



Supporting the Implementation of NGSS through Research: Engineering

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Engineering has always been implicitly a part of the National Science Education Standards (National Research Council [NRC], 1996) and has recently become a topic of increasing interest in science education. With *A Framework for K-12 Science Education* (NRC, 2012) and the *Next Generation Science Standards* (Achieve, 2013), the importance of including engineering as an integral part of science education has been brought to a new level with implications for teacher preparation, assessment, curriculum development, and student learning. The *NGSS* recommends an integration of engineering into science through two modes: (a) as a pedagogical approach to teaching science content and (b) as an important content area in and of itself. Hence, engineering promises new opportunities for improving science education and the development of 21st century skills which are closely aligned with engineering habits of mind (Katehi, Pearson, & Felder, 2009).

As K-12 teachers, school leaders, policy makers, and teacher educators look at the *NGSS* for the representation of engineering, it is necessary to consider the entire document. The *NGSS* taken as a whole, including the Dimension 1: *Scientific and Engineering Practices*, Dimension 2: *Cross Cutting Concepts*, and Dimension 3: *Disciplinary Core Ideas*, emphasizes design as central to engineering practice, and incorporates cross cutting concepts such as systems and models along with disciplinary core ideas such as energy, ecosystems, and natural resources. However, the performance expectations themselves paint an incomplete picture because they are itemized, which presents the various components of engineering as disconnected from one another. For this reason, we recommend that all of the *Engineering Practices*, *Cross Cutting Concepts*, and *Disciplinary Core Ideas* related to engineering be considered together to see how engineering is represented as a whole in the *NGSS*. This lens provides a way to interpret the individual standards that are marked with engineering context.

It is important to note that different aspects of engineering are represented in each of the three dimensions of the framework. For example, the *Engineering Practices* describe the work of the engineers with the expectation that students will engage in engineering design including defining problems, developing models (physical, mathematical, and computational), designing investigations, constructing design solutions, and arguing for one's ideas. The *Cross Cutting Concepts* allow for the integration across disciplines that are inherent in engineering. These concepts focus on science, society, and technology at all grades and systems and systems thinking at secondary levels. In addition, the *Disciplinary Core Ideas* emphasize the aspects of engineering knowledge, such as optimization, problem scoping, and idea generation, that the student should focus on. Engineering as a discipline encompasses all of these dimensions, and

therefore it is necessary to consider *NGSS* document as a whole as it relates to engineering. There are numerous studies, some of which are highlighted in the sections below, support *NGSS*' focus on engineering.

The Relationship between Engineering Design and Science Learning

It is important to note that not all design is engineering: if engineering activities do not meaningfully integrate science and mathematics content, they also no longer fully represent engineering. Thus, integration of engineering and science is, at its core, consistent with engineering practices and goals. In addition, the literature on science education has explored student learning of scientific content that occurs through engineering or design-based learning as a pedagogical method (Svarovsky & Shaffer, 2007; Kolodner, Crismond, Gray, Holbrook, & Puntambekar, 1998; Penner, Lehrer, & Schauble, 1998). Many of these studies have shown that engineering design-based approaches result in significant learning gains in science content such as chemistry (Apedoe, Reynolds, Ellefson, & Schunn, 2008) and physics (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Svarovsky & Shaffer, 2007; Wendell & Lee, 2010). However, targeted teaching methods such as explicit discussion of science content (Roth, 1996), explicit transfer activities (Walkington, Nathan, Wolfgram, Alibali, & Srisurichan, in press), and scaffolding questions (Crismond, 2001) also influence how much students learn. *NGSS* promotes these two types of learning environments together – asking that students are put in engineering design learning environments as well as environments that emphasize high-quality science pedagogies.

