Engineering Physics: Modding and Making

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Overview

Students are so immersed in technology that they often miss the subtlety of how it functions, when a knowledge of high school physics is enough to understand the forces, torques and basic circuits that drive the items they interact with on a daily basis. Technology is viewed as a "black box," where the end product mystifies students, even though they have a grasp of the individual components. Students should be able to consider he individual systems present in a device to see how their interactions turn an input into an action. This analysis would put making a similar system well within their reach instead of far above their heads.

This unit fuses the modern MakerEd movement with the rigor required of an Advanced Placement Physics class. While the content and activities are tailored for the new AP Physics 1: Algebra based course, it will transfer well to any course that covers mechanics and DC circuits. In addition, care will be taken to discuss the overarching ideas and structure that are required to have a successfully implemented and evaluated MakerEd project, regardless of subject area.

The end product for students will be some sort of robot. Specifically, they will design an Arduino-based system that receives input, processes the input and then reacts. The drive is to have students gain experience in design, engineering and applied physics through doing. To provide additional focus to such an open ended prompt, learning experiences are structured to provide foundational ideas and inspiration in the areas of robotic systems, DC circuits, sensors, actuators, programming and design. Students are given the option to create freely or structure their ideas within the framework of Design Thinking.

Rationale

Scientists and engineers are intensely creative people who rarely arrive to a job knowing everything. The bulk of their high level learning and discovery comes from exploration. Scientists conduct research by first observing something strange and then pushing the boundaries of that phenomenon. Engineers create by identifying problems and trying solutions. The key is that both professions place a value on implementation of ideas and allow for an expansion of understanding as the situation dictates.

For a child, the role of play and tinkering is foundational in early learning, but the practice is largely suppressed as an educational tool by high school. The MakerEd movement looks to embrace that spirit to leverage learning. Born from the larger Maker Movement, it attempts to fuse a "Do It Yourself" ethic with the study and implementation of technology, engineering, fabrication and design. The maker is a one who learns by doing and in the process creates objects and systems of personal meaning, leading to an intense ownership of their own learning. Makers collaborate and network to learn from each other and share their knowledge.

Design Thinking is a process that focuses on problem solving through design. By going through a cyclic process of ideation, experimentation and evolution, students are able to refine a solution to real world problems in order to benefit their community. Design thinking is a structured approach to creation and development.

Both approaches are similar in the sense that they emphasize learning by doing and student-centered generation of ideas. Both are open-ended systems where students make things of meaning, solve problems and exercise their creativity.

Where they differ, however, is more important than how they are similar. Design Thinking is a clearly defined process that develops solutions to problems. MakerEd is a much looser approach that thrives on open-ended prompts and diving feet first into the creative process. For some students, the freedom to respond to the blanket prompt of "make something" allows them to explore their mind and produce amazing products that evolve quickly under only a few restrictive parameters. For others, the lack of focus is too overwhelming. In this situation, the process of Design Thinking can take away some of the paralysis of a fully open prompt and allow students to instead focus on an iterative process that systematically cycles them through thinking, experimenting and revising.

The specific benefits include, first and foremost, student engagement. Student buy-in is at its highest when they are creating objects of personal significance. Second, since each team is addressing a different issue and creating a different object, the sense of direct competition is reduced, leading to more collaboration. Students are also afforded the opportunity to learn about the topics they specifically find interesting or necessary to achieve their specific goals, leading small groups to become “class experts” on certain topics.

The guiding challenge is giving students enough skills and background information so that they can make educated and informed decisions about the direction of their creations while balancing the amount of steering that the teacher does. The goal is to have every aspect of the project be student generated, so that they can claim full ownership of the entire creation. Too often, projects and laboratory excursions can feel like students are just going though teacher-defined motions instead of taking control of their entire learning experience.

Another byproduct is that students only learn what the teacher elects to show them. In a sense, this holds knowledge hostage. By opening up the creative process, learning is student-driven, with teams pursuing a combination of the ideas that interest them and the ideas they need to make their vision a reality. In addition, since they will use community and classroom resources, the process will improve their research skills and personal independence.

