association (NGA), 2007). The problem is not just a lack of proficiency but also a lack of interest among American students in STEM content areas and careers (PCAST, 2010). STEM education is seen as a key component to overcoming the challenges facing this nation in an increasingly interconnected and competitive world (NGA, 2007). The general consensus is that an improvement in K–12 STEM education will help meet these needs.

The skills acquired in STEM content areas during the middle school years lay the foundation for a successful career in the STEM workforce (Woolley, Strutchens, Gilbert, & Martin, 2010) as many STEM occupations require competencies in science, mathematics, technology, and problem solving. Because the future is changing at such a rapid pace, it is crucial to focus on the development of middle school students (George, Stevenson, Thomason, & Beane, 1992). Without the proper scaffolding, more advanced study is impossible.

The presence of engineering in K–12 classrooms is important because of the implications engineering education has on the future of STEM education (Brophy, Klein, Portsmore, & Rogers 2008). Implementing engineering education in K-12 schools may improve student learning and achievement in STEM subjects; increase student awareness of engineering and the work of engineers; boost youth interest in pursuing engineering as a career; and increase the technological literacy of all students (Brophy et al., 2008). Advancement in engineering education may even be a key for a more coalesced and effective K–12 STEM education system in the United States (NRC, 2009).

Literature Review

Using design-based learning experiences in middle school STEM classrooms can provide real-world context to otherwise abstract and difficult STEM concepts, potentially helping students retain what they learn more effectively (NRC, 2009). Current research regarding hands-on learning experiences have shown improvement in student learning and achievement in mathematics and science (Akinoglu & Tandogan, 2007; Kanter, 2010). Design-based learning has also proven to enhance students' interest in STEM subjects (NRC, 2009). Educators and administrators are interested in this hypothesis because of the lack of significant improvements from other means to improve STEM achievement and interest in K-12 education (NRC, 2009).

Engineering Design

Engineering design is an open-ended problem-solving process with specific constraints and goals. Over several iterations, students create, test and refine solutions until they have satisfactorily met the required specifications. This process provides key relevance because most real-world problems are not well defined (Dym, Agogino, Eris, Frey, & Leifer, 2005).

The ratification of the Next Generation Science Standards (NGSS) is indicative of the emerging view of national education leaders that engineering design is an integral and complementary part of scientific literacy (Cajas, 2001). In fact, the NGSS place engineering design on the same level as scientific inquiry. The rationale for this emphasizes the value of engineering in solving meaningful problems and providing opportunities for students to deepen their understanding of science by applying the knowledge they gain in a real-world context (NGSS, 2013). These national standards indicate teaching science through engineering design may be a worthwhile endeavor.

Enabling students to reason scientifically is one of the key elements in successful science teaching (Chinn & Malhotra, 2002). Traditionally however, science teaching has used pedagogical methods such as lectures, readings, worksheets, and demonstrations to impart facts and rudimentary skills to the science student (Silk, Schunn, & Cary, 2009).

Theoretical knowledge alone does not provide students with the skills necessary to translate that knowledge into solving real-world problems (Horwitz, 1995). High school students who scored well on question-and-answer tests of electrical circuits could not build or troubleshoot physical circuit models. Building, testing, and refining real models can close the gap between theoretical and applied knowledge and increase scientific understanding. The National Research Council (2009) purports that a classroom should be an environment in which more emphasis is given to knowledge that is useful. Engineering design is an approach that offers the ability for teachers to implement the

NRC's recommendation. It provides students the opportunity to explore science concepts through the construction of models in a relevant context (Silk et al., 2009).

Engineering design curricula may have several benefits including engaging students in science reasoning. Using engineering design may help students better realize the usefulness of scientific knowledge in solving real-world problems (Fortus, 2005). When students participate in problem-solving in a relevant context they are more likely to engage and question the results of the experiment, rather than accepting what the books says even if their data results are contrary to the book (Benenson, 2001). Engineering design activities also provide opportunities to model difficult concepts with physical representations. This requires students to take into account physical limitations that may not be apparent with images in a book and providing a real-world representation of the concept being learned so that other students can learn from and critique the model (Roth, 2001). This model requires teachers to allow students to direct their own experimentation. It also requires that both teachers and students be willing to accept and even embrace failures during the iterative process (Smith, 2015).

Digital Fabrication

The rapid development of low cost, easy to use digital fabricators has allowed schools to adopt these advanced manufacturing machines in many classrooms (Bull & Groves, 2009). Digital fabrication is being used to promote higher order thinking and problem solving skills in middle school students by allowing students to conceptualize an idea and then realize the idea in a physical form (Bull & Groves, 2009).

Digital fabrication involves automated conversion of a digital design into a physical object through a computer-controlled fabrication system. The Society of

Manufacturing Engineering (SME) concludes that personal digital fabrication will offer "revolutionary changes for both manufacturers and the everyday consumer." The Society lists personal fabrication as one of the key *Innovations that Could Change Engineerin*g, noting that the U.S. Department of Education has identified innovations of this kind as vital to future prosperity.

Other findings have shown that by fabricating artifact based on scientific concepts, students can demonstrate a fuller understanding of the science principles being studied (Hmelo, Holton, & Kolodner, 2000). For high-risk urban middle school classrooms implementing the engineering design process significant content gains were reported in the science classroom (Silk et al., 2009).

Achievement Gap

It is often assumed that girls are less likely than boys to perform well in mathematics and science classes and are more likely to lose interest in STEM subjects in the middle grades (Kahle, Meece, & Scantlebury, 2000). In many cases, though, empirical research is not definitive and in some cases no differences are observed (e.g., Pine et al. 2006). Furthermore, the gender gap may not involve the same causation among different ethnicities (Kahle et al., 2000).

The gap in STEM interest and achievement between boys and girls has been the subject of several research studies (Choi & Chang, 2009). Although previous studies have demonstrated that male students perform better in STEM areas than female students, Choi and Chang (2009) reported that recent studies have shown mixed results. As Knezek, Christensen and Tyler-Wood (2011) argued, the gender gap is less of an ability gap than a gap in perceptions of science careers.

While girls often score higher on math achievement in the classroom than boys, it is the opposite for standardized math scores (Liu, 2008). These gender differences related to math types of scores have been attributed to females thriving in the social aspect of the classroom while standardized tests are typically given in a more impersonal environment. Including social aspects in science and mathematics activities may be a more effective learning environment for girls. Fewer than 10% of engineers in the United States are female (Hirsch, Carpinelli, Kimmel, Rockland, & Bloom, 2007).

Some argue that many women are relatively uninformed about STEM fields and many are thought to have a higher attraction to career fields perceived as being of service to society (Hirsch et al., 2007). Other studies have found that traditional technology and engineering courses are not taught in a style that will appeal to females (Weber, 2012) yet when these types of courses incorporate engaging, real-world activities, both males and females are engaged (Mitts & Haynie, 2010; Weber & Custer, 2005).

Challenges Faced

Despite the national and international focus on STEM education, our understanding of how K-12 students learn science through engineering design is still limited. Engineering design is difficult to learn, teach, and assess, and there is not yet a large body of studies that have explored this topic (Katehi, Pearson, & Feder, 2009). The National Academy of Engineering report, *Engineering in K-12 Education,* concludes that existing science curricula do not fully take advantage of the connections between engineering and the other STEM subjects (Katehi et al., 2009).

The difference in the results and time constraints of implementing an engineering design in a diverse population can be significant (Kuhn & Dean, 2008). Li, Klahr, and

Siler (2006) found that students from affluent homes could design an experiment within two days while students from less affluent homes could take up to three weeks depending upon the classroom and school. The population in which research is conducted must be accounted for when determining the effectiveness of the intervention (Lee, Deaktor, Hart, Cueva, & Enders, 2005).

With these challenges in mind, Fortus, Dershimer, Marx, Krajcik, and Mamlok-Naaman (2004) found significant gains in students who engaged in design-based learning in science classrooms. These students constructed scientific knowledge through hands-on activities that encouraged them to problem solve and demonstrate their knowledge gains. Other findings have shown that by fabricating models of a scientific concept, students demonstrate a deeper understanding of the science being studied (Hmelo, Holton, & Kolodner, 2000).

Research Questions

The relatively recent emergence of the importance of engineering education in K-12 has exposed several key questions for educators, policy makers, and researchers to consider. How should engineering be taught in K–12 schools? What instructional materials, curricula, and instructional methods are currently being used to teach engineering education? Has current implementation of engineering in K-12 schools improved student achievement in STEM subjects or increased interest and awareness in STEM careers (NRC, 2009)?

This study builds upon previous research which indicates engineering design projects may reduce the achievement gap among students while boosting standardized test scores in science subjects (Cantrell, Pekcan, Itani, & Velasquez-Bryant, 2006) by testing the following questions:

1. What effect does participation in an engineering design module on waves and sound have on middle school students' content knowledge of science, mathematics and engineering concepts?
    a. Do male and female students differ in the content knowledge gained in science, mathematics and engineering content after participation in an engineering design module?
    b. Do students in separate classes differ in their levels of content knowledge gained in mathematics and engineering content after participation in an engineering design module?

Methods

This study executed a quasi-experimental design with a one group pre-test/post-test design (Campbell & Stanley, 1966). Quantitative research methods were used to measure and examine data to explore the research questions.

Participants

This study was conducted as a pilot in a middle school located in a mid-Atlantic state. The population was comprised of 48.4% African American, 40.9% White, 6.7% Hispanic, and 4% Asian/Pacific Islander students. Fifteen percent of students speak English as a second language. Twenty-nine percent of the students have been identified as gifted and 14.7% are classified as special education students. Students in three eighth-grade science classes served as participants for this study.

A total of 54 students in three different classrooms participated in this engineering design module. However, due to absence caused by a multitude of reasons including sickness, discipline, and familial circumstances, only 21 were present for each day of instruction and completed the pre- and post-test (13 males and 8 females).

The teacher for each of the three sections is a veteran public school teacher with 27 years of experience that includes teaching physical science at the middle and high school levels. His philosophy of teaching embraced project-based learning, and he is an advocate of STEM initiatives that encouraged students of all backgrounds to become involved in STEM subject areas.

Intervention

Overview. The engineering design module was comprised of five 90-minute block classes in an eighth-grade physical science course over the span of two weeks. Teams of students were given the task of building two speakers. One speaker was to be designed to play low frequencies, referred to as the woofer. The second speaker was to be designed to play higher frequencies and was called the tweeter.

Students learned progressively more about the behavior and manipulation of waves throughout the five lessons. Each of these lessons included hands-on activities utilizing several advanced manufacturing machines such as 2D and 3D fabricators to create tangible objects from computer-aided design software. Using advanced manufacturing tools allowed students to test their designs and make the necessary changes to create more effective models. In building, testing, and refining the speakers, the students engaged in the engineering design process.

Digital fabrication. Digital fabrication is a process that creates tangible physical objects from digital designs. The digital design can be created on a tablet or computer using a myriad of software-based solutions. Digital fabrication offers many options for the classroom educator to implement project-based learning while building skills in subject areas such as mathematics, science, and engineering.

Advanced manufacturing machines such as 3D printers and die cutters can be coupled with technology such as 3-dimensional computer design software, computers and tablets and sound level meters. The die cutters us a small razor to automatically cut out shapes of all kinds on 2-dimensional materials such as paper and cardstock.

The computer aided design (CAD) software allowed students to design and draw objects on the computer using real dimensions and preview their object before fabrication. This provided the students with the opportunity to use software to design something that would come to life, just like an engineer would. The students used the software to send it to the die cutter which cut it out to the specifications set by the students so that they were ready to fabricate a working model.

An example of digital fabrication in this experiment was when students created the cone for their speakers. They began by drafting rough design dimensions onto paper before using the FabLab Model Maker software to draw the cone on the speaker. The digital design was exported to the Silhouette CAMEO which cut the cone from cardstock paper.

Software and hardware. FabLab Model Maker (Aspex, London) was the primary CAD software program students used to design the speakers. This particular software was chosen because of the built-in hardware support for 2D and 3D fabricators.

Microsoft Excel was used to develop the frequency response graphs which students used to measure the efficacy of each subwoofer and tweeter.

The 2D fabricator employed was the Silhouette CAMEO die cutter. Generic decibel meters were utilized by students while creating frequency response curves. AFINIA 3D printers were also introduced to the students. However, incorporating the 3D printer into the five lessons became non-viable due to time constraints. Students utilized the 3D printer later in the semester to improve their speaker design but data and observations from that extension are not included in this paper.

The students also used a sound level meter to test the loudness or amplitude of their speaker. This allowed the students to capture an intangible concept and relate it to their speaker design. The sound level meter brought a reality to the idea of volume so that they could see what their speaker could do.

Curriculum. The learning objectives of this unit included learning the properties of soundwaves while building, testing, and refining a set of working speakers using advanced manufacturing technologies.

Day one. Students created a pre-designed paper speaker using the FabLab Model Maker software to test and compare with commercial speakers using low, mid, and high tones to enhance their understanding that different speaker designs are used to functionally play different tones more efficiently. This speaker became the base design from which changes, modifications, and adaptations were made to fulfill the design specifications for the subwoofer and tweeter speakers.

Day two. Students explored some of the properties of waves including wavelength, amplitude, frequency and period using various commercial and improvised tuning forks. Students further studied this phenomenon by building a pendulum paint-dispensing mechanism. By pulling paper underneath the paint dripping pendulum as it swung, students created sine waves from which they identified the properties of a wave.

Day three. Students explored the features of the FabLab Model Maker software. They practiced making different shapes and cutting them using the Silhouette CAMEO.

Day four. Refinement of the students' speaker began in earnest on day four. Students used pencil and paper to draw, document, and justify planned changes. The designs created included metric measurements for each speaker part to be fabricated. Teams then created digital designs using the FabLab Model Maker software and fabricated their designs using the Silhouette CAMEOs.

Day five. Upon completion of the construction of the speakers, students began testing their designs. Using an online tone generator, students would play specific pre-determined frequencies through each speaker. Students would record the loudness of the speaker at each frequency using a decibel meter. These measurements were entered into an Excel spreadsheet and a graph was created to display the frequency response for the speaker. By combining the frequency response graph for a tweet and a subwoofer, teams were able to determine the range and peak frequencies for their speaker pair.

Instrumentation

Eighth grade students in three different classes of a physical science course took the *Waves and Sound Assessment* prior to participating in the unit. The assessment consisted of multiple-choice and open-ended questions designed to evaluate participants' understanding of sound and sound waves. Included items were retrieved from the following sources:

- The International Mathematics and Science Study (TIMSS);
- Prentice Hall Physical Science Concepts in Action (Wysession, Frank, & Yancopoulos, 2011) by Pearson Education;
- The physical science curriculum framework (eighth-grade) published by the Virginia Department of Education;
- Albemarle County Public Schools' Physical Science Matrix; and
- STEM educators affiliated with the University of Virginia.

The assessment was not validated through formal measurement testing; however, content area experts in science, mathematics, and instructional technology provided iterative feedback during the development of the assessment tool.

Two blinded raters scored all of the pre-assessments. One rater was a former high school technology educator with knowledge of the core scientific principles associated with sound waves and sound. The other rater was a former high school science teacher. Participants' responses received a correct or incorrect notation for all of the multiple-choice items (0 = Incorrect, 1 = Correct). Open-ended questions were rated according to a general rubric that evaluated the presence or absence of scientific understanding of sound and sound waves. The ordinal scale for evaluating open-ended items included the following levels:

- 5 Points: All items are addressed. Full inclusion of science principles. Explanations include proper terms and usage throughout response.
- 4 Points: Response is thorough, missing one element to response to provide complete understanding of science concepts.

- 3 Points: General conceptual understanding. Missing elements to providing a full response that addresses all science principles. Misconceptions may still exist.
- 2 Points: Response is vague and addresses a common understanding, while providing some instances of misconceptions.
- 1 Point: Blank response or no relation to the question asked. Full misconception in response.

The pre-assessments were scored by the two raters and the average measure intraclass correlation coefficient was .903 with a 95% confidence interval from .847 to .938, $p < .001$. A post hoc power analysis was conducted using the software package, *GPower* (Faul, Erdfelder, Buchner, & Lang, 2009). The sample size of 21 was used for the statistical power analyses and the alpha level used for this analysis was $p < .05$. The post hoc analyses revealed the statistical power for this study exceeded .99. Thus, there was more than adequate power.

