Using Design Challenges to Envision General Chemistry Lab for Engineers

Kent Crippen[1], Lorelie Imperial[1], Corey Payne[1], Maria Korolev[2], Chang-Yu Wu[3], Philip Brucat[2],
[1]School of Teaching and Learning, University of Florida, [2]Department of Chemistry, University of Florida,
[3]Engineering School of Sustainable Infrastructure and Environment, University of Florida

Abstract

We have developed a unique approach to the laboratory curriculum for undergraduate general chemistry for engineers that is intended to promote the persistence of engineering majors. ChaNgE Chem Lab is a series of Design Challenges that are based upon the NAE Grand Challenges for Engineering. These problem-based laboratory activities involve chemistry concepts and skills in an authentic engineering context with procedures that parallel the engineering design process. For engineering majors, contextualizing the learning of chemistry in such a way is theorized to strengthen the connection between the domain knowledge of chemistry and its application in everyday work, which enhances interest, efficacy and learning. The development and evaluation of this curriculum revolves around the intended users' perspectives, interests and needs. The usability of each Design Challenge for the intended users is tested at every stage of development and the outcomes become the basis for the iterative process of re-design and evaluation. The user-centered design process enables us to keep our focus on the involvement of our target audience in all stages of development. Usability testing allows us to compare both qualitative and quantitative data across all design iterations.
This paper describes the design framework that supports the Design Challenges and the use of usability testing for evaluating the extent to which our design has reached our goals. The outcomes from the first two Design Challenges from a first-semester course are presented. Implications regarding usability, student interest, learning, self-efficacy and perception of engineering are discussed in relation to continued iterative refinement as well as more general curriculum structures that are likely to support the retention of undergraduate engineers.

Keywords

Design challenge, laboratory, curriculum, general chemistry

Introduction

ChaNgE Chem Lab is a curriculum reform model, created to addresses the issue of retaining freshman engineering majors taking chemistry. The model is based upon our previous work transforming the recitation of general chemistry for engineers[1,2]. The current initiative expands and builds upon the model by developing laboratory activities that are contextualized in problems and methods that are unique to engineering and engineers' ways of thinking, learning and collaborating. The model involves a series of Design Challenges that are based upon the NAE Grand Challenges for Engineering.

This study describes the framework that supports the Design Challenges and the use of usability testing from the first two Design Challenges from a first-semester course for evaluating the extent to which our design is reaching the goals. The perspective for this research is user-centered design and chemistry problem solving as situated engineering practice serves as the theoretical framework.

Learning via Design Challenge in the Chemistry Laboratory

For ChANgE Chem Lab, the mission is to begin apprenticing undergraduate freshman students into the engineering community of practice during their first year on campus when they are taking their prerequisite coursework. This is accomplished through an emphasis on cognitive apprenticeship, whereby social interaction supports problem solving, imitation and engagement in activities that approximate the work of a real-world engineer[3]. Such activities target student retention by focusing their work on authentic collaboration and learning of content in context, which is theorized to leverage student interest in order to build personal identity with being an engineer as well as the necessary self-efficacy for persisting with challenging coursework[4,5].

The laboratory activities take the form of *Design Challenges* (DC)—an iterative decision-making process based on evidence and application of scientific knowledge that results in the creation of a model for an authentic engineering purpose. DCs are based upon the following goals: 1) build knowledge of chemistry, skills and interest by giving an authentic application to chemistry in the field of engineering; 2) illustrate the NAE Grand Challenges of Engineering[6] as enduring socially relevant engineering problems; 3) develop professional engineering skills and practice.

DCs involve a three-phase format based upon the ABET Student Outcomes (criteria b): *Design*, *Conduct experiments*, as well as *Analyze and Interpret data*[7]. Each phase accounts for one-week of laboratory instruction. Each DC is built to address one of the NAE Grand Challenges for Engineering that relate to general chemistry topics (Figure 1). The Grand Challenges were formulated at the beginning of this century by a diverse committee of experts of the US National Academy of Engineers with input from the most accomplished engineers and scientists around the world.