Objectives

This unit is designed for 11th grade students currently enrolled in a physics course meeting five days per week for 48 minutes at a time with a double blocked lab period on Fridays. The unit assumes a basic working knowledge of linear mechanics, rotational mechanics and DC circuits. Skills like research, programming and tool work will be taught and developed as the unit progresses.

Specifically, students will deconstruct existing objects to identify their component systems and identify the sensor/computer/actuator structure that is intrinsic to robotics. This deconstructed object will then be modified to supply it with new or different functionality and form. Students will then build circuits on breadboards, interpret computer code and then combine the two skills through the use of an Arduino microcontroller in order to automate systems.

Using an iterative process like Design Thinking or TMI, students will create and improve on a design. This process will be documented, blogged, presented and shared both in person and online, allowing students to connect with maker communities and publicize their own achievements and creations.

Strategies

MakerEd, or the application of Maker-based techniques and mentality to education, is a phenomenal way for students to own their learning and the products of it. Students are encouraged to dive right in and start tinkering, figuring out the details and specifics as they go. Martinez and Stager suggest a simple iterative process in their book "Invent to Learn" called TMI: Think, Make, Improve. The structure of each module in the unit is framed around this idea. Each lesson encourages students to improve on what they've made before as they learn the specifics of each skill through implementation.

Design Thinking is a process by which students can create solutions to real problems. Like TMI, it is an iterative process that occurs in stages, but is driven by problem solving. As students go through the process of discovery, interpretation, ideation, experimentation and evolution, they try different approaches to a problem and continually improve them. Should students elect to tackle a practical problem for their final project, Design Thinking provides an excellent framework for their creation.

Students will need access to computers at all stages of the project. It's not expected that the teacher knows how to do everything the students might want to do, but the teacher should be able to help students find what they need. Students should be encouraged to join forums and Twitter conversations with other students and makers in order to find support. Online resources like Make magazine, Hackaday and Instructables can be good starting points, but students should be encouraged to find and converse with other people, including experts and engineers.

Students should, if at all possible, be situated in an open area with access to large tables, tools, computers and materials. At no point should a quiet class be expected. Students will make mistakes and a mess, but they should have ample space to research, discuss, prototype, sketch out designs and spread out. Since the entire unit is a student-driven endeavor, groups will require different things at different times. Having computers, tools and resources all available simultaneously will allow groups to divide work, research on the fly and get to work constructing quickly.

Classroom Activities

All of the modules (and some of the lessons) are designed to be extremely interchangeable. While the skills they learn build on each other and combine in the final stages, you can edit or omit sections based upon the resources you have access to. It's important that the instructor practices using the tools and techniques that they want their students to use. Everything the students are doing is relatively simple – most of the skills can be developed in a weekend.

Module One: Deconstruct, Document and Modify

For the first module, students are developing a set of basic skills that they'll use throughout the remainder of the unit. The major objectives of the first two activities involve developing independent research skills, selecting and using proper tools, reasoning through how complex systems function, documenting processes and reporting through technical writing.

Lesson One: Deconstruct and Document

Each student (or pair of students) starts with a mechanical or electronic toy or device. For the teacher, it's important to have a bunch of these objects around for students who were unable to bring their own. Toys don't have to be fully functional, but should have (at minimum) a few mechanical or electronic aspects and work somewhat. Good places to source these are thrift stores and yard sales, but be sure to keep an eye out for leaky batteries and corrosion on electrical contacts. The free section of Craigslist is also a great place to find or solicit educational donations.

Once students have their devices, their first job is to disassemble them and document with photographs, diagrams and narrative. As an educator, make sure students have access to the tools they may need (screwdrivers and small prybars should do most of the work) and that they're using the tools properly. Emphasize proper sizing of screwdrivers to not strip the screws and making sure that their disassembly is completely reversible. Encourage students to turn on their devices while they're in this disassembled state, play with linkages and see how they actually work.

Students should then turn to computers to research the components contained within. If their devices contain easily identifiable modules or components, have students search Google for the part numbers stamped on them. Some toys have large modder communities that surround them, so encourage students to reach out to them as they attempt to answer the question, "What does it do and how does it work?" Once students have their pictures, diagrams, narrative and explanations, have them reassemble their devices and create a photo blog with pictures and explanations of their teardown and rebuild. If you can find them, show off some of the old Clymer teardown manuals for motorcycles as an example of what it could look like.