The same assessment was re-administered after the 5-day unit. Pre-test to post-test knowledge gains were compared using paired *t* test; students were then grouped by sex for pre-test to post-test knowledge gain comparisons. Finally, the knowledge gains were compared between the sexes. All alpha levels were set *a priori* at 0.05. Cohen's *d* was used for effect size calculation (Cohen, 1988) and were interpreted as small = .2, moderate = .5, or large > .8.

Results

The multiple-choice items that were scored as 0 for incorrect and 1 for correct were totaled for the TotMC label (possible range of 0 – 13). The open-ended rated items were averaged for a label of OpenAvg (possible range of 9 – 45). The participants were paired and a paired *t*-test was run on the means and sums pre-post. As shown in Table 1, both indicators of content knowledge showed significant gains ($p < .01$) with large effect sizes.

Table 1

Paired Sample Analysis of Content Knowledge Gains, Pre to Post

		Mean	N	Std. Dev.	Sig.	Effect Size
Pair 1	Pre OpenAvg	19.50	20	4.199		
	PostOpenAvg	29.75	20	9.640	.0005	1.38
Pair 2	PreTotMC	6.05	20	2.625		
	PostTotMC	8.65	20	2.641	.0005	0.99

Gender Comparisons

Independent sample *t*-tests were used to compare the mean scores of the 13 males to those of the 8 females in this group of students, as shown in Tables 2 and 3, no significant ($p < .05$) differences in scores by gender for the open-ended questions or the multiple-choice questions, at the pre-test or the post-test time period, were found. Gender-specific analyses of the indices confirmed that both male and female’s score increased significantly over the course of the week-long unit on waves and motions. The effect size for males from pre- to post-test on the open-ended questions was ES = 1.28 (Cohen’s d = 29.4-18.8/Pooled SD) while the effect size for females pre- to post-test was ES = 1.48 (30.4-21.5/Pooled SD). With regard to multiple-choice questions, the effect size for males pre- to post-test was ES = .83, while for females the pre- to post-test gain was ES = 1.45. All would be considered large gains according to guidelines provided by

Cohen (1988). The similar pre- to post-test gains in scores by males and females are graphically illustrated in Figure 1 and Figure 2.

Table 2

Analysis of Open-ended Content Scores by Gender

		N	Mean	Std. Deviation	Sig
PreOpenAvg	Male	13	18.77	4.531	
	Female	8	21.50	3.625	
	Total	21	19.81	4.332	.166
PostOpenAvg	Male	13	29.38	10.813	
	Female	7	30.43	7.721	
	Total	20	29.75	9.640	.824

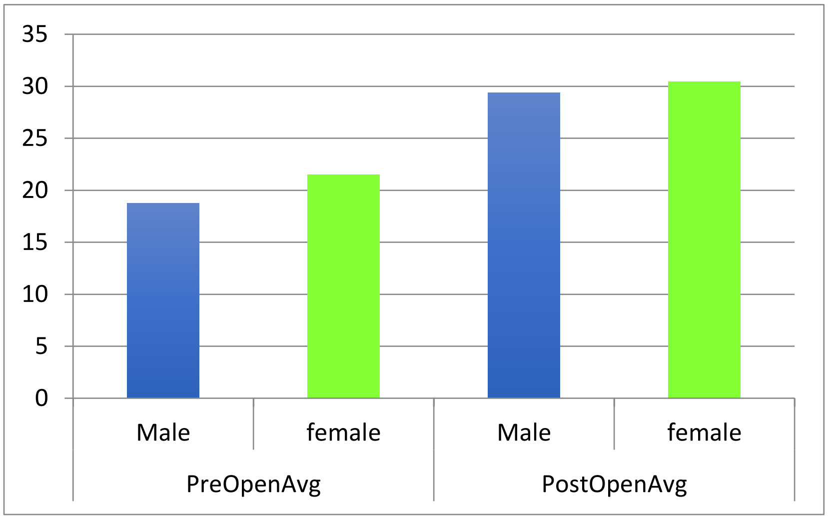

Figure 1. Pre- and post-test comparisons by gender for open-ended content scores.

Table 3

Gender Comparisons for Multiple Choice Content Scores

		N	Mean	Std. Deviation	Sig
	Male	13	5.69	2.983	
PreTotMC	Female	8	6.88	1.727	
	Total	21	6.14	2.594	.323
	Male	13	8.08	2.783	
PostTotMC	Female	7	9.71	2.138	
	Total	20	8.65	2.641	.194

These findings led to the following conclusion regarding research question 2: Both male and female middle school students completing a digital fabrication unit exhibited large gains in content knowledge. No conclusive ($p < .05$) evidence was found to indicate that males versus females began at differing levels of content knowledge, nor that they differed in the extent of knowledge gain.

Comparisons Among Classes

A one-way analysis of variance by class was completed for the three eighth grade classes on their open-ended questions at pre-test and at post-test times (see Table 4). There were small numbers of fabrication activity participants in each group but the differences between classes was found to be significant ($p < .05$) at the pre-test and at the post-test times. With regard to gains, Class 2 gained approximately five points from pre- to post-test, while Class 1 and Class 3 each gained approximately 8 content points. The pre- to post-test effect sizes were: ES = 1.27 for Class 1; ES = .54 for Class 2; and ES = 2.50 for Class 3. Class 2 exhibited a moderate gain (Cohen, 1988) while for Class 1 and

Class 3 the gains were very large (Cohen, 1988). These and other trends are graphically displayed in Figure 3.

Table 4

One-way Analysis by Class on Open-Ended Questions

		N	Mean	Std. Dev.	Sig.
PreOpenAvg	Class 1	8	20.00	3.59	
	Class 2	3	13.67	3.22	
	Class 3	10	21.50	3.69	.014
	Total	21	19.81	4.33	
PostOpenAvg	Class 1	8	28.75	9.00	
	Class 2	3	18.33	11.85	
	Class 3	9	34.44	6.33	
	Total	20	29.75	9.64	.030

One-way analysis of variance by class was also completed for the three eighth grade classes on their multiple-choice questions at pre-test and at post-test times (see Table 5). There were small numbers of fabrication activity participants in each group but the differences between classes were found to be significant ($p < .05$) at the pre-test and at the post-test times. With regard to gains, the pre- to post-test effect sizes were: ES = 1.06 for Class 1; ES = 2.90 for Class 2; and ES = 1.49 for Class 3. Class 2 exhibited an extremely large gain (Cohen, 1988) from its pre-test low starting point (1.67) while for Class 1 and Class 3 the gains were very large (Cohen, 1988). These and other trends are graphically displayed in Figure 4. Note that the effect size for class 2 could have been somewhat inflated by the very small sample size of n = 3. However, it is also possible that Class 2 truly had lower content knowledge at the pre-test time, and that this class exhibited higher gains in basic knowledge commonly assessed by multiple choice questions.

Table 5

One-way Analysis by Class for Multiple-Choice Questions

		N	Mean	Std. Dev.	Sig.
PreTotMC	Class 1	8	6.75	1.83	
	Class 2	3	1.67	.58	
	Class 3	10	7.00	2.11	
	Total	21	6.14	2.59	.001
PostTotMC	Class 1	8	9.13	2.59	
	Class 2	3	4.33	1.16	
	Class 3	9	9.67	1.41	
	Total	20	8.65	2.64	.003

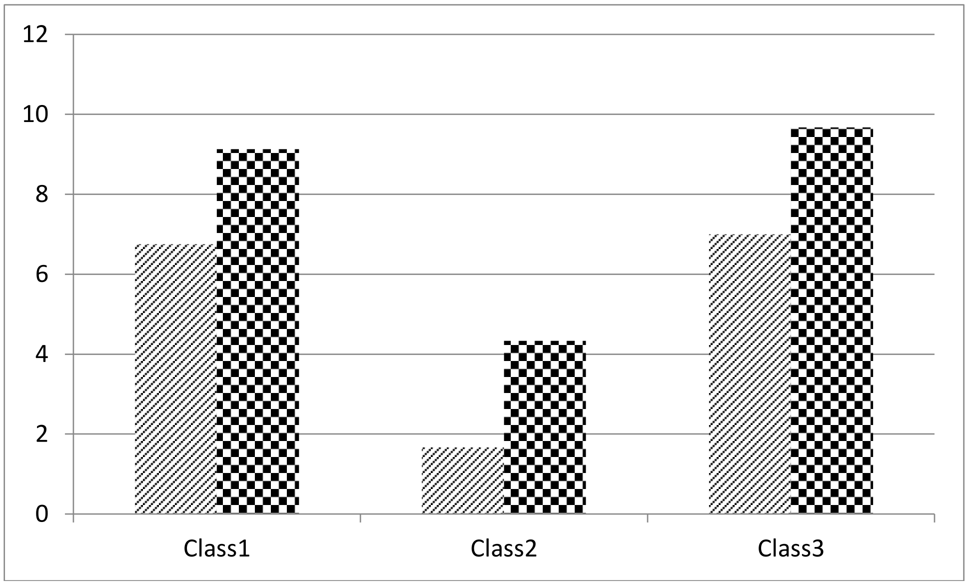

Figure 2. Pre- to post-test multiple-choice items by class.

These findings led to the following conclusion regarding research question 3: There were significant ($p < .05$) differences among middle school students in three classes completing digital fabrication units in their levels of competency in content knowledge of mathematics and engineering. These differences existed at pre-test time, post-test time, and in the extent of gain. In particular, Class 2 began with scores much lower than Class 1 or Class 3 on open-ended and multiple-choice tests, and remained in that relative position at the post test time. However, while Class 2 exhibited the smallest gain among the three (ES = .54) on the open-ended questions, it exhibited the highest gain among the three (ES = 2.90) on the multiple-choice questions. This may be a reflection of the lower versus higher cognitive skills commonly assessed by multiple-choice items versus open-ended items, respectively.

Discussion

The dual methods employed for assessing content gain in this study generally reinforced each other, resulting in similar conclusions regarding the significance ($p < .05$) and magnitude (moderate to large effect) of the gain. Effect size indices are especially important in examining the data from this study as all pre- to post-test measures resulted in effect size gains (Cohen's *d*) greater than ES > .3, the point at which gains would normally be considered educationally meaningful (Bialo & Sivin-Kachala, 1996). These findings have cross-validated the multiple-choice test item portion of the study with the much more time-consuming human-rater scoring of open-ended questions, implying that future studies without extensive human-rater resources might be able to rely on well-formulated multiple choice tests alone.

Student participation in activities that promote engineering design principles while teaching science and mathematics concepts may improve both achievement as well as interest in a STEM career. The students in this study gained a significant ($p < .05$) amount in their scores related to the waves and sound curriculum. On site observations indicated that this activity enhanced student enthusiasm for and engagement in learning. In future studies, direct measurement of attitude change as well as gains in content knowledge might be warranted to address the issues regarding the lack of proficiency and interest among American students reported by PCAST (2010).

Findings from this study are consistent with previous research indicating that fabrication coupled with engineering design projects may reduce the achievement gap among students in science subjects (Cantrell et al., 2006). Fortus, Dershimer, Marx, Krajcik, and Mamlok-Naaman (2004) found significant gains in students who engaged in design-based learning in science classrooms. Similar to findings from previous research (Fortus et al., 2004) these students constructed scientific knowledge through hands-on activities that encouraged them to problem solve and demonstrate their knowledge gains.

Although the educationally meaningful (ES > .3) content gains found in each of three classrooms provides evidence of the ability to replicate the positive impact of the *Waves and Sound* curricular unit, the possibility still remains that students without these activities might have exhibited similar gains. Replication of this study with suitable comparison group data – such as pre- and post-test data from comparable students who did not experience digital fabrication activities – is warranted.

Conclusions

K–12 engineering education may improve student learning and achievement in science and mathematics; increase awareness of engineering and the work of engineers; boost youth interest in pursuing engineering as a career; and increase the technological literacy of all students (Brophy et al., 2008). Advancement in engineering education may even be a key for a more coalesced and effective K–12 STEM education system in the United States (NRC, 2009)

Eighth grade students involved in an engineering design unit using advanced manufacturing tools were found to have measurably large content gains ($p < .01$, ES > .8) (Cohen, 1988) on multiple-choice test items and open-ended test questions featuring waves and motion, the focus of their intervention curricular unit. No significant ($p < .05$) differences were found by gender. Some differences ($p < .05$) were indicated among the three treatment classes. Additional research is needed to isolate the reasons for these differences. Replication studies are warranted to reconfirm these findings in the context of a strong comparison group.

These collective findings led to the following conclusion regarding research question 1: Middle school students completing a digital fabrication unit focused on waves and sounds do indeed gain in content knowledge of science, mathematics and engineering concepts.

REFERENCES

Akinoglu, O., & Tandogan, R. O. (2007). The effects of problem-based active learning in science education on students' academic achievement, attitude and concept learning. *Eurasia Journal of Mathematics, Science & Technology Education, 3*(1), 71-81.

Benenson, G. (2001). The unrealized potential of everyday technology as a context for learning. *Journal of Research in Science Teaching*, *38*(7), 730-745.

Bialo, E. R., & Sivin-Kachala, J. (1996). The effectiveness of technology in schools: A summary of recent research. *School Library Media Quarterly*, *25*(1), 51-57.

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

Bull, G., & Groves, J. (2009). The democratization of production. *Learning & Leading with Technology*, *37*(3), 36-37.

Cajas, F. (2001). The science/technology interaction: Implications for science literacy. *Journal of Research in Science Teaching*, *38*(7), 715-729.

Campbell, D. T. & Stanley, J. C. (1966). *Experimental and quasi-experimental designs for research*. Chicago, IL: Rand McNally.

Cantrell, P., Pekcan, G., Itani, A., & Velasquez-Bryant, N. (2006). The effects of engineering modules on student learning in middle school science classrooms. *Journal of Engineering Education*, *95*(4) 301–309.

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education*, *86*(2), 175-218.

Choi, N., & Chang, M. (2009). Performance of middle school students. comparing U.S and Japanese inquiry-based science practices in middle schools. *Middle Grades Research Journal*, *6*(1), 15.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, *94*(1), 103-120.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*, 1149-1160.

Fortus, D. (2005). Restructuring school physics around real-world problems: A cognitive justification. Paper presented at *Annual Meeting of the American Educational Research Association*, Montreal, Quebec.

Fortus, D., Dershimer, R. C., Marx, R. W., Krajcik, J., & Mamlok-Naaman, R. (2004). Design-based science (DBS) and student learning. *Journal of Research in Science Teaching 41*(10), 1081-1110.

George, P., Stevenson, C., Thomason, J., & Beane, J. (1992). *The middle school and beyond*. Alexandria, VA: Association for Supervision and Curriculum Development.

Hirsch, L., Carpinelli, J., Kimmel, H., Rockland, R., & Bloom, J. (2007). The differential effects of pre-engineering curricula on middle school students' attitudes to and knowledge of engineering careers. Presented at *37th ASEE/IEEE Frontiers in Education Conference*. Retrieved from http://fie-conference.org/fie2007/papers/1205.pdf

Hmelo, C. E., Holton, D. L., & Kolodner, J. L. (2000). Designing to learn about complex systems. *Journal of the Learning Sciences 9*(3), 247-298.

Horwitz, P. (1995). Linking models to data: Hypermodels for science education. *The High School Journal*, *79*(2), 148-156.

Kahle, J. B., Meece, J., & Scantlebury, K. (2000). Urban African-American middle school science students: Does standards-based teaching make a difference? *Journal of Research in Science Teaching*, *37*(9), 1019-1041.

Katehi, L., Pearson, G., & Feder, M. (2009). The status and nature of K-12 engineering education in the United States. *The Bridge*, *39*(3), 5-10.

Knezek, G., Christensen, R., & Tyler-Wood, T. (2011). Contrasting perceptions of STEM content and careers. *Contemporary Issues in Technology and Teacher Education, 11*(1), 92-117.

Kuhn, D., & Dean, J. (2008). Scaffolded development of inquiry skills in academically disadvantaged middle-school students. *Journal of Psychology of Science and Technology, 1*(2), 36-50.