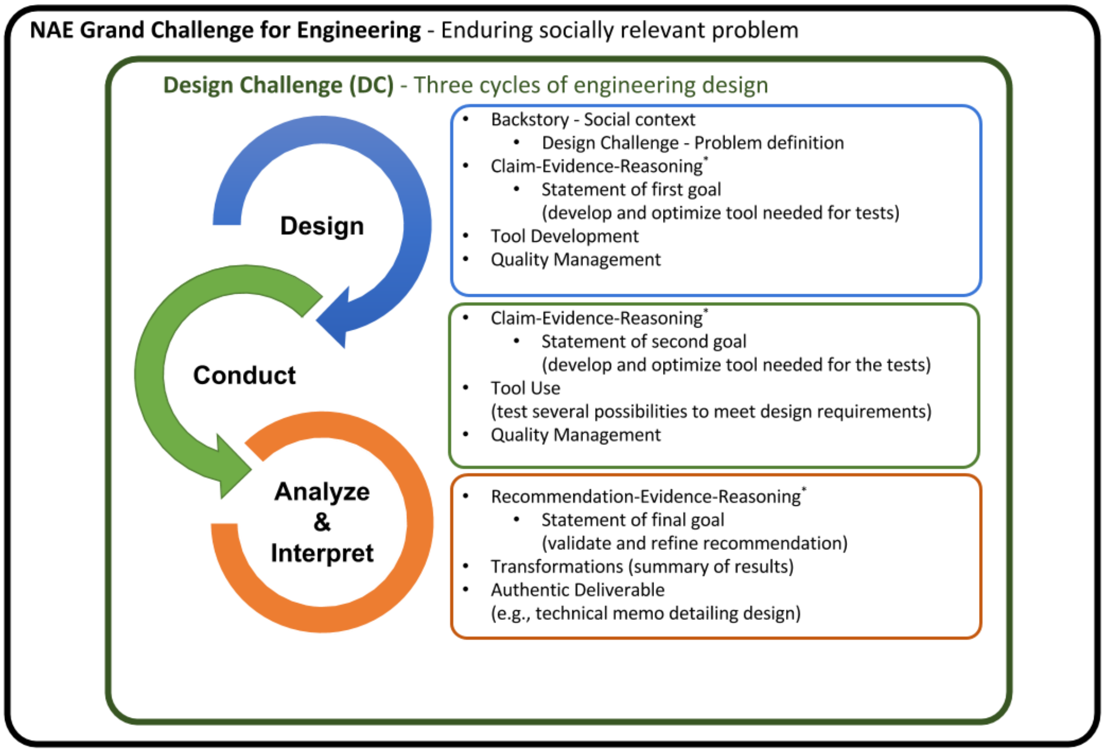

Figure 1. The phases and essential features of a Design Challenge.

DCs are grounded in the principles of model-eliciting activities (MEAs) for engineering education, a proven form of learning task that involves collaborative, model-based learning in authentic engineering contexts[8]. By applying six principles, an MEA requires students to create, test and refine a model for a realistic situation, then present their findings as a deliverable to a potential client (Table 1). Zawojewski and colleagues (2008) have developed a rich history and research program of using MEA's in undergraduate engineering courses as a means for supporting diverse students[9]. This project builds on this work by expanding the scope to include general chemistry courses, those that are prerequisite for an engineering major. Table 2 provides an overview of the first two DCs for a first semester course, which were the focus of the development and usability testing reported here.

Table 1. Embodiment of the MEA Principles within DC.

MEA Principle	Description	Embodiment in a DC
Model Construction	Requires the **construction of a model** by the student team.	Students create **a testing protocol for use in the field**.
Reality	Situated in an **authentic engineering context**. Students consider the constraints of the context as well as the needs of the client.	Use the Grand Challenges to focus on compelling and enduring real-world problems. Context is described with an authentic **backstory** (e.g., RFP). As part of the deliverable, students are asked to describe the problem considering all contextual factors.
Self-Assessment	Provides **opportunities to work as a team to assess the usefulness of the model** from the perspective of the client, their own experience in the context, and the background information.	Students will **work together, as a team,** to develop the protocol, refine it, use **quality management** (QA/QC), and refer back to given the context and constraints to check if their model works. Collaboration is emphasized with team discussion as well as discussion with the teaching assistant.
Model Documentation	Requires **the model to be documented** as the student team's response to the task. Documentation often takes the form of a procedure combined with a spreadsheet or computer program.	In the final phase, students respond to a client in the form of a **proposal** that describes their protocol and findings. Process worksheets[10] support a **laboratory notebook** that includes records of observations, responses to guiding questions, as well as interpretation and transformation of data into a form that is meaningful and useful as evidence in decision-making. Each phase of a DC is synthesized with a key knowledge representation based upon the **claim-evidence-reasoning (CER) framework**[11], which affords the combination of chemistry knowledge with engineering design.
Model Shareability	Requires that **the model be shareable with others and reusable on other sets of data.** The needs of the client require a model. This principle could also be called *local generalizability.*	The protocol should not only be usable in a laboratory, **students will need to consider which method for use in the field** considering who uses, ease of use, cost, safety, consistency. The protocol could be used to test other systems (i.e., other cations) not just the sample tested.
Prototyping	Results in **a product that is globally generalizable and modifiable**.	The protocol should have **use beyond the initial backstory**. Students will list recommended modifications for different scenarios.

