The Pencil-Top Fidget: Reinventing Shop (Metal Drilling and Tapping) in High School Science Classrooms

Dr. Matthew J. Traum, Engineer Inc.

Dr. Matthew J. Traum is founding CEO at Engineer Inc., a Florida-based STEM education social enterprise start-up. Traum invented @HOLM^{TM} lab kits to enable students in on-line courses to build and run engineering experiments remotely at home.

Before founding Engineer Inc., Dr. Traum was a well-known higher education administrator, fund raiser, educator, and researcher with co-authorship of 12 peer-reviewed research journal articles, 18 refereed research conference articles, and 20 refereed pedagogical conference articles. As a PI or Co-PI, Traum has attracted over $816 K in funding for research, education, and entrepreneurial ventures from multiple sources including NSF, NASA, ASHRAE, AIAA, Sigma Xi, the Texas State Energy Conservation Office, and several industry sponsors including Toshiba and Oshkosh.

Most recently as Associate Professor and Director of Engineering Programs at Philadelphia University, Dr. Traum led the Mechanical Engineering Program through a successful ABET interim visit resulting in no deficiencies, weaknesses, or concerns.

Previously, Dr. Traum was an assistant professor at the Milwaukee School of Engineering (MSOE), one of the top-ten undergraduate-serving engineering universities in the U.S. Dr. Traum coordinated MSOE's first crowd-funded senior design project. He also co-founded with students EASENET, a start-up renewable energy company to commercialize waste-to-energy biomass processors.

Dr. Traum began his academic career as a founding faculty member in the Mechanical & Energy Engineering Department at the University of North Texas - Denton where he established a successful, externally-funded researcher incubator that trained undergraduates to perform experimental research and encouraged matriculation to graduate school.

Traum received a Ph.D. in mechanical engineering from the Massachusetts Institute of Technology where he held a research assistantship at MIT's Institute for Soldier Nanotechnologies. At MIT he invented a new nano-enabled garment to provide simultaneous ballistic and thermal protection to infantry soldiers. Dr. Traum also holds a master's degree in mechanical engineering from MIT with a focus on cryogenics and two bachelor's degrees from the University of California, Irvine: one in mechanical engineering and the second in aerospace engineering. In addition, he attended the University of Bristol, UK as a non-matriculating visiting scholar where he completed an M.Eng thesis in the Department of Aerospace Engineering on low-speed rotorcraft control.

Dr. Sharon Liz Karackattu, Oak Hall School

Sharon L. Karackattu earned a B.S. in Interdisciplinary Studies: Biochemistry and Molecular Biology from the University of Florida in 2000 and completed a Ph.D. in Biology at the Massachusetts Institute of Technology in 2006. She served as a postdoctoral associate in MIT's Biological Engineering Division before spending two years as a Research Coordinator for Student Development at University of North Texas. She is currently a high school science instructor specializing in chemistry and the life sciences. She has taught college-level courses in the biosciences and maintains an interest in studying students pursuing the STEM fields.

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Abstract

Shop classes where students use tools to fashion useful and functional objects from metal, wood, plastic, and other materials are disappearing from most American high schools in favor of more theoretical subjects. Multiple factors contribute to this transition including 1) cost to maintain shops, 2) liability concerns, 3) focus on exam-driven standards-based testing, 4) and curriculum realignment for improved college admissions. There is interest in re-introducing elements of shop class back into high schools enabling students to learn by doing and to become more aware of how things are made.

Borrowing upon foundational Energy Engineering Laboratory Module (EELM™) pedagogy, we propose that engineering can be taught to students in all Science, Technology, Entrepreneurship, Arts, Engineering, and Mathematics (STEAEM) courses through practical hands-on learning experiences. Therefore, instead of resurrecting standalone shop classes in their original Industrial Arts manifestation, we recommend an alternative. Inexpensive and topically-relevant hands-on learning activities should be developed competent for ubiquitous and seamless insertion into STEAEM courses. When offered to teachers as educational kits, these activities could be selected a la carte from a catalog to integrate with existing classes. This approach induces minimal curriculum disruption, facilitates easy instructor adoption, and allows high schools to continue offering modern and relevant college preparatory courses. In parallel, however, this approach also enables schools to bring back the empowering, tactile, project-based educational benefits of an Industrial Arts shop class. Plus, these experiences can be harnessed to expose students to the engineering mindset of open-ended problem solving.

To demonstrate the principle, we present a simple hands-on fabrication project deployed in a required high school STEM course for 9th and 10th graders. Following the popular “fidget spinner” trend, students were challenged to each create their own customized pencil-top fidget from a nylon bolt, a metal lock nut, and a 1” x 1” x 1/4" aluminum block. Starting with those three raw parts and basic tools appropriate for a high school science classroom, each student 1) located and drilled holes in metal and plastic, 2) tapped a threaded hole in metal, and 3) assembled a completed working pencil-top fidget device.

Cycling a classroom of ~25 students through a safety talk and all fabrication process steps to device competition took four 45-minute class periods, and these activities were repeated across multiple periods each day. To assess indirectly the activity’s impact, students (N = 79) filled out an exit survey with questions posed against a Likert-like response scale. 35.44% and 65.82% of respondents respectively reported never using a drill press or threading a hole prior to this project. Reflecting on the project, 89.87% agreed or strongly agreed it demonstrated how holes are made on drill presses, and 91.14% reported new understanding of how taps cut screw threads into holes. Overall, 88.46% reported that they were exposed to new skills by the project, and 79.49% agreed the project was interesting to them. This project can be effectively and seamlessly inserted into high school STEAEM classes and used to introduce students to the essential and beneficial hands-on fabrication elements of shop class.

Next steps to develop the pencil-top fidget learning activity into an open-ended and entrepreneurial engineering design and manufacturing module are also discussed.

Introduction

Shop classes where students use tools to fashion useful and functional objects from metal, wood, plastic, and other materials have disappeared from most American high schools in favor of more theoretical "college preparatory" subjects. Multiple internal factors within schools contributed to the near-extinction of shop including 1) cost to maintain workshops, 2) liability concerns, 3) focus on exam-driven standards-based testing, and 4) curricular changes for admissions alignment with four-year colleges. Compounding external pressures to phase out high school vocational programs stem from historical, social, political, and academic sources acting since the 1940's heyday of Industrial Arts: 1) ongoing social stigma devaluing vocational training in favor of more "academic" fields; 2) lack of qualified Industrial Arts teachers with no training pipeline; and 3) mandated state and federal testing standards that emphasize students identifying one right answer over engineering design thinking that values developing and exploring multiple simultaneous solutions.

