i.e.: inquiry in education

Volume 8 | Issue 2 Article 5

2016

Engineering Design for Engineering Design: Benefits, Models, and Examples from Practice

Ken L. Turner Jr.
University of Dubuque, kturner@dbq.edu

Melissa Kirby
Kettle Moraine School District, kirbym@kmsd.edu

Sue Bober
Schaumburg High School, sbober@d211.org

Follow this and additional works at: http://digitalcommons.nl.edu/ie

Recommended Citation
Turner, Ken L. Jr.; Kirby, Melissa; and Bober, Sue. (2016). Engineering Design for Engineering Design: Benefits, Models, and Examples from Practice. *i.e.: inquiry in education: Vol. 8: Iss. 2, Article 5.*
Retrieved from: http://digitalcommons.nl.edu/ie/vol8/iss2/5

Copyright © 2016 by the author(s)

i.e.: inquiry in education is published by the Center for Practitioner Research at the National College of Education, National-Louis University, Chicago, IL.

Cover Page Footnote
Ken Turner, Melissa Kirby, and Sue Bober acknowledge and extend gratitude for the support from professors, teachers, administrators, and students from University of Dubuque, Kettle Moraine School District, and Schaumburg High School

This article is available in i.e.: inquiry in education: http://digitalcommons.nl.edu/ie/vol8/iss2/5

Engineering Design for Engineering Design

Benefits, Models, and Examples From Practice

Ken L. Turner, Jr.
University of Dubuque, Dubuque, USA

Melissa Kirby
Kettle Moraine School District, Wales, USA

Sue Bober
Schaumburg High School, Schaumburg, USA

Abstract

Engineering design, a framework for studying and solving societal problems, is a key component of STEM education. It is also the area of greatest challenge within the Next Generation Science Standards (NGSS). Many teachers feel underprepared to teach or create activities that feature engineering design, and integrating a lesson plan of core content with an engineering design perspective can be a daunting task. Nevertheless, engineering design can be a useful tool in building students' confidence in science, engaging students in science classes, building relationships with the community, and empowering underrepresented groups.

The problem-solving approach of engineering design can become a template for how a teacher creates new engineering design activities. Engineering design is an ally to the teacher framing the process so that the teacher can creatively and collaboratively find innovative ways to reach and teach their students. The Engineering Design Wheel for Teachers can help teachers to get organized, and the Engineering Design Quality Framework can help teachers to self-assess the newly created activity.

Key words: engineering design, NGSS, STEM, curriculum

Introduction

STEM education, whose areas relate to and often integrate science, technology, engineering, and math, is an important topic in science education and education in general. The unmet need for people with STEM education and skill is becoming a worldwide concern (English, Hudson, & Dawes, 2012). Given that there is an increase in demand but a decreasing supply, the benefits for those students who choose STEM fields can be enormous. The Next Generation Science Standards (NGSS) remind us that science continues to be the pivotal education thread if the US is to continue to exert leadership in innovation and job creation (2013). The international recognition of the necessities of scientific literacy is noted by Sever and Guven (2014), “The need for individuals literate in science and technology who will carry their societies into contemporary civilization has been understood by the international education community” (p. 1601). Thus, the need for STEM education is understood both in terms of providing a better life for the individual as well as holding benefits for the student’s community and country as a whole.

Engineering tends to be the part of STEM that gets left out. Many teachers feel underprepared to teach engineering design (Turner, 2015a; Turner, 2015b). Engineering design has not typically been a part of college science education curricula (Lederman & Lederman, 2013). And it may be the most challenging part of the NGSS (Padilla & Cooper, 2012). But the benefits to using engineering design are too numerous to ignore. Engineering design is one of the standards within the NGSS. Each standard purposely integrates the three dimensions, Science and Engineering Practices, Disciplinary Core Ideas, and Crosscutting Concepts (NGSS, 2013). We are suggesting that the problem-solving perspective of engineering design can be used by teachers to collaboratively create science/STEM activities that teach and utilize engineering design. This will lead to more engaged students, with benefits for those students. The purpose of this paper is to provide clarity and support for teachers in creating engineering design activities.

Engineering design is typically not the focus of the unit you create; instead, it is the perspective through which the unit is taught.