Lee, O., Deaktor, R. A., Hart, J. E., Cuevas, P., & Enders, C. (2005). An instructional intervention's impact on the science and literacy achievement of culturally and linguistically diverse elementary students. *Journal of Research in Science Teaching*, *42*(8), 857-887.

Li, J., Klahr, D., & Siler, S. A. (2006). What lies beneath the science achievement gap: The challenges of aligning science instruction with standards and tests. *Science Educator*, *15*(1), 1-12.

Liu, F. (2008). Impact of online discussion on elementary teacher candidates' anxiety towards teaching mathematics. *Education, 128*(4), 614-629.

Livingston, A. (2008). *The Condition of Education 2008 in Brief (NCES 2008-032).* Washington DC: National Center for Education Statistics.

Mitts, C., & Haynie, W. (2010). Preferences of male and female students for TSA competitive events. *Technology and Engineering Teacher, 70*(1), 19-26.

National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. (2011). *Rising above the gathering storm revisited: Rapidly approaching category 5.* Condensed version. Washington, DC: The National Academies Press.

National Governors Association. (2007). *Innovation America: A final report*. Washington, DC: Author.

National Research Council (2009). Katechi, L., Pearson, G., & Feder, M. (Eds.). *Engineering in K-12 education: Understanding the status and improving the prospects committee on K-12 engineering education*. Washington, DC: The National Academies Press.

National Science Board. (2007). *National action plan for addressing the critical needs of the U.S. science, technology, engineering, and mathematics education system*. Arlington, VA: National Science Foundation.

NGSS Lead States. 2013. *Next Generation Science Standards: For States, By State*s. Washington, DC: The National Academies Press.

President’s Council of Advisors on Science and Technology (PCAST). (2010). *Prepare and inspire: K-12 education in science, technology, engineering, and math (stem) for America's future.* Washington, DC: Executive Office of the President.

Pine, J., Aschbacher, P., Roth, E., Jones, M., McPhee, C., Martin, C., & Foley, B. (2006). Fifth graders' science inquiry abilities: A comparative study of students in hands-on and textbook curricula. *Journal of Research in Science Teaching, 43*(5), 467-484.

Roth, W. M. (2001). Learning science through technological design. *Journal of Research in Science Teaching, 38*(7), 768-790.

Silk, E. M., Schunn, C. D., & Cary, M. S. (2009). The impact of an engineering design curriculum on science reasoning in an urban setting. *Journal of Science Education and Technology, 18*(3), 209-223.

Smith, S. (2015). Epic Fails: Reconceptualizing failure as a catalyst for developing creative persistence within teaching and learning experiences. *Journal of Technology and Teacher Education, 23*(3), 329-335.

Weber, K. & Custer, R. (2005). Gender-based preferences toward technology education content, activities, and instructional methods. *Journal of Technology Education*, *16*(2), 55-71.

Weber, K. (2012). Gender differences in interest, perceived personal capacity, and participation in STEM-related activities. *Journal of Technology Education*, *24*(1), 18-33.

Woolley, M. E., Strutchens, M. E., Gilbert, M. C., & Martin, W. G. (2010). Mathematics success of black middle school students: direct and indirect effects of teacher expectations and reform practices, *The Negro Educational Review*, *61*, 41-60.

Wysession, M., Frank, D., & Yancopoulos, S. (2011). *Prentice hall physical science concepts in action*. Boston, MA: Pearson Education.

Manuscript 2

Learning about Electricity and Magnetism Using the FabNet Solenoid Invention Kit

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ABSTRACT

This study follows 30 middle school students as they experience a hands-on learning module through the implementation of the FabNet Solenoid Invention Kit. Through the collection and analyzation of pre-test and post-test data conceptual changes have been documented. Results show a marked changed in the student's understanding of electricity and magnetism and demonstrate the possible value of hands-on project-based learning modules to address electricity and magnetism, as well as show where improvements to the curriculum need to be made.

Introduction

This study follows 30 middle school students as they experience a hands-on learning module through the implementation of the FabNet Solenoid Invention Kit. Through the collection and analysis of pre- and post-test data conceptual changes have been documented.

According to the U.S. National Assessment of Education Progress reports 75% of eighth graders in the U.S. lack proficiency in mathematics or science when they complete eighth grade (President's Council of Advisors on Science and Technology (PCAST), 2010). Additionally, employers report job applicants lack skills needed in these subject areas to succeed in some work places (National Governors' Association, 2007). STEM education may help in overcoming the challenges this nation is facing (National Governors' Association, 2007).

The foundation for a successful career in the STEM may be best built up from skills acquired in STEM content areas during the middle school years (Woolley, Strutchens, Gilbert, & Martin, 2010). Middle school is reported to be a crucial stage in student development (George, Stevenson, Thomason, & Beane, 1992). Without the proper scaffolding, more advanced study may be impossible.

Background

Middle school science curriculum has many abstract concepts. Students in middle school often find these concepts difficult to understand (Chi, 2005). Electricity and magnetism (E&M) is an especially difficult area for students to master (Başer & Geban, 2007; Fredette & Lockhead, 1980). They often do not have a clear understanding of fundamental concepts in electricity, such as voltage, current, and resistance, nor do students understand how these concepts relate to magnetism. These abstract and complex concepts may not be well represented through traditional instructional methods, and may not address some of the misconceptions that students already have about E&M. It has become increasingly important to develop sound pedagogical methods to teach complex science concepts.

Concrete and authentic experiences can help ground a student's understanding of abstract concepts (Hayer & Papert, 1991). Research reports indicate technology-based and hands-on instruction can improve the learning of science concepts, and can be more effective than traditional methods (Ekmekci & Gulacar, 2014). Allowing a student to learn through a hands-on project can make concepts tangible, and engages the student in a way that direct instruction or simply reading out of a textbook may not. Using these methods, students engage with the content in their own way, which can be more conducive to groups of students with a diverse range of learning competencies and preferences (Hayer & Papert, 1991).

The focus of this study is hands-on learning environments, where students build tangible representations of a particular concept, allowing them to construct their own knowledge around it. This paper explores the use of a hands-on project in a middle school engineering class to teach fundamental concepts of E&M. The project required students to build a solenoid and then use it in several different applications, including at least one application designed by the students. An assessment was then used to determine the students' understanding of E&M. The results of the study show that a hands-on instructional approach can increase the number of normative conceptions among student that align with the scientific community, as well as address the misconceptions that do not align.

Laboratory School

This study was conducted in the Laboratory School for Advanced Manufacturing (Lab School). John Dewey established the first laboratory school in 1896, founded in a collaboration between faculty at the University of Chicago and local educators, students, and parents. Since then, approximately two dozen laboratory schools have been established in the United States. They are designed to serve as testing grounds for the development of effective educational practices.

In 2013, the Lab School was established as a joint venture by the University of Virginia's Curry School of Education in collaboration with the Charlottesville City Schools and the Albemarle County Public Schools (Bull, Haj-Hariri & Nelson, 2014). Model facilities for integration of emergent technologies into the K-12 curriculum were established at Buford Middle School and Sutherland Middle School. In addition, a K-12 Fabrication Laboratory was established to support this effort in the School of Education at the University of Virginia. The goal of the Lab School is to identify and develop effective educational practices for use of advanced manufacturing technologies in K-12 schools (Bull, Haj-Hariri, Atkins, & Moran, 2015).

The Lab School explores the integration of hands-on learning and advanced manufacturing technologies into the curricula. Advanced manufacturing technologies offer students the opportunity to learn about curricula content through the experience of seeing their ideas realized in form of physical artifacts (Bull & Groves, 2009; Chiu, Bull, Berry, & Kjellstrom, 2012).

FabNet Invention Kits

The Lab School collaborated with the National Museum of American History to tell the story of America's history through the lens of twelve transformational inventions which span the nation's history from 1800 through 1960. These inventions include the electric motor, the telegraph, the telephone, the radio, and other key inventions in the nation's history.

FabNet Invention Kits are open source, digital resource packages which include 3D models of the inventions from the Smithsonian collections, instructional guides, historical primary and secondary sources, and support materials for teachers and students. The goal for the students is not to create an exact physical replica of inventions, but to reinterpret and reinvent a fully-functioning device using low-tech and advanced manufacturing technology. The ultimate objective is to inspire and inform a new generation of problem solvers and to underscore the power that fundamental science and engineering principles can bring to executing new ideas.

FabNet Invention Kits utilize project-based learning (PBL) as a pedagogical framework. In PBL and the Invention Kits, projects are the catalyst around which learning is centered. Using driving questions and real-life problems, complex projects challenge students to problem solve for solutions. This is done through scientific inquiry, peer collaboration, and individual and group research. Over a period of time, students design, prototype, test, and refine products that meet project guidelines. (Thomas, Mergendoller, & Michaelson, 1999).

As advanced manufacturing technologies have decreased in price, many individual teachers are purchasing them for use in their classrooms. Innovative work is emerging from the classrooms of these forward-thinking educators (Bull, Chiu, Berry & Lipson, 2013). But just as the power of computers is amplified when they are networked in an integrated system, the potential of advanced manufacturing technologies is enhanced when coordinated choices are made by educational leaders in schools.

Literature Review

Project-based learning is a student-centered pedagogy that uses projects to drive student learning (Mergendoller, Maxwell, & Bellisimo, 2006). Researchers have purported project-based learning to be more effective in improving problem-solving skills and critical thinking than traditional teaching methods (Mergendoller, Maxwell, & Bellisimo, 2006; ChanLin, 2008). Frequently utilized to enhance student learning in medical disciplines, PBL is now being implemented in elementary and secondary classrooms (Holm, 2011).

Project-based learning encourages students to learn through contextual and practical projects. By situating learning within a real-world problem, PBL projects engage students in problem-solving practices similar to what professionals do in industry. Lectures, whole-class discussions, and seatwork are mostly absent in PBL with students working autonomously or in small groups (Mergendoller & Thomas, 2000).

Students participating in PBL classes have demonstrated positive gains in important areas. These gains include higher scores on content assessments as compared to students in traditional classrooms (Mioduser & Betzer, 2003). For example, three elementary schools Iowa who implemented PBL curriculum demonstrated considerable gains on standardized achievement tests compared to the other ten elementary schools in that district (Expeditionary Learning Outward Bound [ELOB], 1999). Two of the three schools advanced from below average to an average equal to the other schools in that district. The third school started at the same level as the other two but advanced to well above average in comparison to the other district schools. This happened within two years of implementing a PBL environment in these schools. Eighth-grade students in an inner-city middle school in Boston which implemented the same PBL environment as the schools in Iowa raised their standardized scores in reading to second in the district (ELOB, 1999).

It is important to recognize that there are many differing programs all purporting to implement PBL curriculum. The above examples all implemented PBL in a way consistent with available PBL literature. However, the four schools also underwent whole-school reforms that included school organization as well as curriculum and instruction practices (Thomas, 2000).

Students also demonstrated an ability to transfer knowledge gained in a PBL environment to other tasks (Boaler, 1997). Students engaged in PBL have demonstrated significant gains in problem solving, critical thinking, and peer collaboration (Mergendoller, Maxwell, & Bellisimo, 2006; ChanLin, 2008). Further, students' engagement, creative thinking, investigative skills, and learning have all been shown to improve within a PBL environment (Baumgartner & Zabin, 2008; Brush & Saye, 2008; Doppelt, 2009; Tretten & Zachariou, 1995). For example, high-school seniors were enrolled in a PBL class and tested using a problem-solving test. The 78 seniors scored significantly higher than the same number of students in a matched comparison group (Gallagher, Stepien, & Rosenthal, 1992).

Other findings have shown that by fabricating models of a scientific concept, students demonstrate a deeper understanding of the science being studied (Hmelo, Holton, & Kolodner, 2000). For high-risk urban middle school classrooms, significant content gains were reported in the science classroom (Silk, Schunn, & Strand Cary, 2009).

Project-based learning has several key features (Krajcik, Czerniak, Czerniak, & Berger, 2003; Dickinson & Jackson, 2008): PBL units are framed by a driving question. The driving question guides students as they engage in meaningful and contextual exploration; all members of the learning community collaborate in problem solving; students are guided so as not to flail at a solution. Concepts and skill are scaffolded to give students the abilities needed to develop a solution; and students design and construct an artifact displaying the culmination of their learning.

The rapid development of low-cost, easy-to-use digital fabricators has allowed schools to adopt these advanced manufacturing machines in many classrooms (Bull & Groves, 2009). Digital fabrication is being used to promote higher order thinking and problem-solving skills in middle school students by allowing students to conceptualize an idea and then realize the idea in a physical form (Bull & Groves).

Framework

Conceptual change takes place when a student changes a belief to align with scientific evidence. Students do not arrive in the classroom with empty minds but with a complicated structure of beliefs and understandings built upon years of experience. It is part of a teacher’s responsibility to help the student re-organize this complex structure (Vosniadou, 2008; Vosniadou, Vamvakoussi, Skopeliti, & Vosniadou, 2008).

Posner, Strike, Hewson, and Gertzog, (1982) identified conditions that can cause a conceptual change in students. First, the students must be unsatisfied with their current understanding, then new knowledge is introduced in an understandable and plausible manner. Conceptual change may happen naturally or it may happen purposefully (Vosniadou, Vamvakoussi, Skopeliti, & Vosniadou, 2008). Thus, causing a conceptual change in students requires them to confront their misconceptions and then be scaffolded in the restructuring of their cognitive framework (Vosniadou, 2008).

Although conceptual change cannot be directly measured, it may influence variables such as learning and achievement. Thus, conceptual change has been operationalized as a transformation in students' knowledge (Clement & Vosniadou, 2008; Vosniadou, Vamvakoussi, Skopeliti, & Vosniadou, 2001; Vosniadou, 2008). In this study, conceptual change will be measured using a pre- and post-test assessment in conjunction with direct observations and interviews.

Research Question

This study focuses on the building of objects using the FabNet Solenoid Invention Kit and its potential for learning science concepts related to E&M among middle school students. The following research question guided this study:

How does building objects using the FabNet Solenoid Invention Kit promote conceptual understanding of electricity and magnetism in middle school students?

Methods

Participant Selection

The 30 students selected to participate in this research were chosen through purposeful sampling (Patton, 2002). Students were chosen from the Lab School which is implementing project-based learning environments through the use of the FabNet Invention Kits. The Lab School offered a diverse student selection and unique perspectives from which to observe the phenomena.

Study Setting

The setting for this research is Buford Middle School, a partner in the Laboratory School for Advanced Manufacturing. Buford includes students in grades seven and eight and is the only middle school available in a small city. In 2015 the school enrolled 507 students and employed 45 classroom teachers. Just under 40% of the students are Caucasian, 37% are African-American, 11% are Hispanic, 6% are Asian, and the remainder is of other ethnicities. Approximately 53% of Buford's middle school students are eligible for free or reduced lunch (National Center for Education Statistics, 2015).

Design of the Study

This study executed a quasi-experimental design with a one group pre-test/post-test design (Campbell & Stanley, 1966). This study took place during the spring and fall semesters of 2016 and uses pre- and post-test data to study the students as they experienced the FabNet Solenoid Invention Kit. After completing the pre-test, students engage in five labs and two make activities over the course of two to three weeks.

Data Sources

Pre-test and post-test data are collected through an online assessment tool developed using Google's form engine. Questions were developed as formative assessment items to provide insight on how effective the modules were, and so are specific to the solenoid kit. Below is a screenshot of the assessment form used in the study (Figure 1).

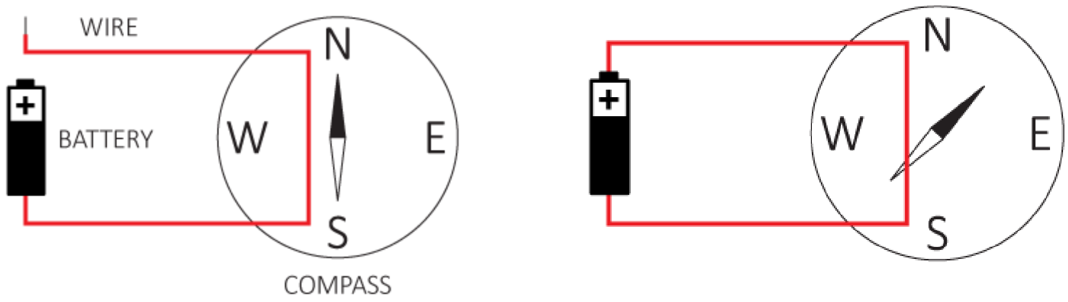


Figure 1. Assessment question.