Reviving standalone high school shop classes in their original Industrial Arts manifestation appears futile against the myriad internal and external oppositional factors in modern secondary education. In one major recent allied attempt, the College Board tried in 2013 to create a studio-focused AP Engineering high school course [1]. However, if it was ever formally offered, AP Engineering is no longer available [2]. Nonetheless, there is interest in and need for hands-on training and engineering design thinking in high schools evidenced by emergence of the DIY/Maker Movement [3], Theil Fellowships [4], the Work Ethic Scholarship Program [5,6], and similar opportunities that promote and/or fund young people postponing or skipping college to pursue independent research, found start-up companies, pursue skilled trades careers, and/or create social movements.

We propose an alternative to resurrecting high school shop: deploy inexpensive and topically-relevant hands-on learning activities into existing conventional high school Science, Technology, Entrepreneurship, Arts, Engineering, and Mathematics (STEAEM) courses. This approach enables theoretical coursework and applied hands-on classroom activities to coexist, providing rich opportunities to complement one another. In parallel this approach enables schools to offer the empowering, tactile, project-based educational benefits of shop class without sacrificing their college preparatory missions or succumbing to social stigmas associated with vocational versus academic educational approaches.

To demonstrate the principle, we present a simple hands-on fabrication project deployed in a required high school STEM course for 9th and 10th graders at St. Francis Catholic Academy (SFCA), a private faith-based college preparatory high school in Gainesville, FL. One key project goal was to create a classroom activity whose product was both simple to fabricate for those with no shop skills or experience but also interesting, relevant, and immediately useful to students; the classic woodshop birdhouse project fails both metrics. Down-selecting from a range of possible ideas, we settled upon a variation of the popular "fidget spinner" device.

Commercially-available pencil-top fidgets, like the ones shown in Figure 1, press fit over wooden pencils, allowing users to spin a fidget nut up and down a threaded rod between two fixed stops. The classroom fabrication project carried out at SFCA enabled students to start from raw components using workshop tools and processes to create their own devices like the commercial pencil-top fidgets of Figure 1. As this paper will show, provided the components and instructions for pencil-top fidgets are available as an inexpensive kit, this activity can be successfully carried out in the context of any high school Science or Mathematics class using a low-cost set of tools appropriate to a high school science laboratory.

Figure 1: Injection molded plastic pencil-top fidgets are commercially available and inspired the design of the fabrication project described here.

Background

Kellman described the history and progression of hands-on “shop” instruction in American secondary education and explained why it has ultimately been marginalized and virtually eliminated [7]. Manual Arts in American secondary education grew out of the Scandinavian Sloyd Movement of the 1860’s and represented an early attempt to bring hands-on training to public schools with focus on carving and joinery. Central to Sloyd was a philosophy that manual labor is integral to the classroom, even for students on professional or academic tracks. The underpinning idea was that hands-on experience instilled all students with understanding and respect for physical labor.

The progression to Industrial Arts in 1940’s secondary education coincided with the modern American Industrial Age, which demanded high volumes of educated workers versed in using tools. The traditional apprenticeship system was too slow to meet demand; so public education ramped up hands-on training to supply needed workers. By the 1960’s, dedicated technical and vocational high schools opened to train students in the trades, allowing graduates to immediately enter their professions.

According to Kellman, the ultimate removal of hands-on education from high school curricula was seeded with the success of vocational high schools [7]. Although effective in training workers for trade professions, vocational schools became a “dumping ground” for students of marginal academic ability as well as those with learning disabilities or behavior issues. An assumption and stigma grew around vocational schools that students wanting to learn trade skills were simultaneously removing themselves from an academic track. That stigma became attached to vocational school students. They were supposedly not smart enough for academic high schools, and by association the value of their vocational studies diminished.

By the 1990’s, focus on educational accountability and adherence to strict and measurable standards further diminished and siloed vocational education. Fewer college programs trained Industrial Arts / Technology Education teachers in a coherent manner. The relevance of Industrial Arts and Technology Education fell further into question as academic standards were instituted that favored academic over vocational disciplines. In response, hands-on classes were systematically removed from most American high school curricula.

According to King, further contributing to the elimination of hands-on classes was introduction of high-stakes standardized tests that narrowed curricula, drove creative teachers out of education, and replaced inquiry-based learning with rote memorization. Standardized tests proved particularly damaging to open-ended engineering design thinking where students must formulate questions, design experiments, interpret unexpected results, and make new and novel connections and observations [8].

In addition to internal and external barriers described above, the political organizational structure of high schools selects against engineering courses. According to Foster, state-mandated science course enrollment necessitates several science faculty organized into a science department at most schools. A lone high school technology or engineering instructor may be loosely tied to the school's science department, but this person usually does not possess enough political leverage to advocate strongly for their own programs [9]. Foster therefore recommends identifying and leveraging science/engineering topical overlaps in secondary education State Standards to deliberately insert engineering thinking into required high school science courses. On the national scale, for example, 19 states have adopted the Next Generation Science Standards for preK-12 science education, which recognizes engineering as an important practice and companion alongside science. Individual state standards were all inspired by the National Research Council's report, *A Framework for K-12 Science Education Practices, Crosscutting Concepts, and Core Ideas* [10].

One approach to implementing Foster's suggestion was carried out by Peterman, et al. who developed an Engineering-Infused Lesson (EIL) Rubric to evaluate whether existing science lesson plans available in online archival banks contained engineering concepts and problem-solving approaches. They argued that science teachers may not be equipped to identify or carry out engineering-based curricula on their own given lack of engineering exposure. So, the EIL Rubric provides teachers with a lesson assessment tool to evaluate the strengths and missed opportunities for teaching engineering in existing lessons [11].