Lesson Two: Modify

Once students have their blogs posted, their next step is do modify their object. They can turn back to any forums or modder communities they may have found or look at project depositories like Instructables to find ideas for their modifications. They only requirement is that they add new functionality or modify an existing function. It's important to note that these modifications don't have to be objective improvements; they only need to make the original device into something different. Allow students the freedom to make any nonfunctional cosmetic modifications they like. Students will need to research any sorts of parts or techniques they'll need to use to perform their modifications. The teacher should act as a resource, guiding students, maintaining safety and assisting where needed.

Students will continue documenting their procedures with photographs and blog posts. Their eventual output will be a how-to article published to Instructables that provides step-by-step instructions on how to perform their modifications and a short, informal, presentation and demonstration of their modification. The presentation should contain a photo slide show of the process, a discussion of challenges overcome and a description of a new skill the students acquired in the process.

Module Two: Design and Fabrication

In module two, students will use Computer Aided Design (CAD) packages to design and produce 3D objects. Lessons and suggested software are provided for both 3D printing and 3D carving applications.

Lesson One: 3D Printing

For many students, 3D printing is a total mystery. The teacher should start by breaking the process down. Additive manufacturing, or any process where material is added to make the final product, can be explained through analogy, video or demonstration. To get students immediately started with CAD, try using a simplified browser based solution, like TinkerCAD. TinkerCAD is great because it uses a very Lego-style approach, where students can create complex objects by combining and modifying simpler ones. A short walkthrough and demonstration of the align, grouping and hole tools should give kids the foundation they need to jump right in to designing. From that point, have them make something small. First warning: expect a lot of key chains. After their initial designs are submitted and quickly proofed for overwhelming errors, start printing them while students work on the next stage of the lesson. If you only have access to one printer, this will take some time, so keeping them busy while they wait for their first products is key. If you have access to no printers but still want to teach CAD, just be sure to proof their designs and send them feedback. One of the great advantages of TinkerCAD is that it integrates directly with Thingiverse, a 3D design depository run by MakerBot. Encourage students to publish their first designs on Thingiverse and browse other designs for inspiration.

After their first designs are done, students should be ready and excited to make a more complex design. The key requirements are that they make an original design and publish it on Thingiverse. Their designs will be printed over time as students work on future modules and lessons. If you don't have access to a printer, student designs can be printed for you by a service like Shapeways and student designs can even be left on that site as products that others can purchase and have printed in the future.

Lesson Two: 3D Carving

3D Carving is the modern name given to CNC routers and carving machines that can create complex shapes in full 3D. As a contrast to 3D printing, 3D carving is a subtractive process, meaning that you start with a block of materials and take away pieces to create the object you want.   CNCs are typically extremely expensive industrial equipment, but as 3D printing becomes more popular, smaller and more affordable machines are emerging, making this technology more accessible to students and schools without large equipment budgets.

Students can use TinkerCAD to create their designs. Another, somewhat newer, competitor is called Easel, which is specifically geared toward 3D carving. Students should create designs, produce them and observe the carver working so that it can be compared and contrasted with the 3D printer. Designs will still be published to Thingiverse.

When students are done with their designs and the objects are made, give them a fair-like space to show off their creations and talk about them informally with other students.

Module Three: Circuits and Automation

This module exists to reinforce prior knowledge on DC circuits as well as introduce the sensor>computer>actuator structure that is key to robotics. The Arduino module forms the basis of their final project for this unit.

Lesson One: Circuits

Before attaching things to a microcontroller, it's important that students are able to put the circuit knowledge they have into practice (without frying too many components). Provide students with breadboards, piles of resistors, jumper wires, LEDs, motors, switches, batteries and a multimeter. If students don't have experience using a solderless breadboard, be sure to demonstrate how the terminals are wired.

Start by having students use the multimeter to measure and organize their resistors. Once they know their values, have them construct voltage divider circuits and verify that they provide specific voltages across each resistor. When attaching LEDs, they need to be wired with a resistor in series so that they don't draw too much current and burn out. Have students wire single LEDs and then progress to arrays of multiple LEDs. Students should drive a motor and then vary the voltage and current in the circuits to control the speed and direction.