Intervention

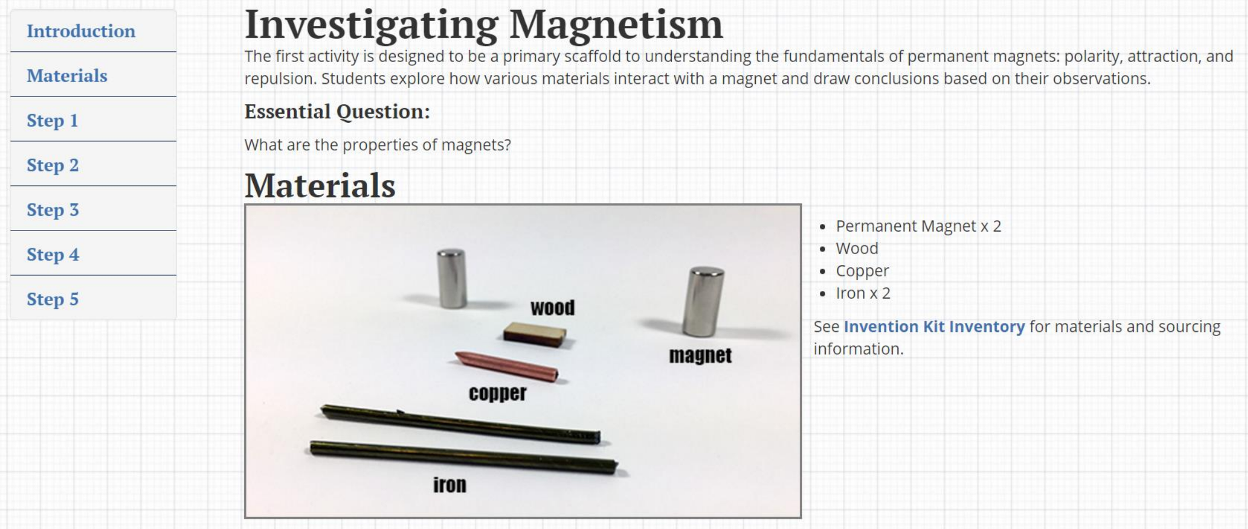
The FabNet Solenoid Invention Kit was implemented in an eighth-grade engineering course. The Solenoid Invention Kit teaches students how electricity generates a magnetic field through building a solenoid, a basic electromagnetic device used in everyday items. The scientific concept is Faraday's Law of Induction, which states an electrical current flowing through a conductive wire will generate a magnetic field, and similarly, a moving magnetic field in the presence of a conductive wire will generate an electrical current. Elementary E&M properties are introduced: conductive, non-conductive (insulator), magnetic (ferrous), non-magnetic materials, current, and voltage.

In order to not overload eighth-grade students, the unit scaffolds these concepts and addresses only elementary properties of Faraday's law. The key concepts we are looking for students to learn about are:

1. An electrical current flowing through a conductive wire generates a magnetic field around the wire (electromagnet).
2. The direction of the electrical current determines the direction of the magnetic field (right-hand rule).

3. Magnetic (ferrous) materials are attracted to a magnetic field, and non-magnetic (non-ferrous) are not attracted to a magnetic field.
4. Permanent magnets repel matching poles and attract opposite poles of electromagnets (and other permanent magnets).

The Solenoid Invention Kit uses a combination of platforms for delivering instructional content and assessments. Currently, all the instructional content is delivered via the maketolearn.org/invention website (Figure 3). This website uses the modern HTML5 blend of technologies – HTML, CSS, JavaScript – to create the learning modules.



Investigating Magnetism

The first activity is designed to be a primary scaffold to understanding the fundamentals of permanent magnets: polarity, attraction, and repulsion. Students explore how various materials interact with a magnet and draw conclusions based on their observations.

Essential Question:

What are the properties of magnets?

Materials

- Permanent Magnet x 2
- Wood
- Copper
- Iron x 2

See **Invention Kit Inventory** for materials and sourcing information.

Figure 2. Screenshot of FabNet Solenoid Invention Kit website.

Labs and Make Activities

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, the radio, the 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 FabNet Invention Kit series. Using five labs and two make activities (Table 1), students discover, explore, and interact with these principles while following in the footsteps of these early inventors.

Table 1.

Solenoid Invention Kit sequence.

Activities	Essential Questions / Skills
Exploring Magnetism	What are the properties of magnetism?
Investigating Conductivity	What are the properties of electricity?
Detecting Magnetic Fields	What is the relationship between electricity and magnetism?
Exploring Electro-magnetism	What are the properties of an electromagnet?
Investigating Solenoids	What are the relationships between solenoids and modern-day inventions?
Making a Continuity Tester	Electronics, Soldering
Making a Solenoid	3D Modeling, 3D Printing

Lab 1. The first lab is primarily a scaffolding activity and is designed to help students understand the fundamentals of permanent magnets: polarity, attraction, and

repulsion. Using manipulatable artifacts, students explore how various materials interact with a magnet and then conclusions based on the results of their experimentation.

Make activity. In the first make activity, students construct a simple continuity tester using a battery, a light-emitting-diode, and two sections of insulated wire. Students learn the skill of soldering electrical components together and can use this device to investigate the conductivity of different materials in subsequent labs and kits.

Lab 2. The second laboratory activity explores the fundamentals of conductivity, voltage, current, and resistance. Students use the conductivity test built in the previous make activity to investigate the conductivity of different materials.

Lab 3. The third lab activity introduces students to the connection between electricity and magnetism by reenacting Hans Oersted's original discovery by placing a compass adjacent to a current-carrying wire. This activity is foundational in the sequence of the FabNet Invention Kits and is used in many later inventions.

Lab 4. The fourth lab activity extends the concept of electromagnetic force to the study of solenoids. Students coil a wire and study how this strengthens the magnetic field generated.

Make activity. In the second make activity, students construct a solenoid consisting of a 3D printed tube and enameled copper wire to explore the properties of electromagnetism. This activity can serve as an introduction to computer-aided design (CAD) and computer-aided manufacturing (CAM).

Lab 5. The fifth lab activity facilitates the investigation of electromagnetism using solenoids. Students use ferrous material (iron) and permanent magnets to explore their interactive properties with an electromagnet. Students develop an understanding of electromagnetism that they can then apply to future projects.

Results

A mathematics teacher, a science teacher, a mathematics educator, and an electrical engineer comprised the team that reviewed the responses to each assessment. The team began by formulating an ideal answer to each question and deriving a rubric from that answer. The four raters scored each answer separately and then met to discuss their ratings. A consensus was reached on most responses but not all. When consensus could not be reached the 4 scores were averaged to provide a final rating.

Question One

The first example of the effectiveness of the FabNet Solenoid Invention Kit on middle school students' conceptual understanding of basic electromagnetism is given below. Students answered the following question prior to and following the completion of the kit (refer to Figure 4): What is the best explanation of why the compass needle moved?

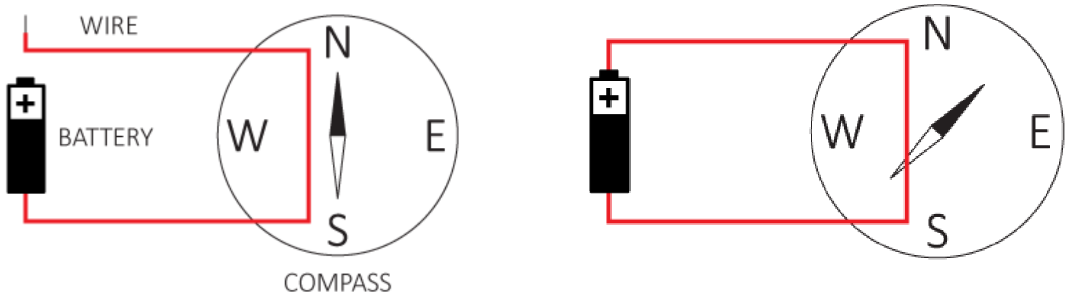


Figure 3. Wire disconnected from a battery, over a compass, and wire connected to a battery, next to a compass.

Rubric. The raters agreed the ideal response should incorporate the concept that current flowing through a wire creates a magnetic field that causes the compass needle to deflect. Based on this answer the raters created a four-point rubric (see Table 2). Example student responses and the code applied by the raters is also provided (see Table 3). “Pre” and “post” in parenthesis following each example response indicates whether the example was taken from a pre-test response or a post-test response.

Table 2.

Question one coding rubric.

Rating	Guide
0	Blank answer or does not demonstrate any conceptual understanding
1	Answer incorporates concept of current or magnetic field in partiality
2	Answer appropriately incorporates concept of magnetic field
3	Good conceptual understanding with no incorrect ideas

Table 3.

Coded student responses

Rating	Student Response
0	The battery is powering the compass so the battery is moving it (pre)
1	The current traveling through the wire attracts the compass needle to the battery (pre)
2	It moved because when the circuit is connected the electrons that flow through the wire and give off a magnetic field (post)
3	The best explanation is that the wire gives off a magnetic field when connected to the battery. The needle moved because the wire was above it with its magnetic field and the needle is a magnet so it would move around as if the wire was a magnet as well (post)

Outcomes. The pre-Invention Kit mean score was 0.38 out of 3 while the post-Invention Kit mean score was 2.16. Overall the raters felt that prior to the implementation of the Invention Kit three-quarters of the participants were unable to demonstrate any understanding of the phenomenon. After completing the Invention Kit three-quarters of these students demonstrated good understanding. On the pre-test some general misconceptions were evident. Several students attribute the movement of the compass needle to the battery. Others describe the compass as an object that can be turned on and off. When the compass is on the needle moves but when the compass is off the needle stays in place. None of these misconceptions persisted on the post-test. The incorrect answers are generally attributable to an inability to use language and vocabulary to appropriately describe the phenomena.

Table 4.

Outcomes from question one.

Score	Rating	Pre-Test	Post-test
<1	No Understanding	22	2
>=1, <2	Limited Understanding	6	5
>=2	Good Understanding	2	23

Positive examples. Following are a few examples of positive conceptual changes from pre-test to post-test (see Table 5). A positive outcome was regarded as a response that received a higher rating in the post-test than the same student's response in the pre-test.

Table 5.

Examples of positive outcomes.

Pre-test Response	Post-test Response
because when connected the	The electrons moving through the wires create a magnetic field that attracts or repels the compass needle. You could even put a

battery makes a pull	battery on one side of a room and a really long wire connecting to the compass and the battery and the same thing would happen.
It created a magnet	The compass needle moves because the Electrical current running through the wire creates a magnetic field. The south pole created by the magnetic field repels the north pole of the compass

Question Two

The second question tests the students understanding of how coiling a wire strengthens the magnetic field generated by the current-carrying wire. Students answered the following question prior to and following the completion of the kit: (refer to Figure 5) Assume the length of the coiled wire is equal to the length of the straight wire. Once the coiled wire is connected to the battery, how will the deflection of the compass needle compare to the deflection of the non-coiled wire?

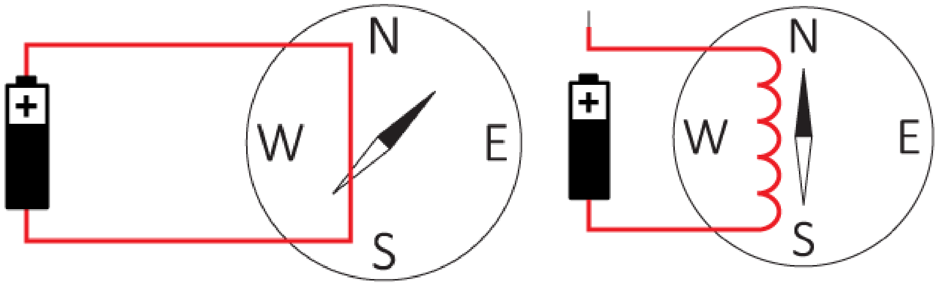


Figure 4. Wire connected to a battery, over a compass and a coil of wire disconnected from a battery, over a compass

Rubric. The raters agreed the ideal response should incorporate the concept that coiling the wire concentrates the magnetic field, creating a stronger magnetic force which will move the compass needle farther faster. Based on this answer the raters created a three-point rubric (see Table 2).

Table 6.

Question two coding rubric.

Rating	Guide
0	Blank answer or does not demonstrate any conceptual understanding
1	Answer incorporates the concept of coiled wire creating stronger magnetic force or moving the compass needle farther faster.
2	Answer appropriately incorporates the concept a coiled wire concentrating the magnetic field, creating a stronger magnetic force which will move the compass needle farther faster.

Example student responses and the code applied by the raters is also provided (see Table 7). “Pre” and “post” in parenthesis following each example response indicates whether the example was taken from a pre-test response or a post-test response.

Table 7.

Coded student responses

Rating	Student Response
0	the coil will give the same effect of the wire (pre)
1	It will pull stronger because the wire will be more tightly wound (pre)
2	The coil of wire shown will have a stronger magnetic force than the others. The compass needle will go towards the twisted wire in greater length than the straight wire.

Outcomes. The pre-Invention Kit mean score was 0.17 out of 2 while the post-Invention Kit mean score was 1.13. Overall the raters felt that prior to the implementation of the Invention Kit almost none of the participants were able to demonstrate an understanding of the phenomenon. After completing the Kit, two- thirds of these students demonstrated good understanding. On the pre-test some general misconceptions were evident. Several students that despite the coiled wire nothing would change in the behavior of the compass needle. Other students described how the coiling of the wire would slow the electricity down or break the circuit altogether. On the post-test both of these misconceptions persisted but in a much smaller number of students.

Table 8.

Outcomes from question two.

Score	Rating	Pre-Test	Post-test
<1	No Understanding	26	10
>=1, <2	Limited Understanding	3	6
>=2	Good Understanding	1	14

Positive examples. Following are a few examples of positive conceptual changes from pre-test to post-test (see Table 9). A positive outcome was regarded as a response that received a higher rating in the post-test than the same student's response in the pre-test.

Table 9.

Examples of positive outcomes.

Pre-test Response	Post-test Response
I really don't know.	The compass needle will move to the point at the wire quicker because a coiled wire gives more magnetic power.
It will have the opposite outcome.	When the wire is connected to the battery I think that the magnetic field will be stronger. Which means that the compass needle will be deflected farther away than in figure 2.

Negative examples. On this question, there was one student who received a rating on the post-test which was less than the rating the same student received on the pre-test (see Table 10). This example was agreed by the raters to be the result of the limitations of the question and the rubric combined. However, it was decided to keep the rating proscribed by the rubric for the sake of the validity of the study.

Table 10.

An example of a negative outcome.

Pre-test Response	Post-test Response
The deflection will be grater because of the coil of the wire is creating a strong magnetic field.	It will be greater than figure two it will probably be east.

Question Three

The third question tests the students understanding of what occurs when a piece of ferrous material is placed in close proximity to a solenoid and why. Students answered the following question prior to and following the completion of the Kit (refer to Figure 6): What will happen to the iron rod when the circuit is switched on? Explain why.

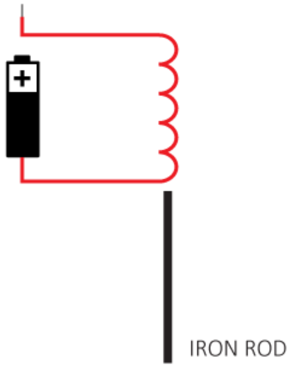


Figure 5. Iron rod, next to a coil of wire disconnected from a battery.

Rubric. The raters agreed the ideal response should incorporate the concept that the iron rod will be attracted to the coil of wire when the circuit switched is turned on. This is because the coil of wire becomes an electromagnet when the circuit is switched on (see Table 11).

Table 11.

Question three coding rubric.

Rating	Guide
0	Blank answer or does not demonstrate any conceptual understanding
1	The answer refers to the iron rod being attracted to the solenoid.
2	The answer refers to the coil of wire becoming an electromagnet when the circuit is switched on.

