Real-World Design Challenges - A Crucial Component of STEM Teaching and Learning

Rebecca Jaramillo[1] [Colin Britcher[2]]

Abstract – Educators at the National Institute of Aerospace's Center for Integrative STEM Education (CISE) develop engineering design challenges for the K-12 classroom. As experienced teachers, NIA educators bring an understanding of student learning and real-world experiences with practicing scientists and engineers to the classroom. Current research drives the development of each design challenge and the accompanying professional development opportunities for educators.

Each challenge developed by the CISE educators is a real-world engineering problem identified by NASA with unique components, ranging from a virtual world platform to interactions on the International Space Station. All challenges incorporate a balance of hands-on activities, modeling and simulation, and testing. Reflective practices are encouraged through open-ended design packets. Access to scientists and engineers is provided to teachers and students through video clips, online tutorials, or synchronous webinars.

This paper will document the CISE team's recent experiences in developing and delivering this wide range of real-world design problems.

Keywords: engineering, design, challenges, NIA, NASA

IMPORTANCE OF ENGINEERING DESIGN CHALLENGES

Standards-Based Relevance

With the unveiling of the 2011 Framework for K-12 Science Education, engineering suddenly became the latest buzz word in the educational arena. The committee responsible for developing the next generation science standards identified three dimensions that should be prevalent in K-12 science education: scientific and engineering practices; crosscutting concepts that unify the study of science and engineering through their common application across fields; and core ideas in four disciplinary areas: physical sciences; life sciences; earth and space sciences; and engineering, technology, and the applications of science [National Research Council,13].

[1] National Institute of Aerospace, 1100 Exploration Way, Hampton, VA 23666, rebecca.jaramillo@nianet.org
[2] Old Dominion University and the National Institute of Aerospace, 100 Exploration Way, Hampton, VA 23666, cbritche@odu.edu

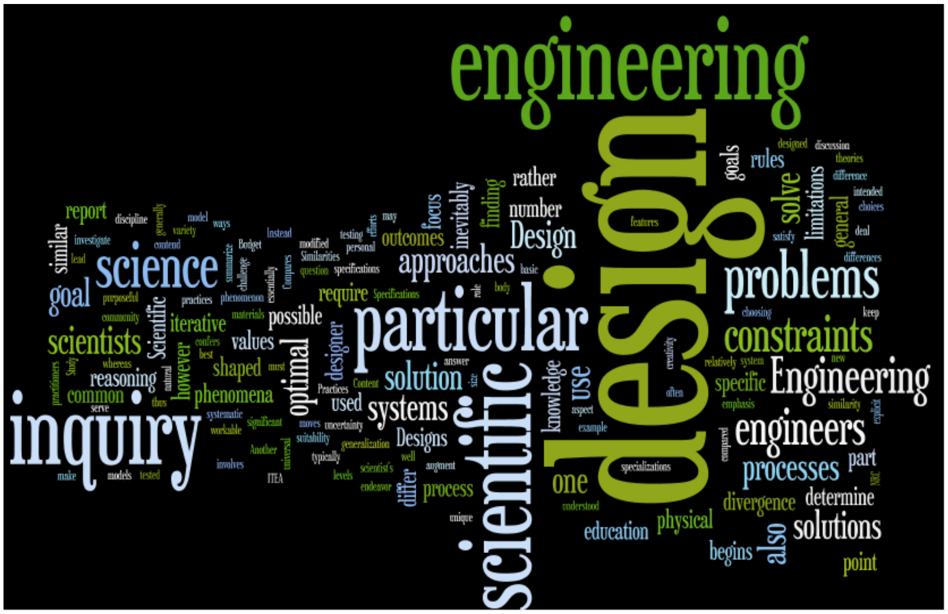

Figure 1. Word cloud visualizing the key words in the crosscutting concepts overview of the 2011 Framework for K-12 Science Education (www.wordle.net).

For the first time, the word engineering takes a prominent place in science classrooms across the United States. Students are challenged to think like scientists and engineers; to understand how engineering and science are similar and how they differ; and to design solutions for real problems. The engineering and technology components are featured to reflect the importance of the designed world and to help students make comparisons between the designed world and the natural world [National Research Council, 13]. But what connection does engineering have to science and how does the introduction of engineering design impact student learning? Educators at the National Institute of Aerospace's Center for Integrative STEM Education (CISE) are delving into the research and using what they learn to develop and deliver real world engineering design challenges for K-12 educators across the nation.