Table 2. Overview of DC 1 & 2 of a first semester general chemistry lab course.

	Design Challenge 1	Design Challenge 2
Grand Challenge	Providing Universal Access to Clean Water	Making Solar Energy Economical
Engineering Context	The Dept. of Environmental Quality (DEQ) is seeking the students' expertise in the form of an RFP for a protocol on how to assess water hardness before the water goes into the pipe systems for distribution. Students will respond to the RFP by designing the protocol that describes how the test will be conducted, the principles behind the tests used, and validation of results using a test water sample.	The USDE is building a concentrating solar power (CSP) that aims to concentrate and store solar energy into a heat storage material. The team's engineering expertise is sought to aid USDE is choosing what material could be used as solar energy storage that would address both cost and height of the CSP tower. The USDE is foresees that the requirements can be addressed by combining two materials to be able to come up with a mixture that will meet the CSP tower design constraints. The students will address USDE's request by testing different materials and making decisions using the concepts specific heat and density, as well as calculations of CSP tower parameters. The response will be in the form of a dual y-axis graph that the USDE could use in building other systems similar to the CSP.
Model Form	Responding to a Request for Proposals on how to detect and quantify water hardness, students will propose a protocol to be used by a technician in the field.	Design an optimum material composition to make an efficient, economical, and accessible thermal energy storage device.
Chemistry Skills and Concepts	Preparation of solutions; dilution; water hardness detection and identification; conductivity; titration, calibration curves	Specific heat capacity; density; volume; area; optimization; dual y-axis graphing
Engineering Disciplines Addressed	Environmental	Chemical, Electrical

Methodology

Usability testing involves the iterative comparison of quantitative and qualitative outcomes for multiple cases (trials). The aim of a usability test is to evaluate each DC with the goal of improving the design based upon the user's (i.e. students) perspectives, interests and needs. The testing protocol was based upon the DECIDE framework[12], which involves a six-step process for evaluating a prototype's capacity to address its design and development goals. The goals for testing were:

- Determine the task success, errors, amount of effort, test time, efficiency.
- Determine the participant's perspective on usefulness, satisfaction and ease-of use.
- Identify usability issues (e.g., problematic behaviors, frustration, misinterpretations).
- Clarify design requirements based on the version of the prototype.

A task breakdown was completed for each phase of each DC and testing involved four data sources: 1) a pre-interaction survey—demographics, 2) a video-recorded of participants completing the activity, 3) a post-interaction survey—participant perspective (e.g., usefulness, satisfaction, ease-of-use), and 4) the laboratory report—problem solving artifact. The video-recordings were coded by subtask for time, help (e.g., asking others or the TA) and issues (e.g., frustration, off-task behavior, misinterpretation). Researchers also rated the overall task success for each participant and scored the participant artifacts based upon a standard rubric. Survey items were mainly presented in a closed form using a Likert-type scale based upon the construct to be assessed. The post-interaction survey also included the 10-item System Usability Scale (a 30-year industry standard). A content analysis was used for all open-ended or qualitative data. A one-way ANOVA with post hoc comparisons using the Tukey HSD test was used to determine differences in outcomes for the iterative versions of each activity and occasionally independent samples t-tests for comparing outcomes across versions.

Sample

The study presents outcomes from the first two DCs implemented during the Fall of 2017 with two course sections of general chemistry for engineers. Participants were $n=30$ undergraduate students.