Example student responses and the code applied by the raters is also provided (see Table 12). “Pre” and “post” in parenthesis following each example response indicates whether the example was taken from a pre-test response or a post-test response.

Table 12.

Coded student responses

Rating	Student Response
0	I know that iron is a conductor but i don't know what will happen (pre)
1	It will move towards it (pre)
2	The iron rod will attract because the electromagnetic field will be turned on (post).

Outcomes. The pre-Invention Kit mean score was 0.07 out of 2 while the post-Invention Kit mean score was 1.23. Overall the raters felt that prior to the implementation of the Kit almost none of the participants were able to demonstrate an understanding of the phenomenon. After completing the Kit three-quarters of these students demonstrated good understanding (Table 13). On the pre-test students expressed the idea that the iron rod would simply become hot when the circuit was complete. Other students described the iron rod delivering an electrical shock if touched while the circuit was complete. Neither of these misconceptions persisted through the post-test. However, several students described the iron rod as developing north and south poles when the circuit was complete.

Table 13.

Outcomes from question three.

Score	Rating	Pre-Test	Post-test
<1	No Understanding	28	8
>=1, <2	Limited Understanding	2	7
>=2	Good Understanding	0	15

Positive examples. Following are a few examples of positive conceptual changes from pre-test to post-test (see Table 14). A positive outcome was regarded as a response that received a higher rating in the post-test than the same student's response in the pre-test.

Table 14.

Examples of positive outcomes.

Pre-test Response	**Post-test Response**
I know that iron is a conductor but I don't know what will happen.	The iron rod will suck into the coil. Iron is not a magnet but its attracted to magnets. Once the coiled wire (solenoid) and battery are connected the magnetic field is created which the iron is attracted to.
It will get an electrical charge.	It will shoot into the coil because it is attracted by the magnetic field. It doesn't matter which way it is turned because the iron rod does not have poles.

Negative examples. On this question, there were no negative outcomes to report.

Discussion

Results show a marked changed in the student's understanding of electricity and magnetism (E&M). On average 25 students received a rating of "No Understanding" on each of the pre-test questions whereas. These results are consistent with prior research cited previously indicating many children have alternative ideas regarding E&M. On the post-test, an average of six students received the same rating of "No Understanding". This positive difference is also consistent with prior research on the benefits of project-based learning.

After experiencing the hands-on approach provided by the Solenoid Invention Kit, 93 percent of the students identified that a magnetic field moved the needle. This was a considerable shift away from pre-test explanations which gave no mention of a magnetic field but instead indicated the battery, wire, or energy moved the needle. Sixty-seven percent of the students were able to explain the characteristics of an electromagnet when presented in the form of a coiled wire (solenoid). These students correctly described the strengthening of the magnetic field due to the coiling of the wire. The third concept students were asked to grapple with was the interactions that occur between a solenoid and a piece of ferrous material. Seventy-three percent of the students were able to correctly identify that the solenoid would attract the piece of iron when the circuit was complete.

Findings from this study are consistent with previous research indicating that authentic, technology-based and hands-on instruction help students' understanding of abstract concepts (Hayer & Papert, 1991; Ekmekci & Gulacar, 2014). The findings are also consistent with Mergendoller, Maxwell, and Bellisimo (2006) and ChanLin (2008) who found significant gains in students who engaged in project-based learning in science classrooms. Similar to findings from previous research (Hmelo, Holton, & Kolodner, 2000), by fabricating models of a scientific concept, students in this study demonstrated a deeper understanding of the science being studied.

This study was only able to use a small sample group of 30 students although the total number of participants was much larger. Only those students who attended the majority of class periods and were present for both the pre-test and post-test were included. Each participant attended the same city school. Future work should be conducted on a larger sample size, including students from various settings: rural, suburban, and urban school districts. Although the conceptual changes reported provide evidence of the positive impact of the FabNet Solenoid Invention Kit curricular unit, the possibility still remains that students without access to this Kit might have exhibited similar gains. Replication of this study including a suitable comparison group is needed.

Conclusion

The results of this study demonstrate the possible value of the hands-on project-based FabNet Solenoid Invention Kit to address electricity and magnetism concepts. The results of this study show that students responses demonstrated conceptual changes after completing the Invention Kit.

The FabNet Solenoid Invention Kit not only provides a more tangible way to address abstract concepts but engages students and facilitates a more comprehensive understanding of the electricity and magnetism. Student responses were more accurate and sophisticated after completion of the solenoid unit. This study also provides insight on how middle school students think about electricity and magnetism concepts. Further research is needed to study the replicability of this Kit.

References

Baser, M., & Geban, O. (2007). Effect of instruction based on conceptual change activities on students' understanding of static electricity concepts. *Research in Science & Technological Education, 25*(2), 243-267.

Baumgartner, E. & Zabin, C. (2008). A case study of project-based instruction in the ninth grade: A semester-long study of intertidal biodiversity. *Environmental Educational Research, 14*(2), 97-114.

Boaler, J. (1997). *Experiencing school mathematics: Teaching styles, sex, and settings.* Buckingham, UK: Open University Press.

Brush, T., & Saye, J. (2008). The effects of multimedia-supported problem-based inquiry on student engagement, empathy, and assumptions about history. *The Interdisciplinary Journal of Problem-based Learning, 2*(1), 21-56.

Bull, G., Chiu, J., Berry, R., Lipson, H., & Xie, C. (2014). Advancing children's engineering through desktop manufacturing. In J. M. Spector, M. D. Merrill, J. Elen, & M. J. Bishop (Eds.) *Handbook of research on educational communications and technology* (4th ed.) (pp 675-688). New York, NY: Springer.

Bull, G. & Groves, J. (2009). The democratization of production. *Learning and Leading with Technology, 37*(3), 36-37.

Bull, G., Haj-Hariri, H., & Nelson, A. (2014). The lab in the classroom: 3D printers in schools. *Make, 41*, 24-25.

Bull, G., Haj-Hariri, H., Atkins, R., & Moran, P. (2015). An educational framework for digital manufacturing in schools. *3D Printing and Additive Manufacturing, 2*(2), 42-49.

Carspecken, P. F. (1997). Reform and resistance in schools and classrooms: An ethnographic view of the coalition of essential schools. *American Anthropologist, 99*(2), 418-419.

ChanLin, L. J. (2008). Technology integration applied to project-based learning in science. *Innovations in Education and Teaching International,45*(1), 55-65.

Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences, 14*(2), 161-199

Chiu, J. L., Bull, G., Berry III, R. Q., & Kjellstrom, W. R. (2013). Teaching engineering design with digital fabrication: Imagining, creating, and refining ideas. In C.

Mouza & N. Lavigne (Eds.), *Emerging Technologies for the Classroom* (pp. 47-62). New York, NY: Springer-Verlag.

Clement, J. (2008). The role of explanatory models in teaching for conceptual change. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 417-452). New York, NY: Routledge

Creswell, J. W. (1998). *Qualitative inquiry and research design: Choosing among five designs.* Thousand Oaks, CA: Sage Publications

Dickinson, G., & Jackson, J. K. (2008). Planning for success. *The Science Teacher*, *75*(8), 29.

Doppelt, Y. (2009). Assessing creative thinking in design-based learning. *International Journal of Technology Design in Education, 19*(1), 55–65.

Ekmekci, A., & Gulacar, O. (2015). A case study for comparing the effectiveness of a computer simulation and a hands-on activity on learning electric circuits. *EURASIA Journal of Mathematics, Science & Technology Education, 11*(5).

Expeditionary Learning Outward Bound (1999). *Early indicators from schools implementing New American Schools designs*. Cambridge, MA: Expeditionary Learning Outward Bound.

Fredette, N., & Lochhead, J. (1980). Student conceptions of simple circuits. *The Physics Teacher*, *18*(3), 194-198.

Gallagher, S. A., Stepien, W. J., & Rosenthal, H. (1992). The effects of problem-based learning on problem solving. *Gifted Child Quarterly*, *36*(4), 195-200.

George, P., Stevenson, C., Thomason, J., & Beane, J. (1992). *The middle school and beyond.* Alexandria, VA: Association for Supervision and Curriculum Development.

Hayer, I., & Papert, S. (1991). *Constructionism: Research reports and essays, 1985-1990*. New York, NY: Ablex Publishing.

Hmelo, C. E., Holton, D. L., & Kolodner, J. L. (2000). Designing to learn about complex systems. *Journal of the Learning Sciences*, *9*(3), 247-298.

Holm, M. (2011). Project based instruction: A review of the literature on effectiveness in prekindergarten. *Rivier Academic Journal*, *7*(2), 1-13.

Krajcik, J. S., Czerniak, C. M., Czerniak, C. L., & Berger, C. F. (2002). *Teaching science in elementary and middle school classrooms: A project-based approach*. New York, NY: McGraw-Hill.

Livingston, A. (2008). *The Condition of Education 2008 in Brief (NCES 2008-032).* Washington DC: National Center for Education Statistics.

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

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*, *1*(2), 5.

Mioduser, D., & Betzer, N. (2003). The contribution of project-based learning to high-achievers' acquisition of technological knowledge and skills. *International Journal of Technology and Design Education, 18*, 59-77.

National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. (2011). *Rising above the gathering storm revisited: Rapidly approaching category 5.* Condensed version. Washington, DC: The National Academies Press.

National Center for Education Statistics, U.S. Department of Education. (2015). Retrieved February 24, 2016, from https://nces.ed.gov

National Governors Association. (2007). *Innovation America: A final report*. Washington, DC: Author.

National Research Council (2009). Katehi, L., Pearson, G., & Feder, M. (Eds.). *Engineering in K-12 education: Understanding the status and improving the prospects committee on K-12 engineering education*. Washington, DC: The National Academies Press.

National Science Board. (2007). *National action plan for addressing the critical needs of the U.S. science, technology, engineering, and mathematics education system*. Arlington, VA: National Science Foundation.

Patton, M. Q. (2002). Qualitative interviewing. *Qualitative research and evaluation methods*, *3*, 344-347.

Posner, G., Strike, K., Hewson, P., and Gertzog, W. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211–227.

President's Council of Advisors on Science and Technology (PCAST). (2010). *Prepare and inspire: K-12 education in science, technology, engineering, and math (stem) for America's future.* Washington, DC: Executive Office of the President.

Silk, E. M., Schunn, C. D., & Strand Cary, M. (2009). The impact of an engineering design curriculum on science reasoning in an urban setting. *Journal of Science Education and Technology, 18*, 209-223.

Thomas, J. W. (2000). A review of research on project-based learning. Retrieved from http://www.ri.net/middletown/mef/linksresources/documents/researchreviewPBL_070226.pdf

Thomas, J. W., Mergendoller, J. R., & Michaelson, A. (1999). Project-based learning for middle school teachers. *Middle School Journal, 36*(2), 28-31.

Tretten, R. & Zachariou, P. (1995). *Learning about project-based learning: Assessment of project-based learning in tinkertech schools*. San Rafael, CA: The Autodesk Foundation.

Vosniadou, S., Vamvakoussi, X., & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.). *International Handbook of Research on Conceptual Change*. New York: Routledge.

Woolley, M.E., Strutchens, M.E., Gilbert, M.C., & Martin, W.G. (2010). Mathematics success of black middle school students: Direct and indirect effects of teacher expectations and reform practices, *The Negro Educational Review, 61*, 41-60.

Yin, R. K. (2008). *Case study research: Design and methods* (Vol. 5). Thousand Oaks, CA: Sage Publications.

Manuscript 3

A Case Study of Two Middle School Teachers Implementing the FabNet Invention Kits

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ABSTRACT

This study follows two middle school teachers as they implement hands-on learning using the FabNet Invention Kits. The teachers planned and taught the Solenoid Invention Kit, the Linear Motor Invention Kit, and the Linear Generator Invention Kit. This article reports on the common strategies and practices employed by the two teachers. The commonalities emerged through cross-case analysis of the data from both teachers. Data sources include formal interviews, informal interviews, and direct observations of each teachers' classroom practice.

Introduction

This study follows two teachers as they implement a project-based learning environment in their classrooms using the FabNet Invention Kits. There are many facets of project-based learning which can be difficult for a teacher. These include organizing and facilitating small group collaboration and learning, classroom management, time management, incorporating standardized learning objectives, technology utilization, and classroom safety.

This study documents the successes, failures, and challenges these two teachers faced and will benefit teachers who are practicing PBL now and teachers who will be practicing PBL in the future. This study also informs school leaders on the challenges faced and support needed by teachers who are implementing this pedagogical strategy.

Background

Enabling students to reason and problem solve is one of the key elements in successful teaching (Chinn & Malhotra, 2002). Traditionally, however, educators have used pedagogical methods such as lectures, readings, worksheets, and demonstrations to impart facts and rudimentary skills to students (Silk, Schunn, & Strand Cary, 2009). A large reason for this approach is the current format of the majority of textbooks. These textbooks place inquiry in a section or chapter all alone absent the content and context for which it was designed (Silk, Schunn, & Strand Cary).

Furthermore, when textbooks do attempt to include inquiry practices in everyday learning, it is done in a recipe format that precludes any reasoning and problem solving and thus is devoid of the challenges a student might face (Germann et al., 1996). Most of these textbooks conduct a single experiment for a single concept and rarely allow students to produce multiple experiments for multiple hypotheses that would allow for a much deeper and richer knowledge of the concept being studied (Chinn & Malhotra, 2002). The step-by-step instructions which eliminate much of the purpose of inquiry make it very difficult for students to develop conceptual understanding and lead to very little content literacy (Silk, Schunn, & Strand Cary, 2009).

A study by Horwitz (1995) found this type of theoretical knowledge alone did not provide students with the skills necessary to translate that knowledge into solving real-world problems. Horwitz provides the example of high school students who scored well on question-and-answer tests of electrical circuits but could not build or troubleshoot physical circuit models. Building, testing, and refining real artifacts can close the gap between theoretical and applied knowledge and increase scientific understanding. The National Research Council (2011) purports that a classroom should be an environment in which more emphasis is given to knowledge that is useful. Project-based learning (PBL) is an approach that offers the ability for teachers to implement the NRC's recommendation. It provides students the opportunity to explore concepts through the construction of models in a relevant context (Silk, Schunn, & Strand Cary, 2009).

Laboratory School

John Dewey established the first laboratory school in 1896, founded in a collaboration between faculty at the University of Chicago and local educators, students, and parents. Since then, approximately two dozen laboratory schools have been established in the United States. They are designed to serve as testing grounds for the development of effective educational practices.

In 2013, the Laboratory School for Advanced Manufacturing (Lab School) was established as a joint venture by the University of Virginia's Curry School of Education and School of Engineering and Applied Science in collaboration with the Charlottesville City Schools and the Albemarle County Public Schools (Bull, Haj-Hariri & Nelson, 2014). Model facilities for integration of emergent technologies into the K-12 curriculum were established at Buford Middle School and Sutherland Middle School. In addition, a K-12 Design Laboratory was established to support this effort in the School of Engineering and Applied Science at the University of Virginia. The goal of the Lab School is to identify and develop effective educational practices for use of advanced manufacturing technologies in K-12 schools (Bull, Haj-Hariri, Atkins, & Moran, 2015).

The Lab School explores the integration of project-based learning and advanced manufacturing technologies into the curricula. Advanced manufacturing technologies offer students the opportunity to learn about curricula content through the experience of seeing their ideas realized in form of physical artifacts (Bull & Groves, 2009; Chiu, Bull, Berry, & Kjellstrom, 2012).

FabNet Invention Kits

The Lab School is currently collaborating with the Smithsonian Institution of American History to tell the story of America's history through the lens of invention. Twelve transformational inventions span the nation's history from 1800 through 1960. These inventions include the electric motor, the telegraph, the telephone, the radio, and other key inventions that were inflection points in the nation's history.

The FabNet Invention Kits are open source, digital resource packages which include 3D models of the inventions from the Smithsonian collections, instructional guides, historical primary and secondary sources, and support materials for teachers and students. The goal for the students is not to create an exact physical replica of inventions, but to reinterpret and reinvent a fully-functioning device using low-tech and advanced manufacturing technology. The ultimate objective is to inspire and inform a new generation of problem solvers and to underscore the power that fundamental science and engineering principles can bring to executing new ideas.