Methods

Pedagogical Foundation

Borrowing from Foster and from Peterman, et al. the idea to deliberately insert engineering thinking into required high school science courses, a pedagogical and experiential foundation is needed. We draw upon the Energy Engineering Laboratory Module (EELM™) educational pedagogy for this guidance [12-30]. EELM™ states that energy is a topic ubiquitous to all STEAEM fields, and therefore energy-focused experiences can be developed for ubiquitous and seamless insertion into any STEAEM course at any level. Following the underlying pedagogy narrative of New Learning developed by Kalantzis and Cope [31], EELM™ experiences are hands-on, accessible, student-centered, economical, and "turn-key". Needed hardware must be affordable for an institution with limited resources and be buildable and operable by a handy course instructor or technician without situated knowledge or access to specialized tools or equipment. Recently, EELM™ was demonstrated successfully (with need for minor modifications) at the high school level using a college-level Thermodynamics laboratory re-cast for an AP Physics II class [32], suggesting its viability as a pedagogical framework for inserting engineering content into non-engineering high school classes.

Drawing on the EELM™ foundation, our four-step method to implement and evaluate this project was to:
1) Develop an inexpensive, topically-relevant, age-appropriate, hands-on learning activity that teaches engineering
2) Insert this activity into a required high school STEAEM course
3) Evaluate the activity using an indirect survey to measure students' self-reported achievement of Learning Outcomes [see Appendix A]
4) Develop kits for dissemination to other instructors to make the learning activity "turn-key"

Student Learning Outcomes for the project were selected to align with the following Florida State Education Standards.
1. Standard 02 CTE-TECED.68.ENTECH.02: Demonstrate proper and safe procedures while working with technological tools, apparatus, equipment, systems, and materials.
2. Standard 01 CTE-TECED.68.MANTEC.01: Demonstrate an understanding of and be able to select and use manufacturing technologies.

The project's Student Learning Outcomes were as follows:
1. Students will carry out the proper procedure of process steps to drill & tap a threaded hole through the center of a square piece of aluminum bar stock.
2. Students will select the proper equipment and tools to carry out the drilling & tapping process described in Outcome #1.

Hands-On Activity Description
While the pencil-top fidget assembly learning activity was inspired by commercially available pencil-top fidget toys (Figure 1), the choice to guide students through fabrication of handheld fidgets was predicated on producing simple, beneficial, and useful devices for students. Among learners with Autism and Attention-Deficit/Hyperactivity Disorder (ADHD) fidget devices reduce disruptive sensory seeking behavior, such as touching peers at inappropriate times [33]. These devices have been shown to improve fine motor control in adult users [34]. They also improve on-task focus among disabled middle schoolers while rating as socially acceptable to those students' peers [35]. In fact, handheld fidgets have proven so beneficial, normalizing, and acceptable for students with focus disorders that researchers at UC Santa Barbara developed a curriculum allowing middle schoolers with ADHD to design and fabricate their own custom hand-held fidgets as a STEAEM activity [36].

For the SFCA high school project described here, each student was given the necessary raw materials and challenged to assemble a finished device. Toward this end, they were taught by the instructor how to modify the pieces using the classroom's fabrication capabilities into the final product.

Each pencil-top fidget assembly was built from three basic components purchased from McMaster-Carr: 1) a nylon bolt, 2) a metal lock nut, and 3) a 1" x 1" x 1/4" aluminum blank; see Figure 2. Appendix B gives the part numbers, description, and current costs for these raw materials. From those three foundational parts and a basic set of machine tools appropriate for a high school physics classroom (outlined in Appendix C), each student carried out the following process steps:

1) Located and marked the centers of the nylon bolt and aluminum blank
2) Drilled a 15/64” diameter blind hole about 2 inches deep in the nylon bolt (Figure 3A)
3) Centerpunched a pilot mark into the aluminum blank
4) Drilled a 27/64” diameter through-hole in the aluminum blank (Figure 3B)
5) Tapped the aluminum blank hole with 1/2”-13 threads (Figure 3C)
6) De-burred and finished the aluminum blank and nylon bolt (Figure 3D)
7) Assembled the completed pencil-top fidget device and mounted it on a pencil (Figure 4D)

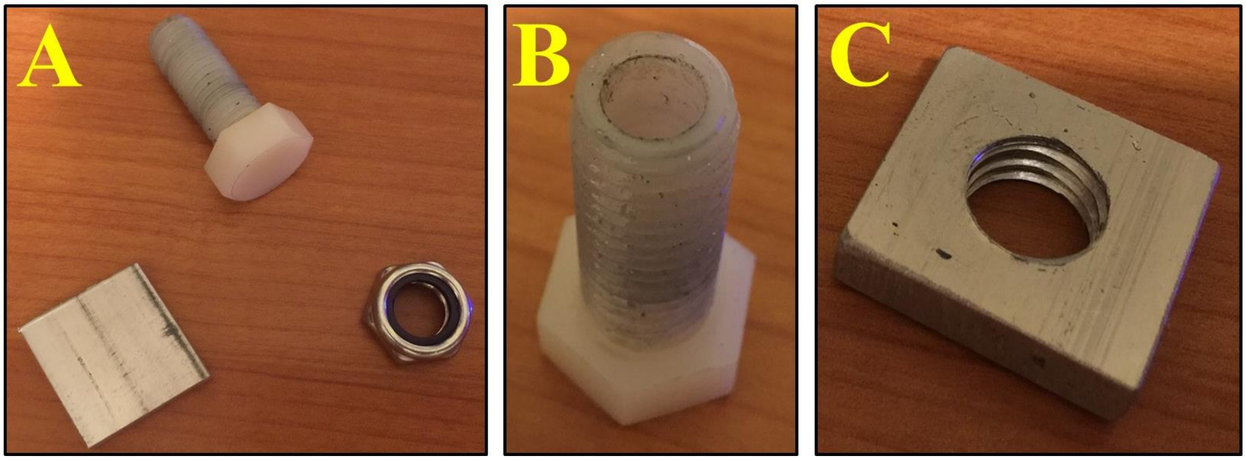

Figure 2: (A) Each pencil-top fidget was made from three fundamental components, a 1/2”-13 nylon bolt, a metal lock nut, and a blank aluminum square. (B) The center of the nylon bolt was drilled with a 15/64” blind hole to facilitate mounting the finished assembly in a pencil. (C) The aluminum blank was drilled and tapped with 1/2”-13 threads to fit over the nylon bolt and freely spin.

Cycling a classroom of ~25 students through a safety talk and all fabrication process steps to device competition took four 45-minute class periods, and these activities were repeated across multiple periods each day to guide 107 total students through the project in less than one week.