Lesson Two: Control Coding with Arduino

If you don't have Arduinos available, 123D Circuits is a good online alternative. 123D Circuits uses a virtual breadboard, so it's important for students to have experience with a physical breadboard to make sense of the virtual representation.

The teacher should start by showing the students the Arduino IDE environment and loading the sample sketch "Blink," which causes the onboard LED attached to pin 13 on the Arduino to blink. After breaking down the sample sketch, students should modify the code to have the onboard LED do something different. Using the materials they had from lesson one, the teacher should walk students through attaching an LED to one of the other digital pins and modifying the Blink code to now control that external LED. Once their single LED is working, students will start attaching multiple LEDs to different pins and using the Arduino to control all of them. Advanced students should start to use loops and pulse width modulation (PWM) to control the pattern and brightness of the LEDs, as well. For reference, they can start from the example sketch (Students will post video, wiring schematic and the code they used to control their system to their blogs.

Lesson Three: Responding to Input

Programming LEDs is all well and good, but this entire process gets significantly more interesting when student creations are able to make decisions based upon input. The instructor should start by explaining and demonstrating if/else statements as a way to make decisions. A good demonstration would be trying to write a series of if/else statements to sort a classroom by age. Have students start generating instructions and then carry them out, so they can see flaws in their logic and develop an idea of how to write coherent and solid if/else statements.

Working again from example sketches (Button, AnalogInput), students should take an input device (button, potentiometer or switch) and use if/else statements to control their LED array. Once students feel comfortable making decisions based upon their input device, they should design a simple game that can be played using their LED array and device.

Lesson Four: Control Something Else

At this point, students should start having all sorts of different ideas of things they could possibly control with an Arduino. One of the great things about the platform is that it's so open ended with a huge amount of community support. Their next task should be controlling something new. If students have their own ideas of what to automate, great! If they don't, there are inexpensive RGB LED bulbs and strips, buzzers, servos, motors, vibration sensors, temperature sensing transistors, accelerometers and a whole host of other sensors and objects that students can control. For whatever they do, students will update their blog and include a link to a how-to and code they've posted to Instructables. After students have finished their projects, there will be another informal fair-type sharing session.

Module Four: Tying It All Together

At this point, students should be well acquainted with online resources, documenting their builds, basic techniques and a few different types of control and fabrication. From here, it's their time to shine and make something. The actual parameters should be completely open, with the only actual requirement be that it is Arduino controlled and responds to some sort of input. This leaves space for purely creative projects that are more like physics-based art to coexist with engineered solutions to real world problems. Students should plan and research their projects before they get started. The builds will be documented on their blogs with daily postings that include photos, reflections and reference links. A final "polished" version of their how-to will get posted on Instructables. The role of the teacher during this is mostly as guiding resource. Students should be pushing themselves to learn new techniques and find new resources to make their vision a reality. Don't be afraid to challenge or guide them, but the true place for the instructor is as a roaming resource.

When the students have finished, that's the time to plan a big event for them to show off their creations. Having students invest in setting up a school MakerFaire is a great way for them to demonstrate to future students what sorts of things they're doing in your class. Coordination can also be done with the art department to show off other types of student-produced work. The short informal presentations and constant blogging will help students prepare to discuss their work in the casual setting.

Endnotes

An enormous push in education reform seems to be in the direction of more assessment. How does an educator assess authentic projects and learning experiences like these? The projects themselves should be immune from assessment, because there's no right way to classify something one student made as "better" than another. The importance and value in this style of learning is that it is self-guided and fueled by projects that the students are interested in and passionate about. The blogging, formal reporting and loose requirements for each lesson provide ample opportunity for students to communicate about the work that they've done and be assessed based upon the quality and development of that communication. Students are required to write about their work, photograph their work, videotape their work and talk about their work, leaving space for any type of student to effectively communicate.

Annotated Bibliography/Resources

Reading List

Lang, David. *Zero To Maker: Learn (Just Enough) to Make (Just About) Anything.* Maker Media, 2013.

David Lang's book is part autobiography, part how-to. If you're not familiar with making, tinkering and building things on your own, he outlines how he went from being curious to being productive in a clear and accessible way. There's a lot of theory and background on what motivates him to make, how to procure materials and how to develop a supportive community feel. Much of what he says is directly applicable to how you'll approach implementing MakerEd in your classroom.