What Is (and Is Not) Engineering Design

There are some misconceptions about engineering design. Because it contains the word “engineering,” it is often thought that only an engineer can teach the material, or that an engineering design activity will require something to be built. But the “engineering” in engineering design has more to do with an engineer’s perspective on problem solving than a requirement for engineering coursework. And, although it can have physical construction (bridge building and testing in physics classes, for example), it does not have to have that component. Engineering design is also evaluating solutions against a wide range of constraints and criteria, using computational thinking or software to model competing solutions, and/or iteratively proposing and testing solutions.

Another common misconception we have encountered is that teachers often think they will need to create a unit designed specifically to teach engineering design. Engineering design is typically not the focus of the unit you create; instead, it is the perspective through which the unit is taught. The goal is to teach core content and science and engineering practices *through* engineering design. That is not to say that students will already know how to “do” engineering design. It is possible that students in your building may not yet have any experience with it. The background knowledge in engineering design depends on the state, the community, even the building where the lesson is taught. Every community of learners has had a different pathway in their adoption of NGSS and engineering design. But whatever level of experience your students have will be used as the instructor begins to imagine and create the unit of study.

Benefits of Teaching Engineering Design

Students can learn more and be more engaged when learning with an engineering design perspective (Heroux, Turner, & Pellegrini, 2010). Students who are taught with engineering design can become more self-motivated (Coryn, Pellegrini, Evergreen, Heroux, & Turner, 2011). The effectiveness of the instruction increases when students are more involved in their learning, and engineering design places the student in the role of scientist/engineer. The student *is* the scientist/engineer.

Furthermore, Cooper (2013) reminds us that we are doing a disservice to our students if we do not mindfully incorporate engineering design into our lessons. Students seek an engaging experience. Hattie (2009) states, “In the end, it is the students themselves, not teachers, who decide what students will learn. Thus, we must attend to what students are thinking, what their goals are, and why they would want to engage in learning that is offered in schools” (p. 241). Engineering design puts the student in the position of scientist/engineer, a very engaging perspective for the student, and this increase in student engagement can lead to gains in student achievement. Metz (2014) argues for the use of engineering design based on its ability to foster learning at a deeper level, increasing scientific literacy and empowering portions of the population that are historically underrepresented in science and engineering fields. For all of these reasons and more, we need to overcome any barriers that stand between our students and our use of engineering design in instruction.

Engineering Design: Designing the Lesson

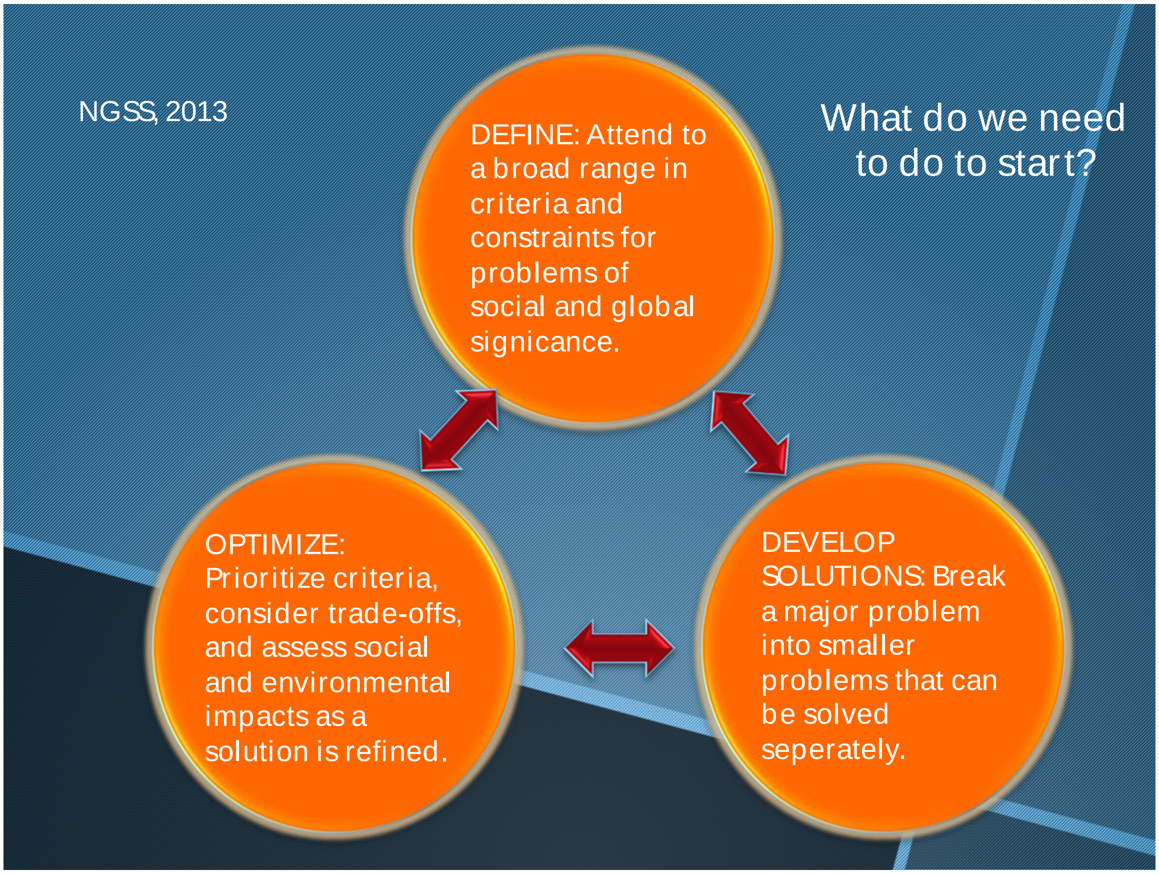
How can we create a lesson that uses engineering design by using engineering design? Start in collaboration, working with a like-minded colleague who teaches the same subject or level. Also, collaborate with many teachers using a web support system like Maker Space (makerspace.com). Once collaborators have been identified, begin with the three interlinked areas of engineering design found in Appendix I of NGSS: Define, Design, and Optimize (2013):