Benefits of Engineering Design

So what does engineering specifically bring to the classroom? The National Center for Engineering and Technology Education has taken a firm position that engineering design experiences should be an important component in the high school education of all American youth [Householder, *et al*, 6]. The team made strategic recommendations to successfully incorporate engineering design challenges into science, technology, engineering, and mathematics (STEM) courses. They based their recommendations on several foundational principles. First, that engineering design challenges should be firmly grounded in mathematics and science and that designs must inherently rely on the application of science in the product design [Schunn, 16]. By carefully crafting a design challenge that requires the application of content to solve the problem, a distinction is made between the "gadgeteering" often associated with an inventor's tinkering and the sound analysis of data to find a workable solution [Householder, *et al*, 6]. The committee further recognized that the iterative nature of authentic engineering design tasks changes students' perceptions of failure, allowing them to embrace the opportunity to learn when a design does not work and giving students reasons to redesign for success [Kapur, 7]. As students are called on to solve engineering design challenges, they engage in systems thinking strategies, creating an environment that fosters creativity while encouraging divergent thinking [Dym, *et al*, 5]. An additional benefit of bringing engineering design into the science classroom is that well-crafted design challenges can increase student interests in engineering and engineering careers [Apedoe, *et al*, 1].

GUIDED INQUIRY – NASA ECLIPS DESIGN CHALLENGES

The National Research Council recognizes that high quality education in the STEM disciplines can take place in diverse public school settings and that no single formula nets results in all settings [Committee, 4]. The 2011 report, however, does delineate several indicators for successful STEM education. The report recommends that districts should devote adequate time and resources to science education, especially in grades K-5, and that instruction should include opportunities for students to engage in science learning outside the classroom [Wang, *et al*, 17]. Further, the need for students to actively apply their content understanding to real-world applications held a high priority in the list. So why are design challenges the exception in the classroom rather than the rule?

Authentic Design Challenges

Challenges that require students to solve authentic problems can be powerful learning experiences. Authentic problems must, however, be situations encountered by the learners, their families, or their communities and should reflect real-life situations. Authentic challenges do not have a single right answer as the solution and should require the students to use grounded principles of science, technology, and mathematics to solve [Schunn, 16]. But where do teachers find these challenges and how should they be implemented in the classroom?

In spite of widespread agreement on the importance of providing students with real-world applications for their learning, two issues surface that often prevent teachers from implementing design challenges in the classroom. First and foremost, even the most motivated and prepared teachers are often unable to implement design challenges without special external assistance or the involvement of resource persons who are experts in the field. Second, design challenges, by their very nature, require a paradigm shift from teacher-centered to student-centered classrooms, a shift for which teachers are often unprepared [Householder, *et al*, 6]. Good design challenges involve authentic hands-on activities that motivate students to uncover what they need to know to solve the identified problem. The activities should be firmly grounded in science and mathematics content. Yet few teachers, especially at the elementary level, are trained to deliver engineering instruction and lack the confidence and/or training to implement challenges that do not follow a single path to one right answer.

The educators at CISE have used their experience in the classroom and their understanding of teacher needs to create a series of engineering design challenges for teachers unfamiliar with the process of design solutions. Three initial engineering design challenges were created as part of the NASA eClips™ suite, using the 5-E model of learning and guided inquiry [Bybee, 3] to increase teacher understanding of engineering design and build confidence in the implementation of design challenges. NASA eClips™ is an award-winning educational program that provides NASA-unique experiences, opportunities, content, and resources to educators and students to increase K-12 student interest within science, technology, engineering, and mathematics (STEM) disciplines. Video segments are three to seven minutes in length, consistent with feedback from academic focus groups and an evaluation team from North Carolina State University. Associated educator guides with hands-on activities help students deepen their understanding of academic content while the video segments provide context for learning and a connection to NASA researchers working on real-world problems. The NASA eClips™ videos and educator guides may be found at: www.nasa.gov/nasaeclips.