There are also studies showing that design-based approaches are more effective than scripted inquiry-based teaching methods, especially in support of underrepresented groups such as Black and Hispanic students as well as students with special needs (Mehalik, Doppelt, & Schunn, 2008; Cantrell, Pekcan, Itani, & Velasquez-Bryant, 2006). However, teachers' perceptions of special needs students' ability to engage in engineering can further widen the achievement and equity gap (Schnittka, 2012). In other cases gaps in learning are widened for female students and American Indians (Cantrell et al., 2006). These gaps are often associated with the use of stereotypical and gendered projects such as bumper cars and bridges; research shows that contexts that are gender-neutral and utilize socially and/or culturally relevant issues, such as biomedical and environmental applications, are needed to decrease this gap (Quinn, Lee, & Valdés, 2012; Weber & Custer, 2005; Zawojeski, Diefes-Dux, & Bowman, 2008). These studies suggest that using non-stereotypical, gender-neutral, and socially-relevant contexts for the engineering design-based pedagogies has the potential to engage all students meaningfully.

What Does a Successful Engineering Classroom Look Like?

In a classroom where engineering activities support student learning of engineering practices and disciplinary core ideas, we would see a context for design in which students could engage in problem solving from multiple perspectives. We would see teacher and students engage in engineering discourse and argumentation to identify the most critical criteria and constraints about a given challenge and the trade-offs they may have to make in their designs. We would also observe students asking questions to ensure they understand the context and constraints of the problem, as well as the underlying scientific principles. Students would be then working to

understand the scientific principles upon which the challenge rests and applying these principles when generating ideas, as well as implementing and redesigning solutions. We would see students developing models to quantify criteria that are not easy to quantify (e.g., energy efficiency of a house design, effectiveness of a water filter) and collect data. We would hear students comparing different design solutions as they analyze the data and information gathered through experiments, interviews with stakeholders, or other trustworthy resources. Students would use these data to generate design solutions that meet user needs and to optimize a given design. We would observe students recoding data in their notebooks and making presentations to their peers. In an effective engineering classroom, we would observe the teacher promoting STEM integration by explicitly spelling out science and mathematics concepts students are learning and scaffolding students' ability to transfer science learning to their design solutions.

Often engineering is associated with building and construction activities. While building prototypes is critical during design, these prototypes should not be the end goal but rather be used to start discussion, argumentation, design evaluation, and further data collection. We would observe students using science and mathematics concepts explicitly in their oral and written discourse and presenting evidence in support of their design decisions.

By emphasizing engineering discourse and data-driven decision-making, a successful engineering classroom would dispel misconceptions about engineering and broaden students' understanding of evidence-based decision-making as a critical aspect of engineering practice (Purzer, Strobel, & Cardella, 2014). But educators should also be aware that discourse is often gendered and culture-laden. Teachers need to learn ways to monitor and engage students in discourse that is collaborative and equitable.

Challenges and Opportunities

The *NGSS*' emphasis in engineering presents many challenges and opportunities. Our recommendations are directed towards practices that would support the implementation of *NGSS* in terms of both immediate and long-term action plans. We organized our recommendations in three areas of critical importance: (a) in-service teacher professional development and pre-service teacher preparation; (b) development of and access to curricula, assessments, and other instructional resources; and (c) assessment of implementation efforts.

Challenge #1. In-service Teacher Professional Development and Pre-service Teacher Preparation

For many K-12 teachers, engineering as content to be covered in the science classroom or used as a pedagogical approach is a new idea. A critical and obvious challenge is that most teachers do not have training in engineering and design. Although many teachers see the importance of engineering education in K-12, they do not feel prepared to teach engineering content or practices (Yaşar, Baker, Robinson-Kurpius, Krause, & Roberts, 2006; Brophy et al., 2008). This lack of content and pedagogical content knowledge can result in ineffective and inequitable practices.