Figure 3: Under instructor supervision students (A) drilled out the nylon bolt, (B) drilled a hole through the aluminum blank, (C) tapped the blank with 1/2”-13 threads, and (D) de-burred and finished the machined blank either using sandpaper or a belt sander.

Assessment Data Collection
To indirectly assess the activity's impact, an anonymous post-activity student survey [see Appendix A] was posted online and administered via Survey Monkey. N = 79 of the 107 students enrolled in the classes that conducted the learning activity completed the survey. The survey had ten total questions: three Yes/No, six on a Likert-like response scale, and one open-ended question asking for student feedback to improve the activity.

Results

Figure 4A shows an example finished pencil-top fidget assembly as it was submitted by students for instructor evaluation. Students were asked to document their final product by mounting it to a standard wooden pencil (Figure 4B) and capturing a picture of themselves holding the final product (Figure 4D).

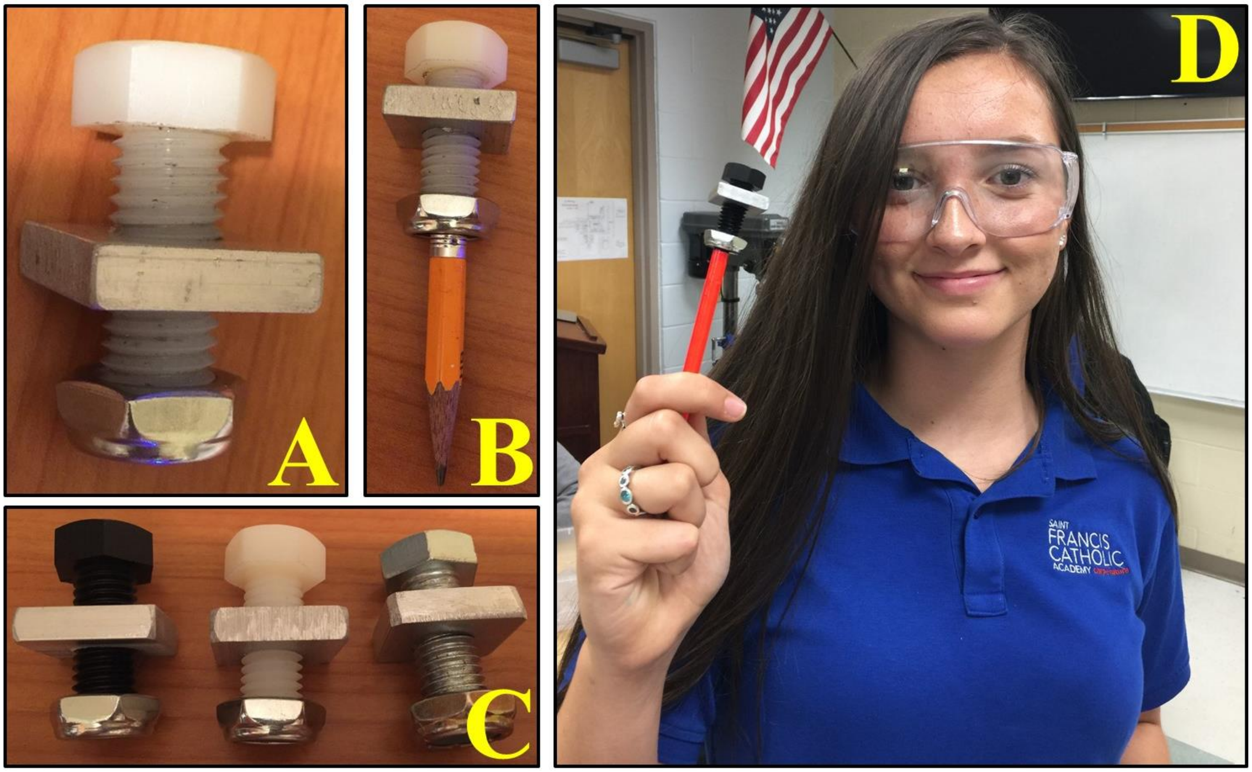

Figure 4: (A) A pencil-top fidget assembly completed by a student. (B) The assembly mounts atop a standard wooden pencil where it can be used as a fidget accessory by students. (C) Black and white nylon bolts as well as silver- and brass-colored lock nuts were available for students to customize their assembles. Stainless steel bolts were available for more experienced students. (D) An St. Francis Catholic Academy student showcasing her finished pencil-top fidget assembly.

To provide some variety and customizability, both black and white nylon bolts were available. Also, the locking nuts were available in silver or brass colors. So, students were able to customize to some extent the appearance of their fidget assemblies by selecting the components' colors, as shown in Figure 4C. For students with previous metalworking and/or workshop experience, steel bolts were available instead of nylon (Figure 4C). Steel is a significantly harder material to drill than nylon or aluminum, and it requires special procedures such as use of cutting fluid and slower drilling speeds. This slight change in material was offered at the instructor's discretion to make the project more challenging for experienced students. Students who accepted the steel bolt option were further challenged by having to calculate needed drilling feed and speed for this different material then correctly plunging a drill into the steel bolt without breaking the bit.