Results

Through the iterative revision and assessment of DC1, the addition of these design elements resulted in positive changes in participant satisfaction, feeling like an engineer and for learning how to collaborate (Figure 2). The addition of process worksheets helped to maintain the level of effort while increasing the task difficulty and improving participant satisfaction (Figure 1). See also below the results regarding forms of directions.

When Quality Management was used, there were less help requests ($M=0.33$, $SD=0.58$) vs. no QM ($M=4.3$, $SD=0.58$); $t(6)=8.49$, $p = 0.001$ and less issues ($M=0$, $SD=0$) vs. no QM ($M=4.3$, $SD=3.2$). The help requests were also of minimal severity. In addition, there was a much smaller time needed ($M=11.2$, $SD=2.82$) vs. no QM ($M=29.4$, $SD=4.79$); $t(6)=5.66$, $p = 0.009$. With QM, tasks required an average of one-third the time.

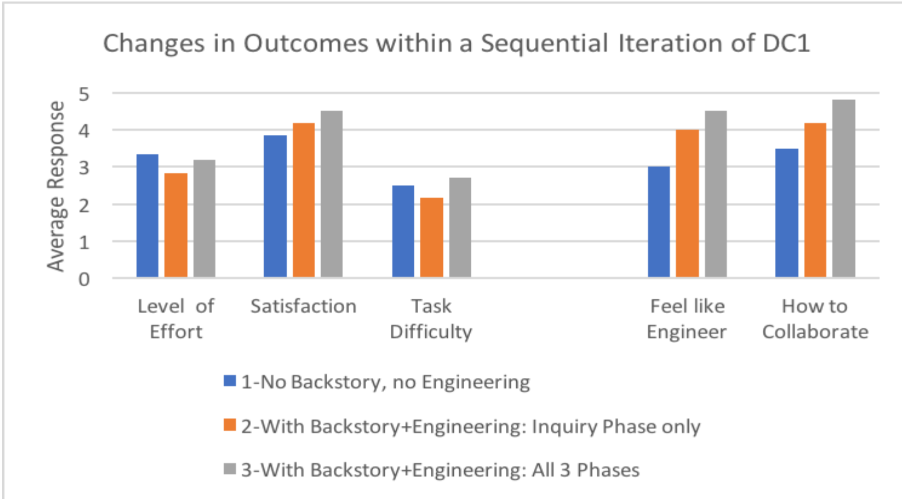

Figure 2. Evidence for usability improvement through iterative testing.

By comparing two different forms of directions for the same DC, a traditional form that was very leading and scripted versus an inquiry form that was more open-ended, we found both to be equally well received by participants and usable (Table 3). However, the inquiry form required more effort, twice the amount of time (+25min) and was significantly less successful, producing more issues and help requests. These results also supported our use of process worksheets in order to mitigate the negative impact of more open-ended directions.

Table 3. Outcomes for two forms of directions with the same DC.

	Traditional		Inquiry	
Outcome	*n*	*M (SD)*	*n*	*M (SD)*
Level of Difficulty	4	1.75 (0.55)	6	2.17 (0.75)
Usability (SUS)	4	73.8 (5.95)	6	73.3 (10.9)
Effort	4	3.75 (0.96)	6	3.17 (0.41)
Time (min.)	4	25.6 (4.41)	6	*51.3 (7.43)
Level of Success	4	2.88 (0.01)	6	*1.86 (0.01)
Help Requests	4	1.00 (1.41)	6	*3.33 (2.08)
Issues	4	2.50 (2.12)	6	*3.33 (.058)

*p<0.05

**Please note that these are partial results, intended to be illustrative of the full complement that will be presented at the conference.

Discussion

This study makes an important contribution to the teaching and learning of science and engineering by improving the quality of STEM education through a unique approach to the laboratory curriculum for undergraduate general chemistry, creating a more contextually relevant and engaging experience for engineering students. This will allow researchers as well as practitioners to better design and develop learning environments that equally attend to the makeup of the student body as well as the quality of their experience. In addition, through development and promotion of a university-wide community of practice for engineering education on our campus, this work increases the capacity and diversity of the STEM education community.

References

1 Crippen, K. J., Boyer, T. H., Wu, C.-Y., de Torres, T., Korolev, M., & Brucat, P. (2016, 6/29). A Pilot Study of Project-Based Learning in General Chemistry for Engineers. *Proceedings of the American Society for Engineering Education (ASEE) Annual Conference & Exposition*, New Orleans, LA.