- *Ineffective practices* can include misrepresentation of design as a step-by-step linear process (Crismond & Adams, 2012). This is similar to problems science educators face

when scientific inquiry is presented as a linear method (Rudolph, 2005; Windschitl, Thompson, & Braaten, 2008). Another outcome of limited pedagogical content knowledge is a narrow focus on building, crafting, or “tinkering until it works” activities (Schnittka & Bell, 2011). This approach is perceived to be engaging by the students but does not help improve science learning. Moreover, removing the systematic use of science from the design activities reduces alignment with engineering practices.

- *Inequitable practices* emerge from misconceptions about engineering and use of stereotypical contexts for engineering projects (e.g., building fastest cars). Such practices do not close achievement gaps for females and other underrepresented populations. In addition, educators who associate engineering with high tech equipment may perceive engineering education as an inequitable practice. There is also a need to develop appropriate language skills for understanding, doing, and explaining engineering. This language needs to be taught, modeled, and practiced. Otherwise many students, especially English language learners, will struggle with the engineering because of the language demands.

Recommendation #1. Our short-term recommendation is state-wide high volume teacher professional development programs to support science teachers in teaching engineering courses. These programs should focus on teacher misconceptions identified in the literature on pedagogical content knowledge in design (Shulman, 2000) and emphasize evidence-based design decision-making through written and oral discourse. In addition, strong collaborations among K-12 educators, engineers, and science and engineering education researchers should be built. Examples of these include the UTeach*Engineering* (n.d.) and Minnesota Mathematics and Science Teacher Partnership (n.d.) programs. These programs provide extended professional development opportunities that include feedback loops and accountability and address the learning theories and practices that are needed for successful integration of engineering into science teaching.

In the long-term, we need to rethink the preparation of pre-service teachers with a focus on developing design pedagogical content knowledge (PCK) and informed conceptions of engineers and engineering (Crismond & Adams, 2012; Brophy, Klein, Portsmore, & Rogers, 2008; Hsu, Cardella, & Purzer, 2010). Changes to the pre-service programs might be different for elementary and secondary certification programs. For example, elementary certification programs might be able to make adaptations of their science methods courses while secondary certification programs might develop an alternative track for science educators with an engineering or STEM integration focus. Moreover, science teacher educators need to develop these ideas as well, perhaps through co-teaching, targeted professional development or peer-mentoring. In addition, any professional development effort should allocate sufficient time for classroom assessment practices that emphasize process and discourse and de-emphasize evaluation solely based on the performance of prototypes.

Challenge #2. Development of and Access to Curricula, Assessments, and Other Instructional Resources

Another critical challenge in implementing the *NGSS* is access to resources that support student learning in science. STEM integration is challenging and requires well-designed and empirically evaluated curricula (Nathan, Tran, Atwood, Prevost, & Phelps, 2010). The resources currently

available are not *aligned* with *NGSS*, have varying *quality*, and perceived to be difficult to *access*.

- There are a number of available engineering curricula (National Academy of Engineering, 2009), but they were designed before 2012 and therefore are not necessarily aligned with *NGSS* (e.g., Stohlmann, Moore, McClelland, & Roehrig, 2011). In addition, except for a few (e.g., Engineering is Elementary [EiE], 2013), these curricula have not been designed to engage underrepresented groups.
- Teachers at schools without resources may rely on easily accessible lesson plans available on the web. Although there are many engineering lessons on the Internet, inconsistent quality (effectiveness and attention to equity) of these activities are a concern, particularly given the above challenge regarding teacher's lack of expertise. Lessons developed by expert teams and published in trustworthy websites should be used (e.g., National Science Teachers Association publications with a focus on *NGSS*).
- Teachers, with misconceptions that equate engineering to high-tech equipment, may feel like they do not have the resources needed to teach engineering due to lack of access to digital technologies (Wang, Moore, Roehrig, & Park, 2011).