- **Define**: Attend to a broad range of considerations in criteria and constraints for problems of social and global significance.

- **Design**: Break a major problem into smaller problems that can be solved separately.

- **Optimize**: Prioritize criteria, consider trade-offs, and assess social and environmental impacts as a complex solution is tested and refined.

Figure 1 illustrates these interrelated facets. The definitions are modified depending on the grade level; high school level is shown. If an activity contains any part of these three areas, the lesson has at least a portion of the engineering design perspective. Consider how this perspective might be used to create a new unit.



NGSS, 2013

What do we need to do to start?

DEFINE: Attend to a broad range in criteria and constraints for problems of social and global signicance.

DEVELOP SOLUTIONS: Break a major problem into smaller problems that can be solved seperately.

OPTIMIZE: Prioritize criteria, consider trade-offs, and assess social and environmental impacts as a solution is refined.

Figure 1. The interrelated facets of Define, Develop, and Optimize (NGSS, Appendix I, 2013).

Designing a *perfect* engineering design unit or lesson may not be attainable. However, what we can do is use a particular design, test it in practice, and improve it as necessary. In other words, piloting a particular design activity will result in the need to improve it for the second iteration (much like engineering design practice). Also, it is unlikely that the unit a teacher designs and implements in his or her building will be identical to the one employed by other teachers. One’s building, classroom, and community are unique, and so is the project one creates. The notion of creating a new unit from scratch can be daunting. One of the purposes of this study is to provide the reader with some templates as guidance. Please note that these templates are generic. The same guidelines cannot be used to create both an evolutionary project for freshman biology and a biodegradable plastics unit in chemistry or a forces and bridge-building unit in physics. Therefore, these templates are meant to be adaptable and to help organize the unique design that one might create.