2 Crippen, K., Wu, C.-Y., Boyer, T., de Torres, T., Brucat, P., & Korolev, M. (2015). A design-based apprenticeship approach to transform freshman chemistry for engineering students. *QScience Proceedings (Engineering Leaders Conference 2014)*, elc2014(71), 1-6. doi:10.5339/qproc.2015.elc2014.71

3 Johri, A., & Olds, B. M. (2011). Situated engineering learning: Bridging engineering education research and the learning sciences. *Journal of Engineering Education*, 100(1), 151-185

4 Capobianco, B. M. (2006). Undergraduate women engineering their professional identities. *Journal of Women and Minorities in Science and Engineering*, 12(2-3), 95-117.

5 Krapp, A., & Prenzel, M. (2011). Research on Interest in Science: Theories, methods, and findings. *International Journal of Science Education*, 33(1), 27-50. doi:10.1080/09500693.2010.518645

6 National Academy of Engineering, Grand Challenges for Engineering http://www.engineeringchallenges.org/

7 Criteria For Accrediting Engineering Technology Programs, 2014, ABET Engineering Technology Accreditation Committee (T001-15-16-ETAC-Criteria-05-04-15.pdf)

8 Diefes-Dux, H. A., Hjalmarson, M. A., Miller, T., & Lesh, R. A. (2008). Model-eliciting activities for engineering education. In J. S. Zawojewski, H. A. Diefes-Dux, & K. J. Bowman (Eds.), *Models and Modeling in Engineering Education: Designing Experiences for All Students* (pp. 17-36). Rotterdam: Sense Publishers.

9 Zawojewski, J. S., Diefes-Dux, H. A., & Bowman, K. J. (Eds.). (2008). *Models and Modeling in Engineering Education*. Rotterdam, Netherlands: Sense Publishers.

10 Nadolski, R. J., Kirschner, P. A., & Van Merriënboer, J. J. G. (2005). Optimizing the number of steps in learning tasks for complex skills. British Journal of Educational Psychology, 75(2), 223-237. doi:10.1348/000709904X22403

11 Bennett, S., & Gotwals, A. W. (2017). Construction with Scaffolds: Helping Community College Students Build Explanations. Journal of College Science Teaching, 46(6), 12-19.

12 Rogers, Y., Sharp, H., & Preece, J. (2011). Interaction Design: Beyond Human - Computer Interaction: Wiley.

Biographical Information

Kent Crippen, University of Florida

Kent Crippen is a Professor of STEM education in the School of Teaching and Learning at the University of Florida and a Fellow of the American Association for the Advancement of Science. His research involves the design, development, and evaluation of STEM cyberlearning environments as well as scientist-teacher forms of professional development. Operating from a design-based research perspective, this work focuses on using innovative, iterative and theoretically grounded design for the dual purpose of addressing contemporary, complex, in situ learning problems while concurrently generating new theoretical insight related to the process of learning and the relationships among the people, tools and context of the problem space.

Lorelei Imperial, University of Florida

Lorelei Imperial is a Doctoral Student in Science Education in the School of Teaching and Learning at the University of Florida. Her research interests include curriculum design and student learning of chemistry.

Corey Payne, University of Florida

Corey Payne, a former high school chemistry teacher, is a Doctoral Student in Science Education in the School of Teaching and Learning at the University of Florida. His research interests include mentoring relationships in research laboratory settings.

Maria Korolev, University of Florida

Maria Korolev is a Lecturer of Chemistry and teaches freshmen chemistry for engineering majors as well as for the general education requirement. She directs and supervises the course design process for the ChaNgE Chem Lab and leads the pilot testing of materials.

CY Wu, University of Florida

Chang-Yu Wu is Professor and Head of the Department of Environmental Engineering Sciences at the University of Florida. His teaching and research interests are in air pollution control, aerosol, incineration and engineering education. He has published more than 130 refereed journal articles, given more than 260 conference presentations and delivered 70+ invited speeches. He has received numerous recognizing his achievements in research and education, including the Lyman A. Ripperton Environmental Educator Award from Air &Waste Management Association in 2015 and the New Teacher Award from ASEE SE in 2001.

Phil Brucat, University of Florida

Phil Brucat is an active physical chemist, Director of General Chemistry and Chair of the Department laboratory reform initiative.