Recommendation #2. Our short-term recommendation is that schools should conduct review and alignment studies of their current curricula. Many existing curricula (e.g., *Models and Designs* in the Full Option Science Systems [FOSS, n.d.] kits) include components that involve design-based learning activities. In the long-term, models for modifying existing science curricula to include engineering through evidence-based design need to be developed (Moore, Stohlmann, Wang, Tank, & Roehrig, in press). These models should guide the development of new curricula that:

- explicitly and intentionally integrate STEM content;
- include classroom assessments aligned with *NGSS* and provide formative feedback on student learning;
- are validated with empirical studies;
- pay close attention to equity issues by avoiding stereotypical design projects that are not sensitive to gender, culture, language, and people with disabilities;
- take teachers' concerns about time and resources into account;
- support meaningful versions of the scientific and engineering practices;
- engage students in critical thinking, oral and written discourse, and informed decision-making; and
- include educative materials for teachers that clarify how engineering fits into science education and support their development of engineering/design content and pedagogical content knowledge.

Challenge #3. Assessment

There are a number of assessment issues associated with the challenges discussed above. These issues range from classroom and large-scale assessment of student learning to the evaluation of professional development efforts and teaching. While improving student learning is the ultimate goal of professional development and curriculum design efforts, data on student learning are dependent on the validity of arguments driven from assessment data.

Practical challenges associated with classroom assessment are as following:

- A general tendency in classroom assessment is a focus on professional skills such as collaboration and communication. Another tendency is making evaluations of student learning based on the performance on the prototypes students have developed. It is critical to note that a solution that is scientifically and theoretically sound may not perform well during testing due to limitations of materials used for construction. While such assessments have value, they do not provide information on student science learning or evidence-based decision-making.
- Teachers' implicit bias or perceptions of student abilities based on gender, ethnicity, or prior achievement record may influence their interactions with the students. In fact teachers may find that students who are typically seen as underachieving in the classroom may outperform others when presented with an engineering design challenge. Similarly, students who are highly successful in science and mathematics may not be comfortable with the failure of their design solutions and the lack of "a correct answer."
- Idea fluency (i.e., generating multiple solutions) and justifying decisions with empirical evidence may be difficult for many.

Other challenges associated with the evaluation of programs include:

- Assessment bias as developers of curriculum and professional development activities engage in evaluation without the engagement of external and unbiased entities in these efforts.
- The use of assessment instruments or scales that are not validated or are not sensitive to the type or duration of interventions (e.g., assessing change in teaching self-efficacy following a two-hour teacher workshop).
- Limited scope of evaluation that does not extend to assessing fidelity to professional development in the classroom and the assessment of student learning as a measure of professional development effectiveness.

Recommendation #3. Research on assessment on topics such as classroom assessment practices, large-scale performance assessment, issues of validity in program evaluation is an evolving area. Attending to issues of validity and bias should be made a priority in both classroom assessment and program evaluation efforts. Quality assessment tools and methods need to be developed to measure student learning and student learning processes; teacher concerns, readiness, and self-efficacy; and teaching practices and fidelity of classroom implementation. For example, new generation performance assessments that can track, synthesize, and help visualize informed design processes can be developed to support research and student assessment (e.g., Purzer et al, in press). We need research as to the best ways to assess students' ability to practice informed design, engage in evidence-based argumentation, and their understanding of the underlying science concepts. Data that demonstrate how and why students are learning are needed rather than just summative studies of what students are learning.

In addition, professional development programs should allocate time for classroom assessment as a critical and embedded component of their programs. Assessment data need to inform implementation efforts and formative and summative assessments, which are needed if we are to expect schools and teachers to make this shift to engineering education as outlined in the NGSS.

Conclusion

Engineering provides opportunities to engaging students in meaningful tasks that support STEM learning. However, *effective, equitable, and accessible* teaching and learning and *valid and reliable* assessment does not happen without careful planning and implementation. Sustained efforts are needed to build capacity and produce results that make a difference in student learning and readiness for college, careers, and citizenship. We invite all stakeholders to pay close attention to equity issues across all of three challenges and opportunities we presented above. The implementation of NGSS needs to be supported through quality research as well as research-based practical resources for educators.