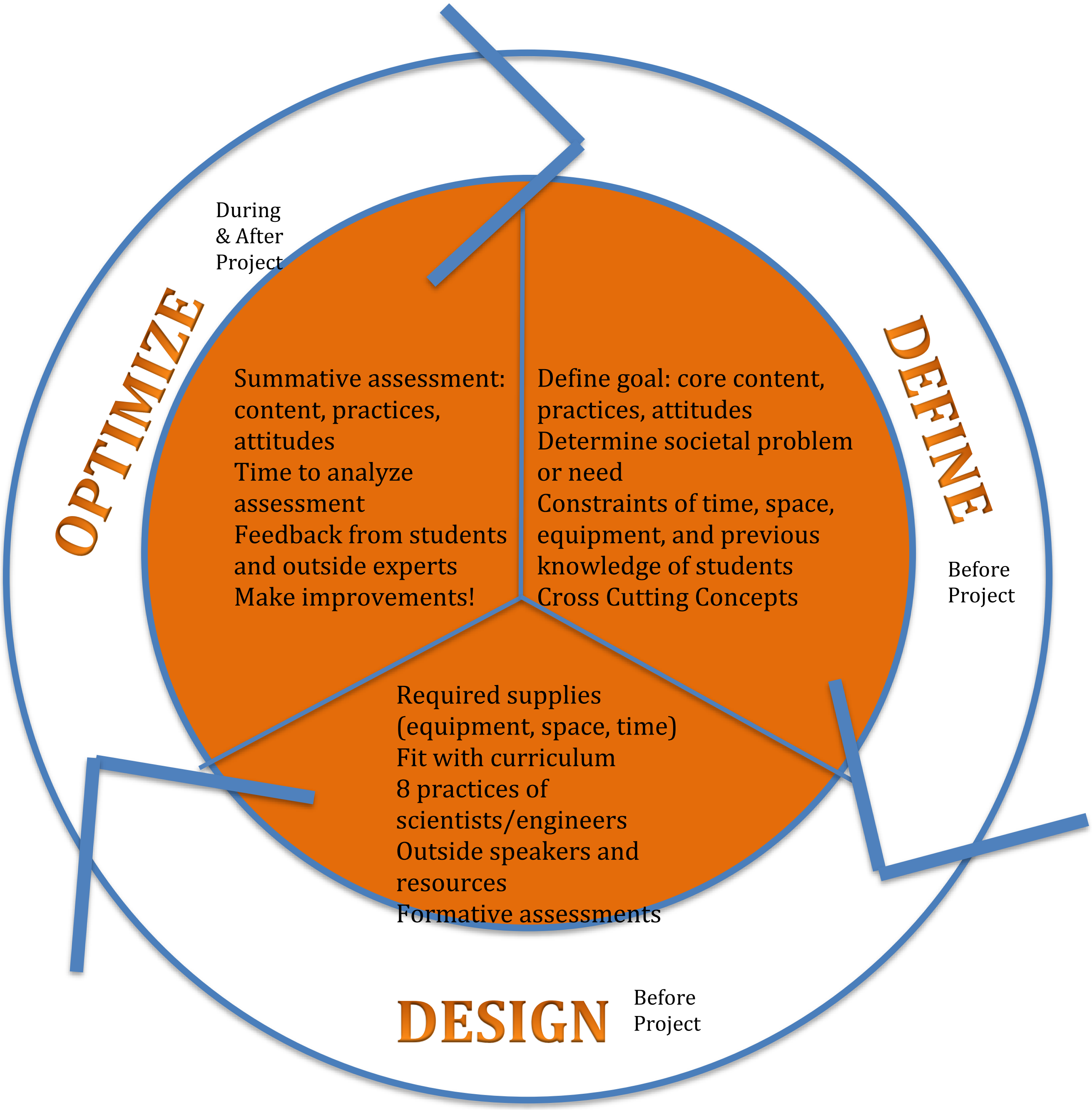


Figure 2. The Engineering Design Wheel for Teachers: an organizational tool to help teachers create activities.

Figure 2 is one of these adaptable templates. It demonstrates some of the most important things a teacher has to consider when designing an engineering design project. Start with the Define stage and move toward the Design stage, both of which should be completed before the students are ready for the project. The Optimize stage is implemented while the students are working on and completing their projects. The process of optimization is intended to improve the project and start over again, moving through the wheel. What follows is a detailed description of each step of the Engineering Design Wheel for Teachers.

Define
Creating activities that utilize engineering design requires a thorough consideration of determining the criteria and the constraints for the problem to be solved. The criteria would probably begin with the core content to be covered. Perhaps the teacher is hoping to teach solution chemistry in a chemistry class, or a unit on evolution in a biology class, or energy concepts in a physical science class. List the objectives or goals for the unit. These are the criteria for the problem, the problem of writing a unit that utilizes engineering design.

As an example of how the first step might look, Table 1 shows the criteria for the goal of writing a new unit on natural selection and evolution. This unit was cowritten by the authors and implemented with excellent results in MK's classes. Similarly, designing an engineering design-rich lab for a college chemistry class could involve a goal of minimizing the impact of microbeads in the environment (Hoffman & Turner, 2015). Choosing which part(s) of Define, Design, and Optimize are also part of the criteria. Thus, determine which parts of Define, Design, and Optimize, or all of them, to use based on the content of the unit and its purposes.