Libow Martinez, Sylvia. *Invent To Learn: Making, Tinkering and Engineering In The Classroom.* Constructing Modern Knowledge Press, 2013.

This book is the absolute best text on MakerEd projects that exists. It covers essentially every aspect, from designing good prompts, to collecting materials, to convincing administration to allow you to set up a space. The first part is all well-reasearched educational theory, while the rest is just practical considerations. If there's only one book on this list that you physically buy, make it this one.

Make: Education. <http://makezine.com/education/>

This is the education section of *Make* magazine, the most prolific publication within the Maker movement. The education section of their website is a monstrous collection of resources, from instructions on fabricating tables, to contacts for other educators, to local MakerFaire events to just project ideas and galleries. It's frequently updated and full of amazing resources.

Teacher Resources

Design Thinking for Educators. < http://www.designthinkingforeducators.com/>

A primer for educators on the process of design thinking. It contains K-12 specific resources for implementing the Design Thinking process in your classroom projects.

MakerBot Education. <http://curriculum.makerbot.com/>

MakerBot is the company that makes the Replicator 2, which is one of the most effective (and nicest looking) 3D printers for educational settings. They devote a great deal of time and resources to educational uses for 3D printers and here is where you can find models, lesson plans and other resources.

MakerSpace Playbook. PDF requested from: http://makerspace.com/

This PDF is incredibly organized material lists, safety procedures and practical suggestions to help you get your own MakerSpace outfitted and off the ground.

Shapeways. <http://www.shapeways.com/>

Shapeways is a 3D printing resource that can allow you to order physical prints of your designs, in case you don't have access to a 3D printer. Prices are somewhat expensive, but if a printer isn't in your budget, student fees could fund the prints. They also have an option to upload and sell your designs.

Student Resources

Adafruit Learning System. <http://learn.adafruit.com/>

Adafruit is a company that sells electronics kits and components. They've made a big commitment to bringing Electrical Engineering to high school students, so they have tons of kits and projects that are targeted toward young adults and children. Their Learning System is full of tutorials and how-to information for different techniques, like programming, soldering and other key bits that will be incredibly valuable and inspirational to students.

DIY.org. <http://diy.org>

An alternative to Instructables, DIY.org is a more kid-targeted project documentation site. They have a great iPhone app and achievement based skill development to help scaffold kids on their way to learning new and interesting skills. Sharing your projects and achievements is built into the site, so it's also a great way for students to safely connect with likeminded makers.

Easel. <http://easel.com>

Easel is free browser-based software designed to easily develop designs and tool paths for 3D carving machines. It's actively developed by the people who make the Shapeoko 2, entirely browser based and incredibly easy to use.

Instructables. <http://www.instructables.com/>

The best of the project depository sites. They have an enormous library, great features, are free to use and are the site of choice to document projects for most college engineering departments. Students will be able to create free accounts, follow projects they think are interesting, network with each other and share their work with text, photos and video. It's a great resource for documentation and inspiration.

Kemp, Adam. *The Makerspace Workbench.* Maker Media, 2013.

A perfect primer for people who are curious about making things but don't have a ton of experience. Adam goes through everything from planning a safe space to work in, to safety procedures and quizzes to descriptions of different types of tools and fasteners and their uses. A really great reference to have around for yourself and your students.

Make: Projects. <http://makezine.com/projects/>

An project site from Make Magazine that is good to use for inspiration and the large and polished collection of how to articles. They rank their projects based on difficulty and have an easy to search database.

TinkerCAD. <http://tinkercad.com>

Browser-based CAD software designed with ease of use in mind. Really simple drag-and-drop functionality based on simple shapes. Built in cloud storage for projects, so students can easily work on their projects at home and then bring them to school. Plays very nicely with many different printers and can automatically share designs on Thingiverse.

Classroom Materials

3D Printers

There are a lot of options and a lot of different routes you can take when purchasing a 3D printer. One issue is that the technology is advancing incredibly rapidly. Should you build one? Should you buy one? I procured a MakerBot Replicator 2 for our school and would recommend it to anyone. It's easy to use, can be run and serviced by students and looks attractive (which is a motivator for some). MakerBot also has a huge investment in education that includes great customer support and partnerships with DonorsChoose, so you could crowdfund a machine for your classroom.