The FabNet Invention Kits utilize project-based learning (PBL) as a pedagogical framework. In PBL and the Invention Kits, projects are the catalyst around which learning is centered. Using driving questions and real life problems, complex projects challenge students to problem solve for solutions. This is done through scientific inquiry, peer collaboration, and individual and group research. Over a period of time, students design, prototype, test and refine products that meet project guidelines (Thomas, Mergendoller, & Michaelson, 1999).

As advanced manufacturing technologies have decreased in price, many individual teachers are purchasing them for use in their classrooms. Innovative work is emerging from the classrooms of these forward-thinking educators (Bull, Chiu, Berry & Lipson, 2013). But just as the power of computers is amplified when they are networked in an integrated system, the potential of advanced manufacturing technologies is enhanced when coordinated choices are made by educational leaders in schools.

Literature Review

Traditional methods of teaching are deductive; that is, they begin with a theory or formula and progress towards the application of the theory or formula. An alternative to this method is inductive teaching. The inductive method begins with some problem or observation while the theory or formula is discovered and taught as the need arises (Prince & Felder, 2006). Instead of learning content for some future purpose, students are motivated to learn because they themselves perceive the need to know (Albanese & Mitchell, 1993).

Project-based learning (PBL) is an inductive, student-centered pedagogy that uses projects to drive student learning (Mergendoller, Maxwell, & Bellisimo, 2006). Researchers have purported project-based learning to be more effective in improving problem-solving skills and critical thinking than traditional teaching methods (Mergendoller, Maxwell, & Bellisimo, 2006; ChanLin, 2008). Frequently utilized to enhance student learning in medical disciplines, PBL is now being implemented in elementary and secondary classrooms (Holm, 2011).

Encouraging students to learn through contextual and practical projects is one of the goals of PBL. By situating learning within a real-world problem, PBL projects engage students in problem-solving practices similar to what professionals do in industry. Lectures, whole-class discussions, and seatwork are mostly absent in PBL with students working autonomously or in small groups (Mergendoller and Thomas, 2000).

Project-based learning has several key features (Krajcik, Czerniak & Berger, 2003; Dickinson & Jackson, 2008): PBL units are framed by a driving question. The driving question guides students as they engage in meaningful and contextual exploration; all members of the learning community collaborate in problem solving; students are guided so as not to flail at a solution. Concepts and skill are scaffolded to give students the abilities needed to develop a solution; and students design and construct an artifact displaying the culmination of their learning.

Students participating in PBL classes have demonstrated positive gains in important areas. These gains include higher scores on content assessments as compared to students in traditional classrooms (Mioduser & Betzer, 2003). Students also demonstrated an ability to transfer knowledge gained in a PBL environment to other tasks (Boaler, 1997). Problem solving, critical thinking, and peer collaboration are skills which students engaged in PBL have demonstrated significant gains (Mergendoller, et al., 2006; ChanLin, 2008). Further, students' engagement (Brush & Saye, 2008), creative thinking (Doppelt, 2009), investigative skills (Baumgartner & Zabin, 2008), and learning confidence (Tretten & Zachariou, 1995) have all been shown to improve within a PBL environment. These positive gains make PBL an attractive methodology for teachers to enact in their classrooms.

However, project-based learning environments can be challenging for teachers to implement. They can feel overwhelmed by the scope of the projects and by the time-consuming nature of the units (Marx, Blumenfeld, Krajcik, & Soloway, 1997). Learning and incorporating new pedagogy, classroom management, and technology is difficult and assessing PBL units in an authentic manner can be challenging (Doppelt, 2009).

An added challenge comes from the FabNet Invention Kits, which while utilizing the PBL framework, offer many opportunities to interact with advanced manufacturing technologies such as 3D printers, 2D die-cutters, and laser cutters in the classroom. This presents teachers with the need to master the content covered by the kits, the pedagogical strategies required by PBL, and also the appropriate use of technology. The technological pedagogical and content knowledge (TPACK) framework can be used as a guide to study how teachers implement project-based learning environments with technology in their classrooms. TPACK is based on the acceptance that teaching is highly complex, requires many diverse types of knowledge (Mishra & Koehler, 2006), and requires access to a vast and complicated knowledge system (Shulman, 1986, 1987). These systems include knowledge of student thinking and learning, and knowledge of subject content (Mishra & Koehler, 2006).

One of the more challenging skills a teacher must have in this diverse and technologically advanced educational society is the ability to properly and effectively implement technology into the classroom (Mishra & Koehler, 2006). Many teachers are unaware of how to effectively integrate technology into their curriculum because they did not experience effective integration as students (Niess, 2011). Instruction typically approaches technology integration in a technocentric way, focusing on the affordances and constraints of particular technologies, instead of focusing primarily on the curriculum content (Niess, 2011; Papert, 1987). As evident from the insufficient and inconsistent instances of technology integration in K-12 schools, these methods are creating unsatisfactory results (Harris, Mishra, & Koehler, 2009).

The TPACK framework is a way of thinking that allows a teacher to integrate the when, where, and how of their curricula into effective teaching strategies using technology to enhance student learning (Niess, van Zee, & Gillow-Wiles, 2011; Shavelson, Ruiz-Primo, Li, & Ayala, 2003). Abbitt defines TPACK as “a conceptual model for the knowledge that supports effective technology integration into classroom teaching practices” (2011, p. 135). The TPACK framework offers the science teacher a new way of thinking about technology integration, one that directs focus towards the convergence of content knowledge, pedagogical knowledge, and technological knowledge to find a better way of teaching than the current practices associated with technology integration.

It is a constant struggle for the teacher to effectively integrate technology into the classroom and failure to do so is to the detriment of both teacher and learner (Valanides & Angle, 2005). Mishra and Koehler (2006) stress the importance of realizing that no one body of knowledge operates singularly from another. Content can be jointly considered and synthesized and then employed effectively (McGrath, Karabas, & Willis, 2011). Learning is not a tool for technology, but technology must be a tool for learning (Niess, 2011).

Conceptual Framework

The TPACK framework is the foundation for good teaching and requires the educator to have an understanding of appropriate pedagogy to use in the classroom (Mishra & Koehler, 2006). TPACK is a framework which encompasses the complex nature of technology, pedagogy, and content knowledge. Teachers' content knowledge encompasses more than a mere understanding of the subject matter. Teachers must also know the nature of the content they are teaching including the common misconceptions students bring to the classroom when learning the content.

A clear understanding of the best teaching strategies to use is paramount to successful teaching and learning. In this study, interviews and observations will be used to capture a more complete understanding of what is required of a teacher implementing a PBL environment using the FabNet Invention Kits.

Research Question

How do teachers implement a project-based learning environment using the FabNet Invention Kits?

Methods

Selection of the Teachers

The two teachers, each from a different school, were selected to participate in this research through purposeful sampling (Patton, 2002). Each teacher is implementing project-based learning environments through the use of the Smithsonian Invention Kits. Both teachers are well respected for their educational acumen in their respective schools and divisions.

The schools in which the teachers work are diverse and require different pedagogical and classroom management approaches and thus each provides unique perspectives from which to observe the phenomena. Both teachers have shown a strong interest in participating in this research. Having worked with both teachers, I believe they provide an in-depth understanding of the process a teacher must go through in the implementation of a project-based learning environment through the use of the FabNet Invention Kits.

Design of the Study

This study used case study methodology (Merriam, 1998; Yin, 2008) to examine the process the two teachers use in the implementation of project-based learning environments in their classrooms through the use of the FabNet Invention Kits. The purpose of a case study is to derive an in-depth understanding of a single case or a small number of cases set within their natural or real world context (Bromley, 1986; Creswell, 1998). The multiple case study design investigates more than one case to gain insight into a central phenomenon (Creswell, 2002). This case study took place during the 2016-2017 school year and combined field research (direct observations and in-depth interviews) along with written documents to study each teacher as they implemented the FabNet Invention Kits.

Validity

To ensure this short study is as valid as possible I utilized common qualitative research practices that enhance trustworthiness. These include comparing findings from observations with findings from interviews, member checking previous interviews and observations with the participants in subsequent interviews, and thoroughly dealing with any deviancies I find in the data (Yin, 2008).

Data Sources

In-depth interviews, direct observations, and informal interviews with the teachers were conducted throughout the school year (Carspecken, 1997; Patton, 2002). Each formal interview lasted approximately one hour and focused primarily on the teachers' experience, both past and present, as it relates to the phenomena being studied (Seidman, 2013).

The interview is composed of ten questions. Probing questions were used to enhance the depth of responses. Before each interview, the teachers were given a description of the research as well as an overview of the interview and were informed the interview would be audiotaped.

The first interview question asks the teacher about their professional background. Probing questions are about specific details such as how many schools they have worked in, what subjects and grades they taught, and how long have they held their current position. The next question asks about the teacher's experience teaching with technology, especially technologies associated with advanced manufacturing.

The third question is about the teacher's current classes and students. The fourth asks them about how long they have been employed at their current school. Probes include if they have any other responsibilities other than teaching. The next question asks the teachers to describe a typical lesson they teach. Probing questions ask about planning and preparation resources and student assessment.

The sixth question asks the teachers to describe the expectations their administration places on them. Probes include how these expectations are communicated. The seventh question asks the teachers if they are actively attempting to change how teaching and learning occur in their classroom. The eighth question asks the teachers about the technology they use and to describe an episode in which they did so. Probing questions included what the goals and objectives were, how the students were assessed, and what, if any, artifacts were produced.

The ninth question asks the teachers to describe the challenges they have faced implementing technology and how they overcame those obstacles. The final question is regarding the professional development the teachers received. Probing questions are about the adequacy of the professional development and how the teachers would improve it if possible.

The teachers were observed throughout the school year. These direct observations were conducted during scheduled courses implementing PBL using the Invention Kits. Any critical events identified during the duration of this study were also documented and observed where possible. These observations were used to identify how the teachers' expertise and knowledge were put into practice. These observations also guided the informal interview questions (Carspecken, 1997).

Results

Data associated with each case (teacher) was coded separately using thematic analysis (Stake, 2006). Coded data was bracketed from surrounding data but was not removed from its context during this phase (Bryman, 2006). Resulting codes were organized into themes and sub-themes using an iterative and inclusive process. A cross-case analysis was conducted in a variable-oriented strategy using all themes from the single cases analysis (Denzin & Lincoln, 2005).

Case One: Gary

Gary's educational background is in systems engineering. When he became a teacher he chose to teach math for Teach for America. He now teaches engineering at Buford Middle School. Buford Middle School includes students in grades seven and eight and is the only middle school available in a small city. In 2015, the school enrolled 507 students and employed 45 classroom teachers. Just under 40% of the students are Caucasian, 37% are African-American, 11% are Hispanic, 6% are Asian, and the remainder is of other ethnicities. Approximately 53% of Buford's middle school students are eligible for free or reduced lunch (National Center for Education Statistics, 2015).

Environment

The physical layout of the Buford engineering classrooms is different than other more traditional classrooms in the school. At Buford, the engineering class occurs in a suite of rooms. The first of which is a computer lab. In this space, there are four large worktables in the center of the room. There are twelve computer workstations spread about the room. In addition to the computers, there is one large 3D printer, five digital die cutter fabrication machines, one network inkjet printer, and one large interactive display. Sutherland Middle School does not have a dedicated computer lab. Instead, it relies on the individual laptops that each student is given.

Buford has an engineering/science lab. These rooms are filled with glass windows to let as much natural light in as possible. At Buford, this space has six large worktables with four chairs per table. Around the walls of the space, there are many plastic bins on shelves. These are project bins for each student in the class. Additionally, there are whiteboards at the front of the room and a large interactive display next to the whiteboards.

Finally, Buford has a small room towards the back of the lab which they call the fabrication lab. You can see into fabrication lab from the engineering/science lab through a large glass window in the wall. The fabrication lab contains hand tools, raw materials, lab equipment, and digital fabrication tools. There are two laser cutters along with the filters to clean the exhaust from the laser cutter as it burns materials. 3D printers line a workbench on one side of the room. Opposite the 3D printer is an electronics workbench with soldering irons, student projects, hand tools, and scraps of paper. There is a whiteboard above the soldering stations which contain notes on various projects and the stages each is at.

Content

The content knowledge level of the teacher is critical to student learning. During the 2016-2017 school year, Gary used three FabNet Invention Kits in his engineering courses. They were the Solenoid Invention Kit, the Linear Motor Invention Kit, and the Linear Generator Invention Kit. All three kits can be found at *www.maketolearn.org/invention-kits*. A brief outline of the Solenoid Invention Kit follows and I encourage the reader to view each of the Invention Kits in their entirety using the website address provided.

The FabNet Solenoid Invention Kit teaches students how electricity generates a magnetic field through building a solenoid, a basic electromagnetic device used in everyday items. The scientific concept is Faraday's law of induction; which states an electrical current flowing through a conductive wire will generate a magnetic field, and similarly, a moving magnetic field in the presence of a conductive wire will generate an electrical current. Elementary electricity and magnetism properties are introduced: conductive, non-conductive (insulator), magnetic (ferrous), non-magnetic materials, current, and voltage.

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, the radio, the 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 FabNet Invention Kit series. Using five labs and two make activities (Table 1), students discover, explore, and interact with these principles while following in the footsteps of these early inventors.

Table 1

Solenoid Invention Kit sequence.

Activities	Essential Questions / Skills
Exploring Magnetism	What are the properties of magnetism?
Investigating Conductivity	What are the properties of electricity?
Detecting Magnetic Fields	What is the relationship between electricity and magnetism?
Exploring Electro-magnetism	What are the properties of an electromagnet?
Investigating Solenoids	What are the relationships between solenoids and modern-day inventions?
Making a Continuity Tester	Electronics, Soldering
Making a Solenoid	3D Modeling, 3D Printing

Pedagogy

Gary ensures that students have ample opportunity to share their thoughts and understandings of the content being studied. For example, many interactions between Gary and the students begin with a broad question such as, “What is electromagnetism?” or “What is sound?” This is an example of Gary’s pedagogical content knowledge. He knows the content and what teaching strategies will maximize student learning in that context. Gary then allows time for the students to construct the answer themselves before directing them to resources that help refine their understanding.

Another example of Gary’s pedagogical strategy comes when a student asks a question. Common responses from him are, “I want you to try and figure it out on your own,” and “Why don’t we google what that means?”

Gary actively develops a learning environment that encourages students to be actively involved in the learning process. For example, Nick comes sits down next to Toby and Elijah. He engages in a dialogue with both students, asking them several questions about the design of their speaker parts and writes notes down on his paper before heading back to his project. Gary says,

> Somebody else in this class is working on the same project and likely has the same problem or question that you have. Go find somebody and Elijah, for example, could explain things just as well as I can. Malcolm (another student) has applied everything the way you're supposed to and kids can learn from that. That's something that students definitely need to be trained in because our school trains them the complete opposite way. That when you're stuck go to the teacher. This class is very counter-cultural that way.

At the beginning of each semester, Gary dedicates time to teaching the students how to conduct themselves in this learning environment. “Structure is really important and so at the beginning of the year I am really structured,” Gary says. For example, when students arrive they place their backpacks in a predesignated space. They then pick up their project bins and find their seats. As they sit they open up their notebooks write their name and the date in a particular spot. The first three to five minutes of every section look identical. Gary does this “So they can kind of build consistency and structure, particularly in low-income schools where consistency is really challenging.” This is an example of Gary’s pedagogical knowledge. He knows what type of environment he wants to create and that allows him to instruct students in a manner appropriate for his goals.

Once they have demonstrated discipline, Gary gives the students more freedom to choose how they structure the class time. “When they’ve demonstrated that they’re ready for more autonomy they get it,” Gary says. “Then they kind of freely move throughout the class. They can collaborate with whoever they need to.” For example, Brendan saw Sam walking around the outside of the classroom. Brendan asked, “Hey are you stuck?" Sam answered, “No. I'm just taking a short break.” “Sam has demonstrated that he is going to deal with the break capably,” Brendan states.

When teaching with the FabNet Invention Kits the projects the students build do not always work as intended the first time. “If you didn't do it right the first time, you're going to do it better the next time,” Gary says. For example, after Tom had finished constructing his speaker and was playing music Brendan asked him how he felt. “I messed up so many times,” Tom says and laughs heartily. Gary replies, “Mistakes are part of the process and are normal in this type of work.”