Table 1

Criteria (Core Content Objectives) for the Goal of Writing a New Unit on Natural Selection and Evolution Through the Engineering Design Perspective for a High School Biology Class

HS-LS4-1	Communicate scientific information that common ancestry and biological evolution are supported by multiple lines of empirical evidence.
HS-LS4-2	Construct an explanation based on evidence that the process of evolution primarily results from four factors: (a) the potential for a species to increase in number, (b) the heritable genetic variation of individuals in a species due to mutation and sexual reproduction, (c) competition for limited resources, and (d) the proliferation of those organisms that are better able to survive and reproduce in the environment.
HS-LS4-3	Apply concepts of statistics and probability to support explanations that organisms with an advantageous heritable trait tend to increase in proportion to organisms lacking this trait.
HS-LS4-4	Construct an explanation based on evidence for how natural selection leads to adaptation of populations.
HS-LS4-5	Evaluate the evidence supporting claims that changes in environmental conditions may result in: (a) increases in the number of individuals of some species, (b) the emergence of new species over time, and (c) the extinction of other species.
HS-ETS1-1	1.1 Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.
HS-ETS1-2	Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

HS-ETS1-3	Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.
HS-ETS1-4	Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

Returning to the specific project on natural selection and evolution for a high school biology class (Table 1), note that the criteria have been specifically chosen to address the eight practices of scientists and engineers (NGSS, 2013). HS-LS4-2 and HS-LS4-4 specifically address the practice of “constructing explanations” and “engaging in argument from evidence.” HS-LS4-3 addresses the practice of “using mathematics and computational thinking.” HS-ETS1-1 addresses the practice of “analyzing and interpreting data.” HS-ETS1-2 addresses the practice of “asking questions and/or defining problems.” The entire project addresses the practice of “planning and carrying out investigations,” as well as the practice of “obtaining, evaluating, and communicating information.” Careful choices of the core content can build in the eight practices of scientists and engineers.

Each of the above objectives (criteria) were met as teams of students undertook a four-part natural selection and evolution project. In Part 1, student teams “created” organisms with characteristics that helped it to survive in the habitat they chose for it. They defined the population and the alleles for the traits that helped it to survive. In Part 2, teams suggested possible environmental stresses for their organism—the teacher modified one of these and sent it back to the group. In Part 3, teams chose a means to assign fictitious alleles for a particular trait to their population of 50 organisms. The teacher determined ahead of time if the dominant or recessive trait was selected by the environmental stress. If the organism had the correct combination of alleles, it survived to reproduce. If it did not, it did not survive to reproduce. Several generations of their organism were “impacted” by the environmental stress. Teams then ran a Hardy-Weinberg test on the changes in the population over time. In Part 4, student teams had to support an argument with evidence explaining how the environmental pressure affected the adaptation of a species. Teams did an allele map of five generations illustrating the Hardy-Weinberg equilibrium equation and the changes in the population over time. The entire project culminated with a report from each team to a class of fifth graders. Part of the engineering design for the students was determining the best way to present the information.

No doubt this is a very specific project crafted by a team of teachers in one school, but hopefully readers can see how a mindful selection of core content objectives can be “teamed” with appropriate scientific and engineering practices. In the same way, specific core content can be articulated to previous (and future) learning through the cross-cutting concepts. Again returning to the unit on natural selection and evolution, an emphasis on the cross-cutting concepts of Patterns, Structure & Function, and Stability & Change helped to anchor the new learning within the previous patterns learned by students.

Once the criteria for the goal have been set, the constraints should be considered. The limitations of time and space make for very real constraints within the classroom. How many days (or how many minutes) are available for this unit or project? How much time is there to prepare for the unit? What space will be available for the students to use? What are the typical resources available in the classroom for the students to use? Being aware of these constraints can help to narrow the focus and create an opportunity that requires only what resources are available. It can also make the teacher acutely aware of what resources should be added to the equipment/materials for students. In the creation of a unit on energy which involved the construction of a functioning roller coaster track, finding space for each team's 12 feet of foam insulation was quite a constraint: six different classes and 30 teams were constructing a track in the same room!