K-5 Design Challenges

The first design challenge, *NASA eClips™ Our World: Designing a Shower Clock*, was developed for students in grades K-5. Within the challenge, students think and act like engineers and scientists as they follow the five steps of the Design Process to successfully complete a team challenge. Within this work, students design, measure, build, test, and re-design a shower clock. Once the shower clock is built, students discuss ways to conserve and recycle water. Students view a Teaching from Space NASA eClips™ video segment, then relate water conservation issues on the International Space Station to those in their daily lives [National Institute of Aerospace, 11]. This challenge builds on relevant and familiar science content about water and resource conservation while encouraging students to apply creative solutions to the problem within a given set of parameters. The student solutions can be implemented in their homes, extending learning beyond the classroom and providing personal relevance and social difference, a key developmental component for effective engineering challenges [Apedoe, *et al*, 1].

Barak (2004) recommended that structured methodologies could be used to encourage more open-ended brainstorming [Barak, 2]. The given structure for the NASA eClips™ challenges allow teachers to gradually introduce open-ended, student-centered, collaborative projects. When the problem is broken up into manageable segments aligned to specific goals, students are more likely to be creative in their solutions [Lewis, 9]. To further promote the guided inquiry necessary to solve the water conservation problem, for example, the NIA educators developed an open-ended design packet that can be used with any design challenge. The packet contains questions to help guide student exploration and rubrics to assist the teacher in evaluating student work. The questions are organized around the five steps of an engineering design process, approved by NASA, and modified for younger students. The first step of the elementary engineering design process is *Ask*, with questions prompting the students to define the problem and discover what others have already done to solve the problem. Step 2, *Imagine*, encourages students to brainstorm solutions and decide which one is best. Step 3, *Build*, involves drawing a diagram and making a list of materials before actually creating the design in a physical model. Step 4, *Evaluate*, reminds students that engineering design is iterative, asking them to test their design and make changes based on their results. The final step of the elementary design process, *Share*, extends communication skills as students must explain their ideas to others and reflect on the reasons they chose the design they did in the first place. A colorful graphic depicting the design process is included in the packet and can be accessed electronically or printed to best meet class needs. The Elementary Design Packet can be found at: http://www.nasa.gov/pdf/324205main_Design_Packet_I.pdf .

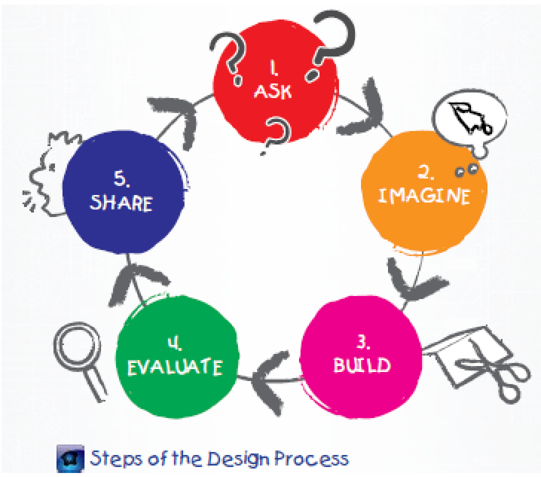

Figure 2. Graphic of Elementary Design Process from *NASA eClips™* Elementary Design Packet.

Design Challenges for Middle School Students

In the *NASA eClips™ Real World: Balloon Challenge*, middle school students are encouraged to think and act like scientists and engineers as they follow the eight steps of the Design Process to successfully complete a team challenge. In the Explore section, students design, measure, build, test, and re-design a neutrally buoyant helium balloon. In the Explain section, students demonstrate how different forces affect motion. In the Extend section, students apply what they have learned about balloons and density to design a series of balloons that float at different heights. Students may attach sensors to the balloons to gather environmental data. Students compare what they observe with a Teaching from Space NASA eClips™ video segment to learn more about forces and motion in a near zero gravity environment and how these forces act similarly or differently than they do in Earth's gravity [National Institute of Aerospace, 12].

This challenge not only requires students to apply science concepts, but allows them to take mathematical measurements over time to understand patterns. The next generation science framework has identified the importance of incorporating modeling and measurement technologies, both of which are integral to the Balloon Challenge.