“Feedback is one of the more critical parts of learning so kids need a task and they need to perceive that they can do that task and they need feedback along the way,” Gary tells us. “I think that the best feedback that I found, doesn't necessarily come from a teacher, but from the physical world.” In conjunction with feedback from the physical world, Gary uses probing questions. For example, “How did you do that? And why is it working?” This is a critical part of Gary’s pedagogical content knowledge. He understands the content and knows what pedagogical strategy he wants to employ with the content. Combined he creates a learning environment that makes student learning effective.

Technology

When it came to teaching the students how to make use of the technology, one of Gary’s challenges was in finding a balance between how much scaffolding was needed.

> The challenge I think is when and where to front load CAD instruction or when and where to let them fail as they go. I've kind of done a combination. I’ve done some smaller chunked assignments and then when they want to learn new things for their actual speaker or their motor, they're going to learn a bunch through doing but they've at least had an introduction to it.

This demonstrated Gary’s technological pedagogical content knowledge. He was able match the content with the appropriate pedagogical strategy and then employ a technology effectively to support it.

There were times during the course of this study where the technology needed troubleshooting during class time. During one class period, Brendan and Toby go into the fabrication lab together to use the laser cutter. After the machine finishing cutting the artifact, Toby pulls out the sheet of material that was being cut. He cannot get his part to come out from the sheet of material because it did not cut all the way through. He tries to force it out and damages it in the process. Several minutes are required to troubleshoot and correct the issue.

Case Two: Chuck

Chuck’s educational background is in elementary education. After several years he transitioned to a middle school science teacher. He now teaches seventh and eighth-grade science at Sutherland Middle School. Sutherland Middle School includes students in grades six through eight and is one of three middle schools available in a large county. In 2015, the school enrolled 607 students and employed 41 classroom teachers. Sixty-nine percent of the students are Caucasian, 9% are Asian, 8% are African-American, 7% are Hispanic, and the remainder is of other ethnicities. Approximately 12% of

Sutherland's middle school students are eligible for free or reduced lunch (National Center for Education Statistics, 2015).

Environment

The physical layout of the Sutherland classroom implementing the FabNet Invention Kits is not very different than the other classrooms in the school. Sutherland Middle School does not have a dedicated computer lab. Instead, it relies on the individual laptops that each student is given. The classroom has four long tables that can accommodate at least eight students at each one. Around the walls of the classroom there are cabinets with sinks and various scientific equipment. Additionally, there is a whiteboard at the front of the room.

Finally, there is a small room towards at the back of the classroom which they call the Shark Tank. You can see into the Shark Tank from the classroom through a large glass window in the wall. The Shark Tank contains hand tools, raw materials, lab equipment, and digital fabrication tools. 3D printers line a wall in the room and across from them a workbench where students can use soldering irons and hand tools. At Sutherland, the laser cutter is housed in a separate room down the hall and is vented directly to the outside negating the need for a filter.

Content

During the 2016-2017 school year, Chuck used three FabNet Invention Kits in his science courses. They were the Solenoid Invention Kit, the Linear Motor Invention Kit, and the Linear Generator Invention Kit. All three kits can be found at *www.maketolearn.org/invention-kits*. A brief outline can be found in the first case study but I encourage the reader to visit the website in order to see the Kits in their entirety.

Pedagogy

Chuck thinks teacher facilitation is an important part of effective classroom instruction. When a student asks a question Chuck will often reply with, “I want you to figure it out on your own,” and “Why don’t we google what that means?” Chuck employs several strategies to help students work through challenges they encounter. These strategies range from using the internet, a fellow student, and notes from previous projects. These various strategies demonstrate Chuck’s pedagogical knowledge. Chuck says,

> Students learn, if they wait, that teachers give the answers. It's like a learned helplessness. What good is that going to do them? It was rare for me to give answers. All on purpose to have students develop their independence, but also gain strategies on how to find the answers when they don't know. I'd help them figure out those strategies, but I wouldn’t give out answers easily. I don't believe that teachers should be the keeper of knowledge anymore.

Chuck encourages each of his students to be actively involved in the learning process. He wants to teach them strategies that will help them become independent, life-long learners. He scaffolds this idea in his classroom by helping his students find answers using repositories other than the teacher.

At the beginning of each semester, the students must be guided in how to conduct themselves in this project-based learning environment. “I start the semesters off by giving the students a lot of freedom,” Chuck says. For example, when students arrive they can choose where to sit and who to sit with. They can create teams on their own and can switch teams if they choose to. However, if they misuse these privileges then Chuck steps in and makes some of those choices for them.

The FabNet Invention Kits often involve making artifact that do not work after the first iteration. “I always want them to take on failure as an okay thing,” Chuck says. He continues:

> Failure and mistakes are a very large component of these kits. Failing but never getting penalized for it. I've had kids turn in whole projects where not a single thing worked, but they could explain every bit of it. Even if they don't get to an end result, they've learned way more than if they had been doing something simple.

Chuck works to make failure a learning opportunity with the students whenever possible. By the end of the semester there was more interest than disappointment when an object failed to operate as predicted.

Chuck purposefully create activities where students must think beyond just getting an artifact to work. For example, when a group of students was successful in creating the linear motor from the FabNet Linear Motor Invention Kit, Robbie was there asking, “What did you discover? What needs improving?” This type of practice demonstrates Chuck’s pedagogical content knowledge. He knows what content he wants to introduce and chooses the appropriate pedagogy to encourage effective student learning.

Chuck encourages this type of thinking by writing the following guiding question for students working on the FabNet Linear Generator Invention Kit: “What is direct and alternating current?” Robbie says,

> I haven't taught either one. They don't know, and I know that most of them don't know what the difference is from pre-assessments. I go, I'm not going to tell you what either one means. As you're building it, I want you guys to start talking about it.

The students begin working to design and their generators. As they test and tinker several groups use the word direct and alternating in their conversations. Robbie says,

> I hear the discussions of how it could be one or the other. I'm listening and I'll ask a question or two depending on what's going on. Sometimes it's just a conversation of we're both observing things and pointing out things. I think that's the key, working with the kids, not instructing the kids.

Chuck is encouraging the students to think independently and create questions of their own accord.

Technology

Technology used in Chuck’s classroom offered its own set of challenges. One example comes from the use of the 3D printer. A student approaches Chuck during class and informs him that the 3D printer is not working. Chuck joins the student in the fabrication lab and determines the nozzle on the printer has become clogged. Chuck and the student work for several minutes removing the nozzle and cleaning out the clog. The student then restarts his print job. “This has happened a few times,” Chuck says. “The students are getting better at fixing this problem themselves but they still need help sometimes.”

Students often have not used the software required by the technologies used in Chuck’s classroom. Regarding his approach to teaching the students how to use the software he says,

> One of the ways I taught CAD would be to just show some basic tools. Then I would just say, make something. Usually what that results in about 30 minutes of the kids being completely lost and confused. Followed by the light bulbs clicking in their heads as things start all making sense. It's fascinating. Fifteen minutes of instruction, 30 minutes of chaos, then smooth sailing from there.

This approach demonstrates Chuck’s technological pedagogical content knowledge. He knows his content and is able to choose a teaching strategy appropriate for that content and his students and then uses technology to enhance both.

Cross-case Analysis

Facilitating. Both teachers express the desire to become facilitators in their teaching. For example, many interactions begin with a broad question such as, “What is electromagnetism?” and “What is sound?” The teachers then allow time for the students to construct the answer themselves before directing them to resources that help refine their understanding.

Another example of teacher facilitation comes when a student asks a question. Typical responses from both teachers are, “I want you to try and figure it out on your own,” and “Why don’t we google what that means?” Both teachers have strategies to help students work through obstacles the students encounter. These range from using the internet, a fellow student, and notes from previous projects.

Peer feedback. Both teachers develop learning environments that encourage peer-to-peer collaboration. While everyone might not be working on exactly the same thing, everyone is working on the same basic principles and concepts. This means that if one student is experiencing a challenge another student will have knowledge about how to overcome that difficulty. In each school, when a student was stuck, the teachers encouraged them to seek help from their peers instead of asking the teacher for an answer

Autonomy. At the beginning of each semester, the students must be guided in how to conduct themselves in this often-unfamiliar learning environment. Gary and Chuck approached this in different ways. Gary started the year with a very clear and strict structure in his classroom. Chuck allowed the student a lot of freedom and autonomy from the start. As students became responsible Gary would give them more freedom while Chucks students were given less if they demonstrated they were not ready for it.

Despite the different approaches at the beginning of the semester both teachers' classrooms looked very similar by the middle of the semester. Students were working effectively in small groups. They were able to move freely around the classroom to use different resources to help them solve problems. These resources include their peers as well as technology such as the internet or an advanced manufacturing tool.

Failure. When teaching with the FabNet Invention Kits another important component demonstrated by the teachers was how they handled their students when an artifact or project did not work. Both teachers wanted failure to be a point of learning and not a source of disappointment. Both teacher strived to not penalize their students for failure and to create an environment where the students understood the principle of testing and iteration. "If you didn't do it right the first time, you're going to do it better the next time," Gary says. He continues, "Mistakes are part of the process and are normal in this type of work."

Feedback. "Feedback is one of the more critical parts of learning so kids need a task and they need to perceive that they can do that task and they need feedback along the way," Gary says. Both teachers purposefully create activities where students encounter common misconceptions. In conjunction with feedback from the physical world, the teachers also use probing questions. For example, when a group of students was successful in creating the linear motor from the FabNet Linear Motor Invention Kit, Robbie was there asking, "How did you do that? Why is it working? What did you discover? What needs improving?"

Discovery and investigation. The teachers both take advantage of the Invention Kits motto of "Make to Learn". They encourage students to interact, build, and tinker with the artifacts. Both teachers model and encourage peer-to-peer and peer-to-teacher conversations in order to promote appropriate communication and collaboration skills. Both teachers purposefully limit their class-wide instruction to allow students to think and question the content for themselves.

Technology

The technological tools used in the middle schools to implement the FabNet Invention Kits are numerous. Both teachers agreed technology is a tool that should enhance students learning and not be used just because it is new and interesting on its own.

A variety of software solutions were used in both middle schools. One of the first mentioned by both teachers was an internet browser. The students used the internet to conduct searches, research concepts, and watch instructional videos. At Buford, project management for each student was done online using SCRUM Boards.

Despite the challenges presented by using this hardware and software both teachers agreed the technology enhanced the students learning. Brendan says,

> I think the biggest educational benefit that a laser cutter and a 3D printer have is the representation of the physical world providing feedback. The fact that they are so rapid that within 10 minutes or with a 3D printer, maybe the next day, your artifact provides feedback that your design works or it tells you to change course.

Robbie noted another benefit the technology brought to his students,

> Kids are normally extremely excited about 3D printers. They're amazed by watching their first thing come to life. It is a magical thing, as something they've created on the computer comes to life in front of their eyes.

Discussion

The TPACK framework is the foundation for good teaching and requires the educator to have an understanding of representations and appropriate pedagogy to utilize in the classroom (Mishra & Koehler, 2006). Both teachers used the TPACK framework as a way of thinking while implementing the FabNet Invention Kits. They successfully integrated technology with the content and their teaching strategies to enhance student learning (Niess, van Zee, & Gillow-Wiles, 2011; Shavelson, Ruiz-Primo, Li, & Ayala, 2003).

One notable highlight of this study is the pedagogical strategies employed by the teachers while using the Invention Kits. Both teachers defined their role as facilitators for students' thoughts, ideas, and initiatives and ensured they were expressed and considered important in their education (Powell & Kalina, 2009). The teachers were also able to educate the students to be actively involved in the learning process by engaging the teacher and his peers (Powell & Kalina, 2009).

The teachers created opportunities and exercises where the students were required to face misconceptions that they might otherwise have ignored (Haney, Lumpe, & Czerniak, 2010). Both teachers facilitated the students in facing these inconsistencies and helped them find new ways to learn using the scientific and engineering principles and tools available to them (Haney, Lumpe, & Czerniak).

The teachers used instructional materials that included interactive and physical activities, drawing information from raw data and first-hand sources (Haney, Lumpe, & Czerniak, 2010). Both teachers encouraged students to use scientific language and terms, thus encouraging authentic dialogue and enhancing their social and communication skills in their collaboration with their teacher and peers (Powell & Kalina, 2009).

Through the use of open-ended questions, peer-to-teacher, and peer-to-peer discussions, the teachers encouraged students to thoughtfully question the content studied (Powell & Kalina, 2009). By allowing an appropriate time for students to answer on their terms the teachers facilitated the students’ deeper inquiry into the subject matter (Brooks & Brooks, 1999).

Conclusion

This study followed two teachers implementing the FabNet Invention Kits. The Invention Kits utilize the PBL framework and offer many opportunities to interact with advanced manufacturing technologies such as 3D printers, 2D die-cutters, and laser cutters. This presented the two teachers with the need to master the content covered by the kits, the pedagogical strategies required by PBL, and also the appropriate use of technology.

Both teachers demonstrated strategies crucial to implementing this type of learning environment using the Invention Kits, while at the same time demonstrating the possibilities this type of environment has to positively impact the students participating. This study provides some insight into what is required of a teacher who wishes to use these types of activities in their own classroom. Further research in different environments and using different teachers is needed to further understand the challenges and strategies inherent in this type of teaching.

References

Abbitt, J. T. (2011). Measuring technological pedagogical content knowledge in preservice teacher education: A review of current methods and instruments. *Journal of Research on Technology in Education, 43*(4), 281-300.

Albanese, M. A., & Mitchell, S. (1993). Problem-based learning: a review of literature on its outcomes and implementation issues. *Academic Medicine, 68*(1), 52-81.

Baumgartner, E. & Zabin, C. (2008). A case study of Project-based instruction in the ninth grade: A semester-long study of intertidal biodiversity. *Environmental Educational Research, 14*(2), 97-114.

Boaler, J. (1997). *Experiencing school mathematics: Teaching styles, sex, and settings*. Buckingham, UK: Open University Press.

Bromley, D. B. (1986). *The case-study method in psychology and related disciplines.* Hoboken, NJ: John Wiley & Sons.

Brush, T., & Saye, J. (2008). The effects of multimedia-supported problem-based inquiry on student engagement, empathy, and assumptions about history. *The Interdisciplinary Journal of Problem-Based Learning, 2*(1), 21-56.

Bryman, A. (Ed.). (2006). *Mixed methods*. Thousand Oaks, CA: SAGE Publications.

Carspecken, P. F. (1997). Reform and resistance in schools and classrooms: An ethnographic view of the coalition of essential schools. *American Anthropologist, 99*(2), 418-419.

ChanLin, L. J. (2008). Technology integration applied to project-based learning in science. *Innovations in Education and Teaching International,45*(1), 55-65.

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education, 86*(2), 175-218.

Creswell, J. W. (1998). *Qualitative inquiry and research design: Choosing among five designs*. Thousand Oaks, CA: SAGE Publications

Creswell, J. W. (2002*). Educational research: Planning, conducting, and evaluating quantitative*. London, UK: Prentice Hall.

Denzin, N. K., & Lincoln, Y. S. (2011). *The SAGE handbook of qualitative research*. Thousand Oaks, CA: SAGE Publications.

Dickinson, G., & Jackson, J. K. (2008). Planning for success. *The Science Teacher, 75*(8), 29.

Doppelt, Y. (March, 2009). Assessing creative thinking in design-based learning. *International Journal of Technology Design in Education, 19*(1), 55–65.

Germann, P. J., Haskins, S., & Auls, S. (1996). Analysis of nine high school biology laboratory manuals: Promoting scientific inquiry. *Journal of Research in Science Teaching, 33*(5), 475- 499.

Harris, J., Mishra, P., & Koehler, M. (2009). Teachers' technological pedagogical content knowledge and learning activity types: Curriculum-based technology integration reframed. *Journal of Research on Technology in Education, 41*(4), 393-416.

Holm, M. (2011). Project based instruction: A review of the literature on effectiveness in prekindergarten. *Rivier Academic Journal, 7*(2), 1-13.

Horwitz, P. (1995). Linking models to data: Hypermodels for science education. *The High School Journal, 79*(2): 148– 156.