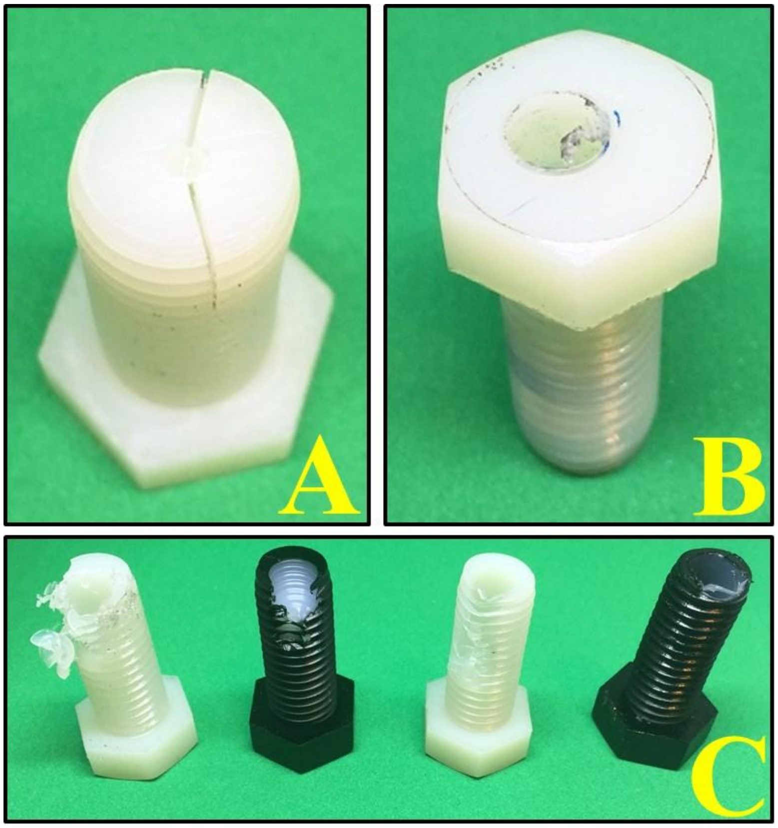

Figure 5: Common pencil-top fidget bolt fabrication errors. (A) Initially a centerpunch was used to mark the nylon bolt for drilling, but this process often split the plastic; so it was discontinued. (B) Some students did not appreciate the difference between a through hole and a blind hole and penetrated all the way through the nylon bolt when drilling; this error caused the fidget assembly to slide off the pencil. However, with a design change to make the hole a press fit on the pencil this modification could be incorporated to intentionally allow the fidget to slide along the pencil shaft. (C) Bolt centers were mismarked, causing drilled holes to be off-center. In extreme cases, internal drilling damaged external bolt threads.

Common Failure Modes

Most students used the classroom fabrication tools to turn their raw materials into pencil-top fidget assembles without any problems. However, a few students faced challenges, scrapped parts, and needed to start over.

The most common failure mode was not running the tap all the way down through the hole in the fidget nut to finish the threads. The resulting threads would accept the nylon bolt, but it was too tight to spin freely. Students who presented this fabrication problem to the instructor were told to re-tap the hole, which usually fixed the problem.

Another common issue was incorrectly centering and drilling the blind hole through the middle of the nylon nut. Common issues with making this hole that scrapped parts are documented in Figure 5. While students were instructed how to find the bolt's center, many just eye-balled it leading to the hole being so far from center that it cut way the external bolt threads (Figure 5C). Some students who did find the center and dimpled it with a centerpunch struck too hard and ended up splitting the nylon (Figure 5A). Others did not know how to read the drill press depth gauge or measured the plunge depth incorrectly and drilled a hole all the way through the bolt (Figure 5B).

Each one of these fabrication failures was treated by the instructor as a learning opportunity harkening back to the Industrial Arts workshop experience. When a student scrapped a part, they were asked what went wrong and what they would do next time to prevent the same failure. Once the instructor was satisfied the student had thought through their process, a replacement part was provided. Students quickly realized that their course grades were not negatively impacted by fabrication mistakes provided they took appropriate corrective measures to prevent the problem from happening again. Anecdotally, this freedom to make, learn from, and correct mistakes made the classroom environment and the resulting student/teacher interactions dramatically different and much more collegial and collaborative than classroom environments focused on assessment through high-stakes standardized tests.

Survey Results

Results from the post-project student survey are given in Table 1. 35.44% and 65.82% of respondents respectively reported never using a drill press or threading a hole prior to this project. 43.04% reported never before assembling mechanical components into a working device. Reflecting on the project, 89.87% agreed or strongly agreed that it demonstrated how holes are made on drill presses, and 91.14% reported understanding from their experience how taps cut screw threads into holes. Overall, 88.46% reported that they were exposed to new skills by the project, and 79.49% agreed the project was interesting to them. 64.10% planned to use their pencil-top fidget by mounting it on a pencil and playing with it. Perhaps this last number was artificially low because the pencil-top fidgets became so popular that the school's principal mentioned to the instructor that they were being confiscated by teachers in other classes. The instructor shared this detail with students, suggesting they take the fidgets home instead of using them in school.

Table 1: Post-project student survey responses to the pencil-top fidget assembly activity.

	No	Yes	Strongly Disagree	Disagree	Agree	Strongly Agree
I Previously Used A Drill Press	51	28				
I Now Understand Drill Presses Cuts Holes			5	3	30	41
I Previously Tapped Threads	27	52				
I Now Understand Taps Cuts Threads			4	3	32	40
I Previously Assembled Components	45	34				
Project Exposed Me To New Skills			5	4	41	28
Project Exposed Me To How Things Are Made			5	7	49	17
Project Was Interesting			10	6	40	22
I Plan To Use My Pencil-Top Fidget			10	18	32	18

Student Comments & Improvement Suggestions

The last survey question was open-ended, inviting students to suggest improvements for the pencil-top fidgets and/or improvements to the overall project. These student suggestions were categorized by the instructor, and the most interesting/relevant ones are repeated here.

Make Fidget Nut Spin Smoother

"Making a bigger hole, or use a different screw to have it spin more."

"One thing that could possibly be done to improve the functionality of this design is possibly oiling before use, for a longer, better spin, but that's more of a repeating temporary addition."

Improve Workshop/Tools

"Better centering ability so that the holes can be precise."

"I would suggest that more tools are available to accommodate the amount of people making the fidget spinner."

De-Burring

"Already pre-sanded metal pieces to make it easier for students and to avoid cuts."

"Change the shape of the metal piece that spins from square to round to prevent sharp edges."

Interesting Design Ideas

"I would put a tiny motor so that the fidget spinner can move by itself."

"Make more complex designs to improve the quality and performance of the fidget."

Fidget Weight

"It's big and heavy and it's hard to fidget with without becoming a distraction."

"Maybe we could figure out a way to make it lighter so the pencil wouldn't be so heavy."

Pencil Selection

"Provide pencils!!"

"I would suggest having the most optimal pencil when building and using the pencil-top fidget."

"To improve the design, we could add something to better hold the pencil in place."

Aesthetics

"You could make the project more fun by adding a variety of colors to make the fidgets."

"I think that it would be interesting if we could have colored it or made some pattern."

"Some decals or designs would make the project more decorative."

"To be able to modify the block we spin. Maybe like a better spinning shape or object."