A Secondary Design Packet was created for students in grades 6-12, using a template for the design process that had already been approved by NASA Education. The guiding questions in this packet explore eight steps of the design process, but continue to emphasize the iterative nature of engineering design. The design process for secondary students asks students to be more specific at each step and introduces terms like criteria and constraints, prototype, and refine. The packet can be found at: http://www.nasa.gov/pdf/324206main_Design_Packet_II.pdf .

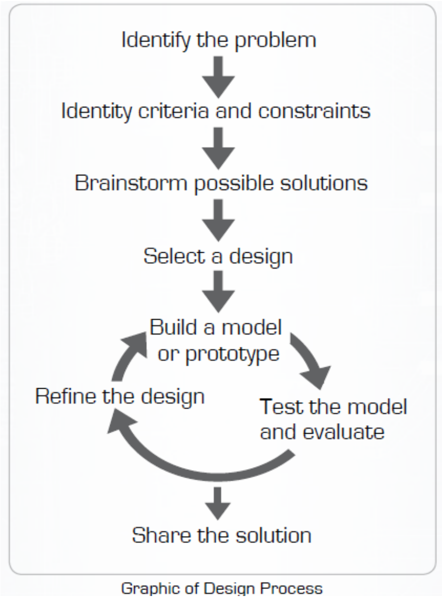

Figure 2. Graphic of Elementary Design Process from *NASA eClips*™ Elementary Design Packet, page 2.

Teachers have the option of using either the five-step or eight-step design process, allowing for differentiated instruction based on student needs. The packet also offers the opportunity to identify and correct student misconceptions in science and math content, a crucial component of any authentic challenge [National Research Council, 13].

High School Design Challenges

High School students think and act like engineers and scientists as they follow the eight steps of the engineering design process to successfully complete a team challenge in the *NASA eClips™ Launchpad: Boomerang Challenge*. Within this task, students design, build, test, and re-design a boomerang. Once the boomerang is built, students explain and demonstrate how different forces affect its flight. Students research and explore basic aerodynamics forces and explain their applications to boomerang flight. Students compare what they observe with a Teaching from Space NASA eClips™ video segment to learn more about how boomerangs react in a near zero gravity environment. To complete this lesson, students must have a basic understanding of vectors [National Institute of Aerospace, 10].

Again, the Secondary Design Packet can be used to help guide student learning and organize student thinking as they plan, build, and test their designs. The packets provide a unique opportunity for students to reflect on the design process. Reflection is a critical component of the engineering process and one which should be synchronous with teaching [Schön, 15].

An external evaluation team from North Carolina State University was asked to conduct ongoing research about the effectiveness of the NASA eClips™ project in general and to assess the impact the videos and hands-on activities had on student learning. The reviewers consistently discovered that the videos provided context for abstract science and mathematics concepts, giving students a foundational understanding to then deepen their conceptual knowledge while providing teachers with tools to help students visualize and clarify academic concepts. They also saw an increased awareness and interest in STEM careers after students had completed the engineering activities. The combination of video segments with the specially crafted activities provide both teachers and students access to NASA researchers who serve as subject matter resources and lend authenticity to the classroom [Osborne, *et al*,14].

OPEN INQUIRY DESIGN CHALLENGES

Virtual World Challenge

The NASA RealWorld/InWorld (RWIW) Engineering Design Challenge (http://www.nasarealworldinworld.org) is one of the most unique challenges developed by the CISE team. RWIW is a team based, problem-centered design challenge in which small groups of middle and high-school students work collaboratively to solve authentic engineering problems in both the classroom and virtual world setting. Teachers have the opportunity to register teams of 2-5 students to participate in the challenge. Over the past two years, more than 900 students in both traditional and after-school programs have been involved in the challenge. Phase 1 requires students to design and build a prototype solution to meet the design specifications. Three real-world engineering problems have been tested in this environment: redesigning the sunshield for the James Webb Space Telescope; redesigning the mirror assembly for the James Webb Space Telescope; and designing a foot for Robonaut 2, NASA's first robotic crew member on-board the International Space Station. Students are given the opportunity to extend their participation by submitting their designs for possible selection for Phase 2. College engineering students, serving as team mentors, review the submissions and select the team(s) to continue design development in an online virtual world. The virtual world, or InWorld phase of the challenge, is done using an ActiveWorlds platform (http://www.activeworlds.com). Within the virtual environment, students use modeling software to build their prototypes and create knowledge spaces to showcase their thinking throughout the engineering design process. Incorporating these instructional technologies into the learning experience promotes engineering habits of mind especially appropriate for the high school level [Katehi, *et al,* 8]. Surprisingly, many students involved in the challenge reported that their use of the 3-D modeling software within this challenge was their first exposure to such computer design programs.