References

- Achieve. (2013). *Next Generation Science Standards*. Retrieved from <http://www.nextgenscience.org/next-generation-science-standards>
- Apedoe, X. S., Reynolds, B., Ellefson, M. R., & Schunn, C. D. (2008). Bringing engineering design into high school science classrooms: The heating/cooling unit. *Journal of Science Education and Technology, 17*(5), 454-465.
- Brophy, S., Klein, S., Portsmore, M. & Rogers, C. (2008). Advancing engineering education in P-12 classroom. *Journal of Engineering Education, 97*(3), 369-387.
- Cantrell, P., Pekcan, G., Itani, A., & Velasquez-Bryant, N. (2006). The effect of engineering modules on student learning in middle school science classroom. *Journal of Engineering Education, 95*(4), 301.
- Crismond, D. (2001). Learning and using science ideas when doing investigate-and-redesign tasks: A study of naïve, novice, and expert designers doing constrained and scaffolded design work. *Journal of Research in Science Teaching, 38*(7), 791-820.
- Crismond, D. P. & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education, 101*(4), 738-797.
- Engineering is Elementary (EiE). (2013). *The 20 units*. Retrieved from <http://www.eie.org/the-20-units> .
- Fortus, D., Dershimer, C., Krajcik, J., Marx, R., & Mamlok-Naaman, R. (2004). Design-based science and student learning. *Journal of Research in Science Teaching, 41*(10), 1081-1110.
- Full Option Science System (FOSS). (n.d.). Retrieved from the Lawrence Hall of Science FOSS Website: <http://www.lhsfoss.org/>.
- Hsu, M., Cardella, M., & Purzer, Ş. (2010). Assessing elementary teachers' design knowledge before and after introduction of a design process model. In Proceedings of the Annual American Society for Engineering Education Conference & Exposition, Louisville, KY.
- Katehi, L. Pearson, G. & Felder, M. (2009). The Status and Nature of K-12 Engineering Education in the United States. *The Bridge, 39*(3), 5-10.
- Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., & Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by design (tm) into practice. *The Journal of the Learning Sciences, 12*(4), 495-547.