Krajcik, J. S., Czerniak, C. M., Czerniak, C. L., & Berger, C. F. (2002). *Teaching science in elementary and middle school classrooms: A project-based approach*. New York, NY: McGraw-Hill.

Marx, R. W., Blumenfeld, P. C., Krajcik, J. S., & Soloway, E. (1997). Enacting project-based science: Challenges for practice and policy. *Elementary School Journal, 97,* 341-358.

McGrath, J., Karabas, G., & Willis, J. (2011). From TPACK concept to TPACK practice: An analysis of the suitability and usefulness of the concept as a guide in the real world of teacher development. *International Journal of Technology in Teaching and Learning, 7*(1), 1-23.

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, 1*(2), 5.

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

Merriam, S. B. (1998). *Qualitative research and case study applications in education*. San Francisco, CA: Jossey-Bass Publishers.

Mioduser, D., & Betzer, N. (2003). The contribution of Project-based learning to high-achievers' acquisition of technological knowledge and skills. *International Journal of Technology and Design Education, 18*, 59-77.

Mishra, P., & Koehler, M. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *The Teachers College Record, 108*(6), 1017-1054.

National Research Council. (2011). *Successful k-12 STEM education: Identifying effective approaches in science, technology, engineering, and mathematics.* Washington, DC: The National Academies Press.

Niess, M. L. (2011). Investigating TPACK: Knowledge growth in teaching with technology. *Journal of Educational Computing Research, 44*(3), 299-317.

Niess, M., van Zee, E., Gillow-Wiles, H., & Staus, N. (2011, March). Advancing K-8 teachers' STEM education for teaching interdisciplinary science and mathematics teaching with technologies. Presented at *Society for Information Technology & Teacher Education International Conference*, Nashville, TN.

Papert, S. (1987). Computer criticism vs. technocentric thinking. *Educational Researcher, 16*(1), 22-30.

Patton, M. Q. (2002). Qualitative interviewing. *Qualitative Research and Evaluation methods, 3*, 344-347.

Seidman, I. (2013). *Interviewing as qualitative research: A guide for researchers in education and the social sciences*. New York, NY: Teachers college press.

Shavelson, R., Ruiz-Primo, A., Li, M., & Ayala, C. (2003). *Evaluating new approaches to assessing learning* (CSE Report 604). Los Angeles, CA: University of California, National Center for Research on Evaluation.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), 4–14.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*(1), 1–22

Silk, E. M., Schunn, C. D., & Strand Cary, M. (2009). The impact of an engineering design curriculum on science reasoning in an urban setting. *Journal of Science Education and Technology, 18*, 209-223.

Stake, R. E. (2013). *Multiple case study analysis*. New York, NY: Guilford Press

Tretten, R. & Zachariou, P. (1995). *Learning about project-based learning: Assessment of project-based learning in InterTech schools*. San Rafael, CA: The Autodesk Foundation.

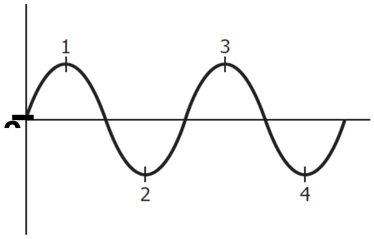
Valanides, N., & Angel, C. (2005). Learning by design as an approach for developing science teachers' ICT-related pedagogical content knowing. In S. Rodrigues, (Ed.), *International perspectives on teacher professional development: changes influenced by politics, pedagogy and innovation* (pp. 79-101). New York, NY: Nova Science.

Yin, R. K. (2008). *Case study research: Design and methods* (Vol. 5). Thousand Oaks, CA: Sage Publications.

Appendix A
Sound Unit Assessment

Instructions: The following assessment is designed to find out what you know about waves and sound. Do not worry if you do not know all of the answers. If you do not know or cannot guess, leave choices blank or write "I don't know" on the lines. Please try to choose the best answer from the choices, and write what you do know about waves and sound on the lines.

Use the diagram of the wave below to answer questions 1-3.



1. The wavelength is best described as the horizontal distance between:
    a. points 1 and 2.
    b. points 1 and 4.
    c. points 2 and 3.
    d. points 2 and 4.

How confident are you in your response to question 1?
1-not confident (a guess), 2-pretty confident, 3-very confident

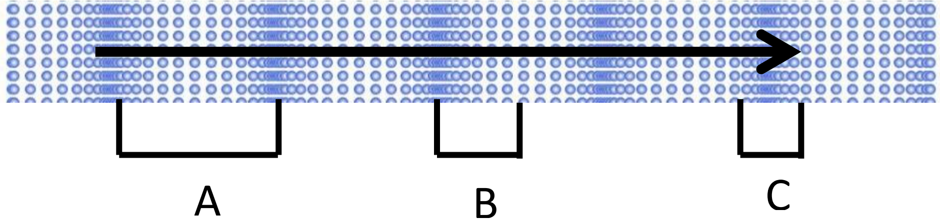
2. The amplitude of the wave is best described as:
    a. the vertical distance between points 0 and 1.
    b. the vertical distance between points 1 and 2.
    c. the horizontal distance between points 2 and 3.
    d. the horizontal distance between points 2 and 4.

How confident are you in your response to question 2?
1-not confident (a guess), 2-pretty confident, 3-very confident

3. The wavelength is depicted by
    a. A
    b. B
    c. C

2. How confident are you in your response to question 3?
3. 1-not confident (a guess), 2-pretty confident, 3-very confident

Use the wave below to answer questions 4-6.



4. Circle an area where the amplitude is highest.

How confident are you in your response to question 4?
1-not confident (a guess), 2-pretty confident, 3-very confident

5. a. List three similarities between longitudinal (compression) waves and transverse waves.
   b. List two differences between these two types of waves.

6. Which of the waves below has the higher frequency? **Need to know what the axis and scale.**
   a. A
   b. B

Explain why you selected the wave you selected.

7. How are the frequency and wavelength of a wave related? Explain your thinking.

8. A sound that you hear is caused by an object vibrating, which then causes:
   a. particles to move to your ear through material (a medium).
   b. particles to move to your ear through material (a medium) or through nothing (a vacuum, such as outer space).
   c. energy to move to your ear through material (a medium).
   d. energy to move to your ear through material (a medium) or through nothing (a vacuum, such as outer space).

How confident are you in your response to question 10?
1-not confident (a guess), 2-pretty confident, 3-very confident

9. A sound wave is transmitted through air, glass, and water. If the vibration starting the sound wave begins at the same instant for all three materials, rank the order in which the sound would travel fastest (from 1- fastest sound to 3- slowest sound).

___ Air
___ Glass
___ Water

Explain your thinking.

10. Your science teacher challenges you to design a speaker cone that transmits sound at specific pitch (frequency).
    a. What effect, if any, will increasing the size of a speaker cone have on the sound you hear? (Consider whether the sound will be louder or softer, higher or lower pitch, etc.) Why do you think so?
    b. What effect, if any, will increasing the size of a speaker cone have on the wavelength of the sound produced? Why do you think so?
    c. How would you design the speaker cone? (Describe the steps you would take or the process you would use.) Why would you do it this way?
    d. How will you know if your design is successful? Explain your thinking.

Appendix B
Solenoid Invention Kit Assessment

Figure 1. Wire disconnected from a battery, over a compass.

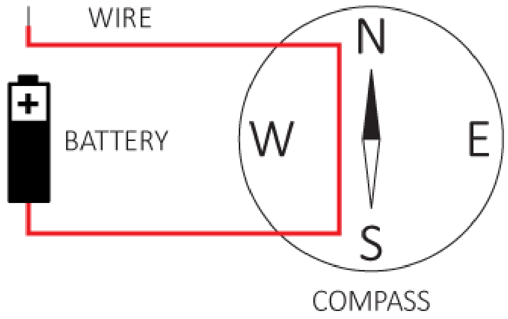
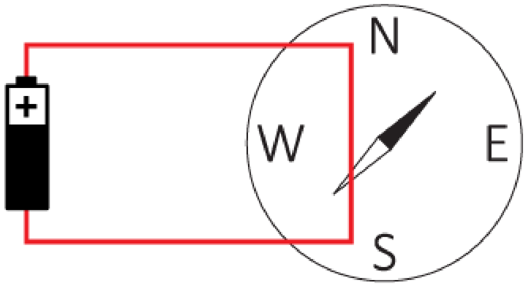


Figure 2. Wire connected to a battery, next to a compass.



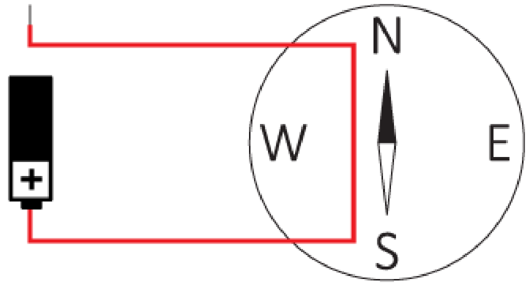
Question 1 (multiple choice): What is the best explanation of why the compass needle moved?

A. The battery becomes magnetic when the circuit is closed.
B. Electric current flowing through the closed circuit creates a magnetic field.
C. The closed circuit creates electrical energy.
D. The compass needs the battery connected to be turned on.

Question 1 (long response): Explain as best you can why the compass needle moved.

____
____
____
____

Figure 3. Wire disconnected from a battery, over compass.



Question 2 (multiple choice): Refer to Figure 2. If the orientation of the battery is changed to that shown in Figure 3, which direction will the black side of the compass needle point when the wire is connected to the battery?
A. The circuit will not work, so it will point north.
B. It will still point to the northeast.
C. It will point in the opposite direction, southwest.
D. It will point northwest.

Question 2 (long response): How does reversing the orientation of the battery affect the deflection of the compass?

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____

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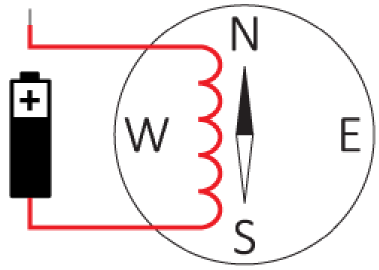
Figure 4. Coil of wire connected to a battery next to a compass.

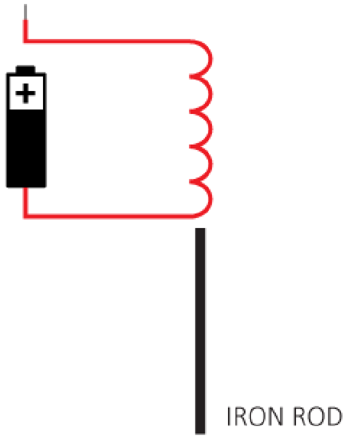


Question 3 (multiple choice): Refer to Figure 2 and Figure 4. Assume the length of the coiled wire is equal to the length of the straight wire. Once the coiled wire is connected to the battery, how will the deflection of the compass needle compare to the deflection shown in Figure 2?
A. They should deflect the same because there is the same amount of current flowing through the wire.
B. The needle deflects more with the coiled wire because the magnetic field generated is more concentrated.
C. They should deflect the same because there is the same length of wire.

D. The needle deflects less with coiled wire because it is harder for the electricity to flow through the wire.

Question 3 (long response): Explain why coiling the wire results in a greater deflection of 6. the compass needle.

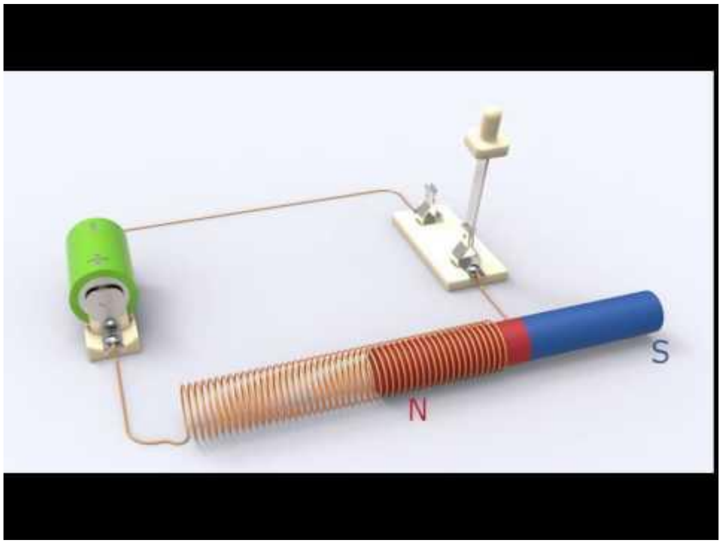
Figure 4. Iron rod next to coil of wire disconnected from battery.



Question 4 (multiple choice): What will happen to the iron rod when the coiled wire is connected to the battery?
A. The iron rod will be pulled into the coil.
B. The iron rod does not move.
C. The iron rod will be repelled by the coil.
D. The iron rod will either be repelled or attracted to the coil depending on which pole of the rod is facing the coil.

Question 4 (long response): What will happen to the iron rod when the circuit is switched 8. on? Explain why.

Video 1. Click on the video to play the animation.



Question 5 (multiple choice): Select the best explanation for what was observed in the animation.

A. Permanent magnets are repelled by copper.
B. The pole at the end of the coil closest to the permanent magnet is south.
C. Permanent magnets are always repelled by a coil of wire with an electric current flowing through it.
D. The pole at the end of the coil closest to the permanent magnet is north.

Appendix C
Teacher Observation Protocol (Sawada & Piburn, 2000)

Lesson Design and Implementation

1. The instructional strategies and activities respected students' prior knowledge and the preconceptions inherent therein.
2. The lesson was designed to engage students as members of a learning community.
3. In this lesson, student exploration preceded formal presentation.
4. This lesson encouraged students to seek and value alternative modes of investigation or of problem solving.
5. The focus and direction of the lesson was often determined by ideas originating with students.

Content

6. The lesson involved fundamental concepts of the subject.
7. The lesson promoted strongly coherent conceptual understanding.
8. The teacher had a solid grasp of the subject matter content inherent in the lesson.
9. Elements of abstraction were encouraged when it was important to do so.
10. Connections with other content disciplines and/or real world phenomena were explored and valued.

Procedural Knowledge

11. Students used a variety of means to represent phenomena.
12. Students made predictions, estimations, and/or hypothesis and devised means for testing them.
13. Students were actively engaged in thought-provoking activity that often involved the critical assessment of procedures.
14. Students were reflective about their learning.
15. Intellectual rigor, constructive criticism, and the challenging of ideas were valued.

Classroom Culture

16. Students were involved in the communication of their ideas to others using a variety of means and media.
17. The teacher's questions triggered divergent modes of thinking.
18. There was a high proportion of student talk and a significant amount of it occurred between and among students.
19. Student questions and comments often determined the focus and direction of classroom discourse.
20. There was a climate of respect for what other had to say.

Student/Teacher Relationships

21. Active participation of students was encouraged and valued.
22. Students were encouraged to generate conjectures, alternative solution strategies, and/or different ways of interpreting evidence.
23. In general, the teacher was patient with students.

24. The teacher acted as a resource person, working to support and enhance student investigations.
25. The metaphor “teacher as listener” was very characteristic of this classroom.

Appendix D
Teacher Interview Protocol

1. What is your teaching background? Where have you taught? (Probe for grades and subjects they have taught, how long they have been teaching).
2. How much experience do you have with using technology to support your teaching in the classroom? Advanced manufacturing technology?
3. What grade levels and subjects are you teaching this semester? This year?
4. How long have you been teaching at this school? Do you have any other responsibilities other than your teaching assignment?
5. How would you describe a typical lesson in your classroom? What resources do you use while planning your lessons? How do you gauge your students' progress?
6. What are the expectations your school administration has of you? How are these expectations communicated to you?
7. This semester, are you actively trying to change the ways teaching and learning happen in your classroom? What are you doing that is different or new?
8. Describe a lesson or activity in which you have used technology? What was the activity? (Probe for what they did, what the students did, what resources were required, what artifacts were produced by the students, if any) (Probe for how they assessed student learning, how they prepared for this lesson, how the students responded).
9. What kind of challenges have you encountered with using technology in your classroom? How have you countered these challenges?
10. How would you describe any professional development that help prepare you to teach these classes? What was most valuable about the professional development? What could be improved?