Students have the opportunity to interact with the scientists and engineers working on the project through facilitated chats, question and answer sessions, and virtual interactions. These kinds of opportunities bring NASA researchers into the classroom to make relevant connections between content and context, and serve as subject matter experts to support teachers. This on-going access to science and engineering resources and professionals provides the external assistance recommended to effectively implement design challenges. The researchers also serve as role models for the students involved in the challenge and can broaden student perceptions of possible STEM careers.

An external evaluation completed by a team at Old Dominion University is currently in pre-publication, but has identified some unique strengths of the virtual challenge. Nearly 90% of responding teachers and students indicated value in the video clips where engineers explained the design process or clarified the science behind the engineering. Student competitors noted that the challenge required creativity and challenged their ability to think critically and to adhere to deadlines. The structure allowed for flexibility in the classroom. All participants reported the importance of knowing that this was indeed an authentic design problem, reinforced by interactions with people working in the field.

PROFESSIONAL DEVELOPMENT

In addition to developing the design challenges, the CISE educators also facilitate professional development opportunities for teachers to familiarize them with engineering design. The teacher workshops are usually a hybrid model of face-to-face training with long-term online support to create a network of practitioners. Webinars, online collaboration tools, Skype, and email are used to extend the impact of initial workshops. The CISE educators have facilitated long duration workshops as part of the NASA Pre-Service Teacher Institute (PSTI), the United States Air Force Academy STEM Boot Camp, numerous school districts' in-service training, and in-service professional development for informal institutions such as the Virginia Air and Space Center.

Research about best practices for teacher professional development and external evaluations for the NASA PSTI have helped shape the methodology for these workshops. Two consistent components for each workshop are the inclusion of one or more engineering design challenges, with the accompanying hands-on activities to support the challenge; and the inclusion of NASA subject matter experts to help teachers understand firsthand what scientists and engineers do and how they approach problem solving in their chosen careers. By exposing teachers to the NASA researchers associated with the real-world challenge, the teachers are better able to communicate to their students the connections between standards-based content and the real-world application of academic concepts. Teachers are encouraged to invite subject matter experts into their own classrooms, either through face-to-face or virtual visits, thus giving the same authenticity to their students.

Conclusion

Through a series of design challenges built on a continuum from guided inquiry to open-ended inquiry, the educators at the National Institute of Aerospace's Center for Integrative STEM Education help bring engineering design into the classroom. The challenges which represent authentic, real-world problems, give students opportunities to think and act like scientists and engineers. Reflective practices allow teachers to assess student understanding and correct misconceptions. The challenges allow students to design and refine their solutions, demonstrating the iterative nature of problem solving, and encourage reflective practices as students carefully evaluate their designs. Professional development opportunities for teachers provide support for implementation of the challenges while virtual and video support from NASA subject matter experts provide content expertise, building teacher confidence and increasing the likelihood that teachers may implement design challenges in the classroom. As CISE educators continue to develop new engineering design challenges, more formal evaluations and long-term studies of impact on both teacher behaviors and student learning will be considered.

References

[1] Apedoe, Xornam., Ellefson, Michelle and Christian Schunn, Bringing engineering design into high school science classrooms: The heating/cooling unit, *Journal of Science Education and Technology*, 2008, pg. 454-465.

[2] Barak, Moshe, Systemic approaches for inventive thinking and problem-solving: Implications for engineering education, *International Journal of Engineering Education,* 2004, pg. 612-618.

[3] Bybee, Rodger, *The BSCS 5E Instructional Model and 21st Century Skills: A Commissioned Paper*. National Academies Press, Washington, DC, retrieved from: http://www7.nationalacademies.org/bose/1Bybee_21st%20Century_Paper.pdf, 2009, pg. 1-24.