- Kolodner, J.L., Crismond, D., Gray, J.T., Holbrook, J., & Puntambekar, S. (1998, December). Learning by Design from theory to practice. Paper presented at the International Conference of the Learning Sciences, Atlanta, GA.
- Mehalik, M. M., Doppelt, Y., & Schuun, C. D. (2008). Middle-school science through design-based learning versus scripted inquiry: Better overall science concept learning and equity gap reduction. *Journal of Engineering Education*, 97(1), 71-85.
- Minnesota Mathematics and Science Teacher Partnership. (n.d.). Retrieved from the Region 11 Math & Science Teacher Partnership website: <http://www.region11mathandscience.org/>.
- Moore, T. J., Stohlmann, M. S., Wang, H.-H., Tank, K. M., & Roehrig, G. H. (in press). Implementation and integration of engineering in K-12 STEM education. In S. Purzer, J. Strobel, & M. Cardella (Eds.), *Engineering in pre-college settings: Synthesizing research, policy, and practices*. West Lafayette, IN: Purdue University Press
- Nathan, M. J., Tran, N. A., Atwood, A. K., Prevost, A., & Phelps, L. A. (2010). Beliefs and expectations about engineering preparation exhibited by high school STEM teachers. *Journal of Engineering Education*, 99(4), 409-426.
- National Academy of Engineering. (2009). *Engineering in K-12 education: Understanding the status and improving the prospects*. Washington, DC: The National Academies Press
- National Research Council (U.S.). (2012). *A framework for K-12 science education: practices, crosscutting concepts, and core ideas*. Committee on a Conceptual Framework for New K-12 Science Education Standards. Board on Science Education Division of Behavioral and Social Sciences and Education, Washington, DC: National Academies Press.
- National Research Council (U.S.). (1996). *National science education standards*. Washington, DC: National Academies Press.
- Penner, D. E., Lehrer, R., & Schauble, L. (1998). From physical models to biomechanics: A design-based modeling approach. *The Journal of the Learning Sciences*, 7, 429-449.
- Purzer, Ş., Goldstein, M., Xie, C., Adams, R. & Zhang, H. (in press). Intersection of Informed Design and Scientific Explanation as High School Students Design Green Buildings. *International Journal of STEM Education*.
- Purzer, Ş., Strobel, J., & Cardella, M. (Eds.). (2014). *Engineering in pre-college settings: synthesizing research, policy, and practices*. West Lafayette, IN: Purdue University Press.
- Quinn, H., Lee, O. & Valdés, G. (2012). Language demands and opportunities in relation to Next Generation Science Standards for English Language Learners: What teachers need to know. Retrieved from http://connect.nwp.org/sites/default/files/file_file/03-quinn_lee_valdes_language_and_opportunities_in_science_final.pdf.
- Roth, W.-M. (1996). Art and artifact of children's designing: A situated cognition perspective. *Journal of the Learning Sciences*, 5, 129-166.
- Rudolph, J. L. (2005). Inquiry, instrumentalism, and the public understanding of science. *Science Education*, 89, 803-821.
- Schnittka, C. G. (2012). Engineering education in the science classroom: A case study of one teacher's disparate approach with ability-tracked classrooms. *Journal of Pre-College Engineering Education Research*, 2(1), article 5. <http://dx.doi.org/10.5703/1288284314654>
- Schnittka, C.G., & Bell, R.L. (2011). Engineering design and conceptual change in the middle school science classroom. *International Journal of Science Education*, 33, 1861-1887.
- Shulman, L. S. (2000). Teacher development: Roles of domain expertise and pedagogical knowledge. *Journal of Applied Developmental Psychology*, 21(1): 129-135.

- Stohlmann, M. S., Moore, T. J., McClelland, J., & Roehrig, G. H. (2011). Year-long impressions of a middle school STEM integration program. *Middle School Journal*, 43(1), 32-40.
- Svarovsky, G.N. & Shaffer, D.W. (2007). Soda constructing knowledge through Exploratooids. *Journal of Research in Science Teaching*, 44(1), 133–153.
- UTeachEngineering Program. (n.d.). Retrieved from the UTeachEngineering Website: <http://www.uteachengineering.org/>.
- Walkington, C. A., Nathan, M. J., Wolfgram, M., Alibali, M. W., & Srisurichan, R. (in press). Bridged and barriers to constructing conceptual cohesion across modalities and temporalities: Challenges of STEM integration in the precollege engineering classroom. In J. Strobel, Ş. Purzer, & M. Cardella (Eds.), *Engineering in pre-college settings: research into practice*. Purdue Press.
- Wang, H.-H., Moore, T. J., Roehrig, G. H., & Park, M. S. (2011). STEM integration: The impact of professional development on teacher perception and practice. *Journal of Pre-College Engineering Education Research*, 1(2), 1-13.
- Weber, K., & Custer, R. (2005). Gender-based preferences toward technology education content, activities, and instructional methods. *Journal of Technology Education*, 16(2), 55-71.
- Wendell, K. B., & Lee, H. S. (2010). Elementary students' learning of materials science practices through instruction based on engineering design tasks. *Journal of Science Education and Technology*, 19(6), 580-601.
- Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, 92(5), 941-967.
- Yaşar, Ş., Baker, D., Robinson-Kurpius, S., Krause, S., & Roberts, C. (2006). Development of a survey to assess K-12 teachers' perceptions of engineers and familiarity with teaching design, engineering, and technology, *Journal of Engineering Education*, 95(3), 205-216.
- Zawojewski, J., Bowman, K., & Diefes-Dux, H. A. (Eds.). (2008). *Mathematical modeling in engineering education: Designing experiences for all students*. Rotterdam, the Netherlands: Sense Publishers.