Design

Designing solutions often requires breaking a big problem down into manageable pieces. In the case of creating an engineering design-rich experience for teaching science content, it will probably require some brainstorming. We recommend the use of collaboration and brainstorming, as well as personal experiences, in developing the projects that support student experiences. Creating engineering design lessons begins with the criteria and constraints previously established in the Define section. Solving small problems gets one closer to solving the overall problem. Thus, determining a schedule of activities is one of those important smaller, more manageable problems. Determining different means of assessment is also an important manageable problem.

Determining a societal problem or need that can be used to teach the goals is a very important step forward. This is perhaps the step that most easily lends itself to the collaborative process. We found it much easier to brainstorm with a colleague or two than do it as a solo act. For example, students can create a battery to learn the activity series or redox reactions; the dead zone can be used to teach solution chemistry; or perhaps cardboard boats can be used to teach area, volume, density, and buoyancy (Nemetz, Noah, & Turner, 1996).

Another tool that we recommend is the Engineering Design Quality Framework (Table 2). As the planning for the project is progressing, this framework may help teachers to self-assess some of the important components of designing an engineering design activity or project. Table 2 has been adapted from the STEM Education Quality Framework (Pinnell et al., 2013, p. 29).

Table 2

Engineering Design Quality Framework (Adapted From Pinnell et al., 2013)

Components	Quality Standard
Integrity of the Academic Content	Learning experiences are content-accurate, anchored to the relevant core content, and focused on the cross-cutting concepts and practices critical to future learning in the targeted discipline(s).
Design Incorporates	Learning experiences require students to demonstrate

Science and Engineering Practices	knowledge and skills fundamental to science and engineering practices: • Asking questions and/or defining problems • Developing and using models • Planning and carrying out investigations • Analyzing and interpreting data • Using mathematics and computational thinking • Constructing explanations and/or designing solutions • Engaging in argument from evidence • Obtaining, evaluating, and communicating information
Design Ties to Cross-Cutting Concepts	Learning experiences articulate with and build onto previous knowledge—and anticipate future experiences—through broad areas of integration: • Patterns • Causation • Scale • Systems • Energy • Structure & function • Stability & change
Authenticity & Relevancy of Societal Need/Problem	The chosen project reflects an authentic societal need or problem—which is perceived as relevant by students.
Adaptive Environment	Learning experience has adaptability to reach various levels of students.
Potential for Engaging Students of Diverse Academic Backgrounds	Learning experiences are designed to engage the mindset and imagination of students of diverse academic backgrounds.
Quality of the Cognitive Task	Learning experiences challenge students to develop higher order thinking skills through processes such as inquiry, problem solving, and creative thinking.
Connections to STEM Careers	Learning experiences place students in learning environments that help them to better understand and personally consider STEM careers.
Individual Accountability in a Collaborative Culture	Learning experiences often require students to work and learn independently and in collaboration with others using effective interpersonal skills.
Nature of Assessments	Assessments gauge content, practices, and attitudes.

	Assessments are valuable for improving project. Learning experiences require students to demonstrate knowledge and practices, in part, through performance-based tasks.

Optimize

If the goal is to create an engineering design-rich experience that teaches science content, the Optimize portion of the process is to make it the best activity possible. It is impossible to know exactly how an activity will work before trying it out in the classroom, but the teacher can (and should) test the activity thoroughly before attempting it. Is this project safe for the students and instructor? Is it grade-level appropriate? Will the students find the challenge engaging and authentic? Can the project be accomplished in the time that has been set aside for it? Do the students have the background knowledge to understand the problem and suggest solutions, or will they need to search for this information? How will the students and the project be evaluated?

Choosing to engage students with the authentic problem-solving approach of engineering design can better prepare them for their futures.

The optimization process deals with evaluation and improvement of the project. Formative and summative evaluations of the students’ learning outcomes belong in the Optimize area. Formative evaluations are those that occur during the lesson, so that the teacher can make improvements as the activity unfolds. Summative evaluations occur at the end of the unit and help the teacher improve the activity the next time it is taught. Evaluating the activity goes beyond assessing student performance on the goals, but it can start there.

Conclusion

Choosing to engage students with the authentic problem-solving approach of engineering design can better prepare them for their futures. K-12 science educators now have standards—NGSS, in the process of being accepted state-by-state—that require teaching engineering design. Teacher education programs should also be motivated to bring engineering design to their classroom and lab practices. Engineering design is essential to preparing future scientists and engineers who can ask questions, develop models, and argue from evidence (Cooper, 2013). These are the skills that need to be addressed in K-20.