3D Carvers

CNC machines are typically incredibly expensive, but are (in my eyes) the ultimate in automated fabrication. A company called Inventables (http://inventables.com) sells a kit called the Shapeoko 2 that is incredibly affordable (1/3 the price of a 3D printer), making it a good choice for the classroom. Inventables is also actively developing the Easel platform, which is user friendly, browser based and has built in cloud storage. Easel functions essentially like a 3D carver-specific version of TinkerCAD that also circumvents all of the other advanced software packages usually necessary to run a CNC.

Arduino

For microcontroller programming, nothing beats Arduino. They're around $30 each, making them incredibly affordable for the functionality you get. I'd suggest getting the Uno, as it's the most common and compatible version. All the software you need to run them is totally free, there's a huge user community and they're the community standard for tinkering with microcontrollers. There's also a large number of different boards, each with slightly different functionality, that all work of the same programming language that is (essentially) identical to C.

Appendix-Content Standards

Next Generation Science Standards

Many states have already adopted the Next Generation Science Standards, which are organized based upon a number of different practices. This unit directly addresses the following standards"

- Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena and solve design problems, taking into account possible unanticipated effects.
- Design, evaluate, and/or refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations.
- Compare and evaluate competing arguments or design solutions in light of currently accepted explanations, new evidence, limitations (e.g., trade-offs), constraints, and ethical issues.
- Evaluate competing design solutions to a real-world problem based on scientific ideas and principles, jointly developed and agreed-upon design criteria, empirical evidence, and/or logical arguments regarding relevant factors (e.g. economic, societal, environmental, ethical considerations).
- Compare, integrate and evaluate sources of information presented in different media or formats (e.g., visually, quantitatively) as well as in words in order to address a scientific question or solve a problem.
- Gather, read, and evaluate scientific and/or technical information from multiple authoritative sources, assessing the evidence and
- Communicate scientific and/or technical information or ideas (e.g. about phenomena and/or the process of development and the design and performance of a proposed process or system) in multiple formats (i.e., orally, graphically, textually, mathematically).

In addition, on the topic of Reflecting on the Processes of Science and Engineering, the authors of the standards state:

> Engaging students in the practices of science and engineering outlined in this section is not sufficient for science literacy. It is also important for students to stand back and reflect on how these practices have contributed to their own development, and to the accumulation of scientific knowledge and engineering accomplishments over the ages. Accomplishing this is a matter for curriculum and instruction, rather than standards, so specific guidelines are not provided in this document. Nonetheless, this section would not be complete without an acknowledgment that reflection is essential if students are to become aware of themselves as competent and confident learners and doers in the realms of science and engineering.

State Standards

The Philadelphia School District is making the shift to the PA Common Core set of standards. The college and career ready standards in Language and Mathematics that are supported by this unit are as follows:

Writing:

- Write informative/explanatory texts to examine and convey complex ideas and information clearly and accurately through the effective selection, organization, and analysis of content.
- Use technology, including the Internet, to produce and publish writing and to interact and collaborate with others.
- Conduct short as well as more sustained research projects based on focused questions, demonstrating understanding of the subject under investigation.
- Gather relevant information from multiple print and digital sources, assess the credibility and accuracy of each source, and integrate the information while avoiding plagiarism.
- Draw evidence from literary or informational texts to support analysis, reflection, and research.

Speaking and Listening:

- Present information, findings, and supporting evidence such that listeners can follow the line of reasoning and the organization, development, and style are appropriate to task, purpose, and audience.

- Make strategic use of digital media and visual displays of data to express information and enhance understanding of presentations.

Language:

- Acquire and use accurately a range of general academic and domain-specific words and phrases sufficient for reading, writing, speaking, and listening at the college and career readiness level; demonstrate independence in gathering vocabulary knowledge when encountering an unknown term important to comprehension or expression.

Standards of Mathematical Practice:

- Make sense of problems and persevere in solving them.
- Reason abstractly and quantitatively.
- Construct viable arguments and critique the reasoning of others.
- Use appropriate tools strategically.