Discussion

By adapting best practices from EELM™ pedagogy to guide insertion of hands-on shop elements into a required STEAEM course, the project's goal was achieved. An inexpensive and topically-relevant applied engineering fabrication learning activity was deployed in a required high school course. Students undertook an empowering, tactile, pragmatic, project-based project to fabricate a real mechanical device in the spirit of an Industrial Arts shop. This goal was accomplished without sacrificing or compromising the school's underpinning college-preparatory, academically-focused curriculum.

88.46% of students self-reported that they learned fabrication skills from the project they had previously not been exposed to: using a drill press, tapping threads in metal, and assembling a mechanical device. 79.49% agreed the project was interesting to them. While these quantitative metrics demonstrate success, the project created more even positive benefits and classroom learning than is reflected in these statistics.

Kellman argued that reliance on high-stakes tests to measure academic performance has taught students that problems have only one right answer, and finding it is the goal of most Science, Math, and Technology courses. The process of discovering the one right answer is minimized and the engineering concept that technical problems can be open-ended with multiple viable solutions is lost. In this educational environment, many students fear saying the wrong answer or asking for help. [7]

The process of working hands-on with tools to fabricate a mechanical device such as the pencil-top fidget deemphasized the artifact itself and emphasized instead the pathway to creating it. Engineering learning occurred along this creation pathway. For example, students quickly saw that there was a range of ‘right’ answers. Holes drilled in the nylon bolt and fidget nut blank could be off-center, yet the assembled device still worked. Placing the hole too far off-center, however, caused the part to be scrapped (see Figure 5). Failure to run the tap all the way through the fidget nut resulted in the threads being too tight. The fidget nut would thread onto the bolt, but it wouldn’t spin freely. Students experimented with how “sticky” their fidget nut felt by driving the tap to different depths. One student intentionally fabricated and assembled the whole device upside down with the nylon bolt head on the bottom and the lock nut on top. The assembly still fit the pencil and worked correctly. The fidget looked different from the others, but for one student that difference was an intentional expression of individuality and creativity rather than a mistake. These examples show how this project transmitted and taught students the essence of engineering: there is not necessary one right answer to engineering problems. A range of possible answers can satisfy the design requirements, and creative expressions from trying something different can lead to valuable and desirable alternative outcomes. In this way, the pencil-top fidget learning activity departed dramatically from exam-driven standards-based testing high school students typically experience in their Math, Science, and Technology classes.

The self-reported student data did include some odd anomalies. Even though all enrolled students completed and submitted a pencil-top fidget assembly 10.13%, 8.86%, and 15.39% respectively reported that they had not drilled holes, tapped threads, or experienced how mechanical devices are made. There are three likely explanations for these self-reported results inconsistent with actual project outcomes. First, some students may have been confused by the survey and simply selected the wrong response (e.g., they marked “Strongly Disagree” when they intended “Strongly Agree”). Second, even though all submitted a finished fidget assembly, some students may legitimately not have done all the process steps themselves. (e.g., they had a friend drill holes and/or tap threads in their raw parts). Third, 20.51% reported disagreement or strong disagreement with a survey statement probing their interest in the project. There was a small contingent who did not resonate with the course and complained about being required to take it. It is possible these disgruntled students intentionally mismarked the survey (e.g., marked “Strongly Disagree” on all questions) to berate the instructor or express frustration with the course. This unfortunate phenomenon is reported in the literature [37], and we have also observed it in our own previous attempts to introduce novel or innovative teaching techniques to the classroom [38]. Unfortunately, there is no way to know the exact causes of these small though apparent anomalies in survey results.

STEAEM Curriculum Connections

Critical to wide dissemination and adoption for the practice of inserting an engineering fabrication project into a core required Math or Science course is connecting the project directly with curricula in the host course. Without this connection, teachers will not see the relevance of adopting this approach since hands-on projects often do not directly address standards-based curricula or support standardized state assessments. There are numerous ways creative Math and Science teachers can connect the pencil-top fidget project to their curriculum, and two ideas are summarized here: one for Math and one for Science.

In an Algebra or Geometry Math course, for example, recommended tabulated drilling feeds and speeds for materials in the fidget assembly (Table 2) could be compared against the underpinning equation (Equation 1),

$$N = \frac{V}{\pi D} \tag{1}$$

where *N* is the spindle speed, the surface speed is *V*, and *D* is the drill bit diameter. Here, students gain practice algebraically manipulating symbolic variables and constants, plugging numerical values into an equation system, converting units (millimeters to meters), and verifying their calculated results from tabulated figures. Comparing tables to equations can even be used to teach rounding since tabulated values are truncated at two significant digits. Furthermore, noting the product πD is a circular circumference swept by the path of the drill bit flutes and *N* is the bit's rotation rate, geometry can be applied to show the equivalency of Equation 1 to the physical situation – calculated flute surface speed, *V*, is literally the linear speed of a drill bit flute in contact with the metal surface it is cutting.

Table 2: Recommendations for drilling feeds and speeds relevant to materials used in the pencil-top fidget project [39].

Fidget Part	**Material**	**Surface Speed $\{V\}$**	**Feed $\{f\}$ (1.5 mm dia. Bit)**	**Feed $\{f\}$ (12.5 mm dia. Bit)**	**Spindle Speed $\{N\}$ (1.5 mm dia. Bit)**	**Spindle Speed $\{N\}$ (12.5 mm dia. Bit)**
[ ]	[ ]	[m/min]	[mm/rev]	[mm/rev]	[rev/min]	[rev/min]
Fidget Nut	Aluminum Alloys	30–120	0.025	0.30	6400–25,000	800–3000
Steel Bolt	Stainless Steels	10–20	0.025	0.18	2100–4300	250–500
Nylon Bolt	Thermoplastics	30–60	0.025	0.13	6400–12,000	800-1500

A slightly more demanding mathematical study could incorporate linear interpolation and experiments to demonstrate and validate the governing equations. The Material Removal Rate (MRR) for drilling is

$$MRR = \frac{\pi D^2}{4} f N \tag{2}$$

where *N* is the spindle speed, *D* is the drill bit diameter, and *f* is the feed rate. The MRR for a fidget assembly component based on its material makeup could be calculated from tabulated *N* and *f* for a bit diameter, *D*. Recommended machining process feed and speed tables like Table 2 give values for a few (often just two) tool diameters, requiring table users to interpolate between these points to determine values for drill bits of intermediate diameter. Students could measure the real drill bit diameters, combine the definition of a line with tabulated values to interpolate feeds and speeds for the measured bits, and then calculate the MRR for a drilling process with those bits. Working in pairs, students could time the real drilling processes and combine process times with the geometry of holes drilled to calculate the true MRR for comparison to the Equation 2.