The time is ripe for educators to collaboratively create a new activity that teaches core content through the practice of engineering design. Teachers can determine the criteria for the success of the activity, even within the constraints of time, space, and materials. They can use the Engineering Design Wheel for Teachers to help plan the new activity. As they plan, they can use the Engineering Design Quality Framework to self-assess the value of what they are writing. The immense effort that will be spent writing this new activity carries with it immense rewards.

Creating a new activity that teaches core content within the practice of engineering design will increase the engagement of students and may increase the likelihood that they will pursue a STEM-related career. This can result in personal gains for the student as well as tangible gains for their community and country. Empowering our students to solve problems from an engineering design perspective while engaging students in real-world problems will change our youth—and change our world!

*Ken L. Turner, Jr., past National Board Certified K-12 instructor, is an assistant professor of science education at University of Dubuque, where he teaches classes in general chemistry, STEM methods, engineering design, and research writing. He earned his EdD from National Louis University. He continues to pursue research at the intersections of chemistry (and broader science), materials science, engineering design, and education. He is coauthor of two supplementary texts (*Composites *and* Smart Sensors *through the Materials World Modules team at Northwestern University) and several manuscripts.*

Melissa Kirby graduated from Carroll University with a bachelor's degree in biology, and then received a master's degree in administrative leadership at the University of Wisconsin-Milwaukee. She has over 16 years of biology teaching experience in high school education. She spent four years teaching the art of teaching at Aurora University George Williams College. Currently, she spends most of her time teaching biological sciences and Project Lead the Way at Kettle Moraine High School. She is also the Science Curriculum Specialist at KM Global.

Sue Bober has been a teacher for 25 years. Currently she teaches at Schaumburg High School in Schaumburg, Illinois. She is a member of the ChemWest Teacher Organization near Chicago, and she has been a frequent attendee of ChemEd conferences.

References

Cooper, M. (2013). Chemistry and the Next Generation Science Standards. *Journal of Chemical Education, 90*(6), 679-680.

Coryn, C., Pellegrini, B., Evergreen, S., Heroux, K., & Turner, K. (2011). Psychometric properties of the science esteem inventory. *Journal of Materials Education, 33*(3-4), 189-202.

English, L., Hudson, P., & Dawes, L. (2012). Engineering design processes in seventh-grade classrooms: Bridging the engineering education gap. *European Journal of Engineering Education, 37*(5), 436-447.

Hattie, J. (2009). *Visible learning: A synthesis of over 800 meta-analyses relating to achievement.* New York, NY: Routledge.

Heroux, K., Turner, K., & Pellegrini, B. (2010). The MWM approach to technological design. *Journal of Materials Education, 32*(5-6), 231-240.

Hoffman, A., & Turner, K. (2015). Microbeads and engineering design in chemistry: No small educational investigation. *Journal of Chemical Education, 92*(4), 742-746.

Lederman, N., & Lederman, J. (2013). Next Generation Science teacher educators. *Journal of Science Teacher Education, 24*, 929-932.

Metz, S. (2014). Engineering a new world. *The Science Teacher*, *81*(9), 6.

Nemetz, J., Noah, J., & Turner, K. (1996). What floats your boat? *The Science Teacher*, *63*(9), 44-46.

Next Generation Science Standards (NGSS). (2013). *Next Generation Science Standards*. Retrieved from www.nextgenscience.org

Padilla, M., & Cooper, M. (2012). From the framework to the Next Genreration Science Standards: What will NGSS mean for STEM faculty. *Journal of College Science Teaching, 41*(3), 6.

Pinnell, M., Rowly, J., Preiss, S., Blust, R., Beach, R., & Franco, S. (2013). Bridging the gap between engineering design and PK-12 curriculum development through the use of the STEM Education Quality Framework. *Journal of STEM Education 14*(4), 28-34.

Sever, D., & Guven, M. (2014). Effect of inquiry-based learning approach on student resistance in a science and technology course. *Educational Sciences: Theory and Practice, 14*(4), 1601-1605.

Turner, K. (2015a). Engineering design case study: Faculty perceptions on preparedness. *Journal of Materials Education, 37*(3-4), 119-136.

Turner, K. (2015b). Perceived barriers and solutions: Engineering design implementation. *Theses and Dissertations*. Retrieved from http://digitalcommons.nl.edu/diss/122/