[4] Committee on the Evaluation Framework for Successful K-12 STEM Education, *Monitoring Progress Toward Successful K-12 STEM Education: A Nation Advancing?* National Academies Press, Washington, DC, 2012, pg. 1-42.

[5] Dym, C.L., Agogino, A.M., Eris, O., Frey, D.D. and L.J. Leifer, Engineering design thinking, teaching, and learning, Journal of Engineering Education, 2005, pg. 104-120.

[6] Householder, Daniel and Christine Hailey (Editors), *Incorporating Engineering Design Challenges into STEM Courses*, National Center for Engineering and Technology Education, http://digitalcommons.usu.edu/ncete, 2012, pg. 1-64.

[7] Kapur, Manu, Productive Failure, *Cognition and Instruction*, 2008, pg. 379-424.

[8] Katehi, Linda and Michael Feder, The status and nature of K-12 engineering education in the United States, *The Bridge: Linking Engineering and Society*, 2009, pg. 5-10.

[9] Lewis, Theodore, Creativity in technology education: Providing children with glimpses of their inventive potential, *International Journal of Technology and Design Education,* 2009, pg. 255-268.

[10] National Institute of Aerospace, Launchpad: Boomerang Challenge, *NASA eClips*, NASA, www.nasa.gov/nasaeclips, Hampton, VA, 2009, pg. 1-15.

[11] National Institute of Aerospace, Our World: Designing a Shower Clock, *NASA eClips*, NASA, www.nasa.gov/nasaeclips, Hampton, VA, 2009, pg. 1-20.

[12] National Institute of Aerospace, Real World: Balloon Challenge, *NASA eClips*, NASA, www.nasa.gov/nasaeclips, Hampton, VA, 2009, pg. 1-16.

[13] National Research Council, *A framework for K-12 science education: Practices, crosscutting concepts and core ideas*, National Academies Press, Washington, DC, 2012, pg 11-16.

[14] Osborne, Jason and Sylvia Nassar-McMillan, When role models are scarce: Using multi-media and online resources to encourage STEM careers in underrepresented populations, a paper presented at the American Counseling Association Conference and Educational Exposition, New Orleans, LA, 2011.
[15] Schön, Donald, *Educating the Reflective Practioner*, Josey-Bass, San Francisco, 1987, pg. 27-35.
[16] Schunn, Christine, How kids learn engineering: The cognitive science perspective, *The Bridge: Linking Engineering and Science*, 2009, pg. 32-37.
[17] Wang, Jing, Weber, Nicole, Strobel, Johannes, and Melissa Dyehouse, Conceptualizing authenticity in engineering education: A systematic literature review, a paper presented at the American Society of Engineering, San Antonio, TX, 2012.

Rebecca Jaramillo

Ms. Rebecca Jaramillo has been an educator for the past 34 years and is currently serving as the Senior Educator at the National Institute of Aerospace's Center for Integrative STEM Education, where she and her colleagues develop award-winning STEM educational resources. She holds a Bachelor of Science in Education degree from Northern Arizona University and is pursuing a Masters degree in Supervision. In 2005, Ms. Jaramillo received the Presidential Award for Excellence in Science Teaching for her innovative teaching methods. Rebecca is an active member of the Illinois Problem-Based Learning Network and an invited speaker at numerous national, state, and local conferences. In 2009, Rebecca received the NASA Langley Research Center Speakers Bureau Speaker of the Year Award. She serves on advisory boards for the Virginia Air and Space Center and the Virginia Children's Engineering Council.

Colin P. Britcher

Dr. Colin P. Britcher earned B.S. and Ph.D. degrees from the Department of Aeronautics and Astronautics at the University of Southampton, U.K.. He served as an NRC Postdoctoral Fellow at NASA Langley for two years, then moved to Old Dominion University, serving in the Department of Mechanical Engineering and Mechanics, and the Department of Aerospace Engineering, where he served as Chair from 2005-2010. He is currently is a full Professor in the Mechanical and Aerospace Engineering Department. His research interests include experimental aerodynamics, ground testing, flight mechanics, and magnetic levitation. He has published around 100 technical papers on these topics. He is an a Associate Fellow of AIAA, has served on the AIAA Ground Testing Technical Committee and is a member of ASEE and SAE.