For a very visual and memorable demonstration, the instructor could even show what happens if the equations are not properly followed when setting real feeds and speeds. Setting spindle speed too high or too low induces a variety of possible failure modes (e.g., the drill press seizes, the drill bit fails to bite into the work, the workpiece melts, the drill bit dulls or breaks, etc.). Hands-on experiments and demonstrations (especially demos that "break" the machines) can strongly connect tangible examples to mathematical concepts that are often abstract and challenging for students to otherwise visualize.

As another example, in a physics course the mechanism used to change the rotation speed of the drill bit on the drill press could be studied in a module on simple machines and mechanical advantage. The electric motor that ultimately drives the drill press spins at constant speed, which can be determined from the motor's nameplate specifications. The rotation speed of the bit itself is then adjusted by moving a pair of belts between two spindles that contain pulleys of several different diameters (Figure 6). With the machine shut off and locked out to prevent injury, students could measure the diameters of the various spindle pulleys. Realizing that a belt attaching two spindles must run at constant linear velocity over both pulleys with which it is engaged, students could work out the relationship between measured diameters, d_i, of connected pulleys and their rotation rates, ω_i:

Figure 6: Drill press bit rotation rate is set by adjusting locations of a pair of belts between pulleys of different diameters mounted on two spindles inside the machine's case. The STEM class's drill press was capable of 16 unique speeds over a range from 200 to 3630 rpms.

$$\frac{d_1}{2}\omega_1 = \frac{d_2}{2}\omega_2 \tag{3}$$

Students could then propagate this relationship over both belts to derive an expression for the drill bit rotation rate as a function of engaged pulley diameters. With the addition of an inexpensive optical tachometer to measure drill bit rotation rate, students could then perform experiments to determine the validity of their equations. The experiment could be further extended to include study of torque and power by drilling into materials of different hardness while simultaneously measuring the drill bit rotation rate for different pulley settings to see whether unloaded rotation rates are maintained when the tool engages the workpiece.

While there are numerous ways to connect fabrication of pencil-top fidgets to Math and Science curricula, in the case of the STEM class here described, this learning activity was used to introduce and develop in the students some basic metal fabrication skills. The STEM class was preparing for an open-ended design challenge where students built winches powered by photovoltaic cells and raced them to see who could pull a heavy load the fastest over a 25-meter distance. In previous iterations of the winch project, students needed basic metalworking skills because the lightweight plastic and wood structures they built often proved too flimsy to support the forces involved. So, in the context of the STEM class described here, the pencil-top fidget project provided a foundation of skills for processes students would likely need to fabricate their winches, supporting a follow-on project heavy on engineering design.

Incorporating Student Feedback To Improve Kit Design

Student feedback on the project provided helpful insights in transitioning from a customized experiment to a “turn key” kit that can be distributed to other educators. To make the fidget nut spin more smoothly, for example, future kits will use a drill bit larger than the recommended 27/64” to create the fidget nut pilot hole for 1/2”-13 threads. Pencils sized to fit the blind hole drilled in the nut will be included with the kit. Deburring the fidget nut was an intended part of the fabrication process, and despite survey comments about students getting cut, there were no actual injury incidents. Nonetheless in the future, fidget nut blanks will be fully deburred before they are given to students with corners and edges broken to avoid any possibility of a student being injured by a sharp edge. After students drill and tap the hole in the fidget nut, they will deburr it again with sandpaper to clean off any burs created while making the hole to emphasize that removal or sharp edges is an important part of the fabrication process.

The SFCA classroom where this activity was conducted had two drill presses. Workflow was set up so drilling the nylon bolt occurred on one drill press and drilling the fidget nut pilot hole occurred on the other. While the activity could be accomplished with one drill press, this arrangement avoided need to swap out drill bits and change drill speeds, and it sped up the process by allowing different students to complete fabrication steps in parallel. Everything was set up and correctly dialed in by the instructor so students could carry out the drilling processes without worrying about minute and more advanced details. Provided half the class started drilling the nylon bolt and the other half started drilling the fidget nut hole, wait times to use machines were not too long. Additional drill presses would eliminate machine access bottlenecks but at increased cost and sacrifice of additional classroom space.

The number one student feedback topic was need to color, decorate, or individualize the fidget nut. To address this feedback for the future, fidget nuts will be treated prior to the activity with a variety of Krylon® Professional All Surface Enamel colors [40]. Students will then be able to customize their pencil-top fidgets beyond just picking a white or black nylon bolt by selecting their favorite fidget nut color.

A few students commented that the pencil-top fidgets made their pencils heavier and noticeably out-of-balance, making writing difficult. This functional concern could be leveraged by an instructor wishing to extend the activity beyond fabrication into an open-ended engineering product design activity. Students could be tasked with redesigning the pencil-top fidget to retain the function of the original device but reduce its weight to make its presence less noticeable during pencil use.

Conclusion

Borrowing upon foundational Energy Engineering Laboratory Module (EELM™) pedagogy, we propose that engineering can be taught to students in all Science, Technology, Entrepreneurship, Arts, Engineering, and Mathematics (STEAEM) courses through practical hands-on learning experiences. Therefore, inexpensive and topically-relevant pragmatic learning activities can be developed that are seamlessly insertable into any STEAEM course. This approach provides the fabrication experience of an Industrial Arts shop class, exposes students to the engineering mindset of open-ended problem solving, preserves the school's college preparatory curriculum, and induces no negative stigmas associated with vocational education.

This principle was demonstrated in a required high school STEM course for 9th and 10th graders at SFCA. Capitalizing on the popular "fidget spinner" trend, students were challenged to each create their own customized pencil-top fidget assembles fabricated from simple components using shop tools appropriate for a high school science laboratory classroom. 107 students in five classes completed the project. Cycling a classroom of ~25 students through a safety talk and all fabrication process steps to device competition took four 45-minute class periods, and these activities were repeated across multiple periods each day.

To assess indirectly the activity's impact, (N = 79) students filled out an exit survey with questions posed against a Likert-like response scale. Overall, 88.46% reported that they were exposed to new skills by the project, and 79.49% agreed the project was interesting to them. Students made several valuable suggestions to improve the project, which will be implemented as the activity is transitioned into commercially available kits for dissemination to other high school educators. Anecdotally, the project conveyed to students the core concept that there need not be only one correct answer or solution to open ended engineering design problems. This valuable outcome is important because it differentiates engineering problem solving from high school Math and Science classes where students learn to pursue one single right answer to the exclusion of other alternatives.

Next Steps

In addition to providing fabrication skills and teaching engineering thinking in Math and Science courses, the pencil-top fidget project can also stand alone as its own engineering design exercise. This proposed exercise will first be piloted as a week-long summer camp in collaboration with a local high school to build instructor experience. Learners will be led through fabrication of standard-design pencil-top fidgets as described in this paper. Feedback will be collected from participants as it was here on suggested improvements to the fidgets. These suggestions will be combined into a Customer Needs Statement to inform a next-generation pencil-top fidget device to be developed, designed, and manufactured by the students for commercialization. Students will form small engineering teams ("companies") challenged to redesign the standard pencil-top fidget they just learned how to make to address the Customer Needs Statement generated using their input.

Student “companies” will be challenged to redesign the fidget to make it more appealing to a wider consumer base. They will need to address issues like the device’s weight and need for additional customizability with a variety of fidget nut colors and shapes. In addition to improving the design, students will need to determine how to increase throughput to manufacture more than a few fidget devices per day by hand. While containing elements of engineering design and manufacturing, this project will also emphasize entrepreneurship as students figure out whether they can sell the products they create to cover costs, determine how much inventory is needed on-hand to meet demand, and compete with other student teams to offer the highest quality fidget products with the most attractive features at the lowest price.

At the end of the 2017-2018 academic year, SFCA cancelled the STEM course in which this project took place and removed it from the curriculum. The course was previously a graduation requirement, but it is no longer offered; not even as an elective. The reason for cancellation was the course did not align with the freshman admission criteria of Florida’s four-year public colleges or universities, and it was therefore not being recognized or considered in higher education admission decisions made by these institutions.

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Appendix A:
Post-Activity Student Survey Questions (Administered Online Via Survey Monkey)

1. Had you used a drill press to cut holes in metal or plastic prior to the Pencil-Top Fidget project?

No *Yes*

2. Owing to the Pencil-Top Fidget project, I understand that a drill press cuts holes in metal and plastic.

Strongly Disagree *Disagree* *Agree* *Strongly Agree*

3. Had you used a tap to cut screw threads into drilled holes prior to the Pencil-Top Fidget project?

No *Yes*

4. Owing to the Pencil-Top Fidget project, I understand that a tap cuts screw threads into holes.

Strongly Disagree *Disagree* *Agree* *Strongly Agree*

5. Had you assembled mechanical components into a working device prior to the Pencil-Top Fidget project?

No *Yes*

6. I was exposed to a new set of skills by participating on the Pencil-Top Fidget project.

Strongly Disagree *Disagree* *Agree* *Strongly Agree*

7. From the Pencil-Top Fidget project, I was exposed to how real mechanical devices are made.

Strongly Disagree *Disagree* *Agree* *Strongly Agree*

8. The Pencil-Top Fidget project was interesting to me.

Strongly Disagree *Disagree* *Agree* *Strongly Agree*

9. I plan to use the Pencil-Top Fidget I built by mounting it on a pencil and playing with it.

Strongly Disagree *Disagree* *Agree* *Strongly Agree*

10. What suggestions do you have to improve the design of the Pencil-Top Fidget and/or to improve the overall project to build a Pencil-Top Fidget from basic mechanical parts?

Appendix B: Bill Of Materials Needed to Construct Pencil-Top Fidgets

Item #	Part Number	Item Name & Description	Cost Per Item	Where To Buy
1	91970A714	Black Nylon Hex Head Screws, 1/2"-13 Thread Size, 1-1/4" Long, Packs of 10	$6.05	McMaster-Carr
2	91244A714	Off-White Nylon Hex Head Screws, 1/2"-13 Thread Size, 1-1/4" Long, Packs of 10	$6.05	McMaster-Carr
3	91309A714	Zinc-Plated Steel Hex Head Screws, 1/2"-13 Thread Size, 1-1/4" Long, Packs of 25	$8.61	McMaster-Carr
4	90566A033	Low-Strength Steel Thin Nylon-Insert Locknut, Zinc-Plated, 1/2"-13 Thread Size, Packs of 100	$9.78	McMaster-Carr
5	94945A224	High-Strength Steel Thin Nylon-Insert Locknut, Zinc Yellow-Chromate Plated, 1/2"-13 Thread Size, Packs of 25	$7.09	McMaster-Carr
6	8975K596	6061 Aluminum, 1/4" Thick x 1" Wide, 6 Feet Long	$12.28	McMaster-Carr

Appendix C: Machines and Tools Needed to Fabricate Pencil-Top Fidgets

Item #	Part Number	Item Name & Description	Cost Per Item	Where To Buy
1	DW1919	DeWalt 19/64-Inch Gold Ferrous Oxide Pilot Point Twist Drill Bit	$5.72	Amazon
2	21670	Vermont American Size 1/2"-13 NC Tap 27/64-Inch Drill Bit Combo	$10.85	Amazon
3	12088	Irwin 0 - 1/2" Hanson Adjustable Tap Wrench	$15.46	Amazon
4	51216	Lube-Cut Heavy-Duty Cutting Oil, 1 Pint Squirt Bottle, Light Fluid	$10.36	Amazon
5	12W-2888-B	120 Grit Dry/Wet Silicon Carbide Sandpaper for Metal Sanding, 9 x 11" Sheets, Pack of 30	$15.99	Amazon
6	M8C	Great Neck Saw M8C Wood Claw Hammer	$4.98	Amazon
7	61786	Central Machinery 13-Inch 16 Speed Bench Drill Press	$269.99	Harbor Freight
8	30999	Central Forge 4-Inch Drill Press Vise	$16.99	Harbor Freight
9	60381	Warrior Center Drill Countersink, 5 Piece Set	$6.99	Harbor Freight
10	60500	Central Machinery 1/3 HP 9-Inch Benchtop Band Saw	$139.99	Harbor Freight
11	3417A6	Marking Punch with Hex Handle, 1/16" Point Diameter	$4.00	McMaster-Carr

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