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High School Science Teachers' Views of Nature of Engineering and Application of Engineering Design Practices (Work In Progress)

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Engineering education in K-12 keeps growing as one of the dominant national educational agendas. Although there is some attempt to expand student interest in engineering careers, enrollment in engineering programs is low [1, 2,3] . Engineering education in US high schools is important for developing engineering literacy and attracting student passion in engineering careers. Next Generation Science Standards (NGSS) underscores the importance of engineering education in science classrooms [4]. In addition, National Academy of Sciences (NAS), National Academy of Engineering (NAE) and Institute of Medicine (IM) voice the need for professional development programs to develop teachers' knowledge and skills for integrating engineering into instruction [5]. Therefore, providing professional development for in-service teachers has the potential to improve teachers' engineering knowledge and increase student interest in engineering.

Previous studies underscored the importance of teacher guidance for students in improving students' views of engineering and choosing STEM fields for their future career path [6,7] . Bearing in mind that teachers lack knowledge about engineering and how to integrate it into their lessons [8,9], researchers have created professional development (PD) programs to improve teachers' knowledge. For example, in one study, a two-week Pre-College Engineering for Teachers PD was developed to emphasize engineering concepts and activities for middle and high school levels. Evaluations showed that confidence about teaching engineering increased [10]. Also, results demonstrated that teachers' skills in engineering instruction were positively affected through understanding the engineering design process (EDP) and learning how to modify a lesson to integrate engineering.

When it comes to views of engineering, past studies focused merely on the description of engineering and of engineers' work. On the other hand, we think that nature of engineering (NOE) is not limited to these two aspects [11,4] and should be widened to encompass nature of science (NOS) aspects. NOS can be defined as key principles which represent science as a way of knowing and describing the characteristics of scientific knowledge [12]. There is no consensus among scientists, philosophers, and science educators about the definition of NOS. However, science educators and educational standards have a common list of NOS aspects that students should learn [13, 4, 14]. These include that scientific knowledge is empirically based, socially and culturally embedded, tentative, subjective, the product of human imagination and creativity [15, 16]. NOE aspects have not been established, but there appears to be substantial overlap with NOS [17].

Although research about engineering education in K-12 is increasing, there is limited research that explores high school science teachers' NOE views. We can expect that high school science teachers are insufficient to teach the EDP, even though they may hold strong inquiry-based content knowledge and confidence. We think that high school science teachers NOE views can be enhanced after enrolling in a graduate level engineering design course. The main purpose of our case study article is three-fold: (1) giving a detailed explanation of a graduate level, NGSS-aligned engineering design curriculum for high school science teachers; (2) exploring a novice high school science teacher's understanding of the engineering design process resulting from the course; and (3) investigating the teacher's nature of engineering views during the course. The following questions guided our research: To what extent did the teacher's NOE views improve after exposure to a NGSS-aligned engineering design challenge course? How successful was the teacher in executing the engineering design process as taught through an engineering design challenge? We provide here a single case analysis for one teacher as a pilot study for future research. The paper provides a brief overview of our case study research in regards to data, methods, and preliminary results. Our data sources include pre/post NOE assessment, in-service teacher written reflections, and assignments.

Curriculum design

Learning goals and overview: The three-credit master's level course was for in-service science teachers and focused on the EDP through an engineering design challenge where teachers built a solar thermal water heater for their classroom. The goal was to provide teachers with the necessary tools and first-hand experience in using the EDP in order for the teachers to incorporate NGSS engineering practices in their classroom. Teachers received a stipend and tuition-reimbursement. The course format was discussion and project-based learning; most sessions involved brief directions, one-on-one discussion regarding project progress, and collaborative work time. The duration was four hours on ten Saturdays for a total of 40 in-person hours. Teachers who needed more time to finish course products were allowed to complete them after the in-person meetings. The course objectives were to (1) introduce secondary teachers to the engineering design practices within NGSS, (2) familiarize secondary teachers with the three main components (Define problem, Develop solutions, Optimize) of the EDP, (3) build confidence in performing engineering design and prototype construction, and (4) obtain sufficient knowledge of solar thermal water heating for secondary education instruction.

Course outline: Using the NGSS-aligned engineering design process as a guide, the course was divided into three phases. In the first phase (2 sessions), after teachers were introduced to the NGSS standards and EDP, teachers learned about defining the problem and creating an evaluation matrix. To complete this phase, teachers needed to write a problem statement, create a list of criteria and constraints, and prepare an evaluation matrix with design goals and scores. In phase two (2-3 sessions), teachers collaboratively brainstormed at least three possible solutions and evaluated them using their matrix. At the conclusion of this phase, teachers determined the best design or combination of designs that would achieve their criteria. In phase three (5-6 sessions), teachers constructed their prototype and optimized the design both on paper and during the construction process. Teachers learned to use the necessary equipment (e.g. soldering iron, power drill) in order to build their solar thermal water heater.

Homework assignments: Course products consisted of assignments tied to the three phases of EDP, three reflection questions, a pre/post assessment based on objectives for student learning, a final report, and a final presentation. EDP assignments, as mentioned in the previous paragraph, included: a problem statement, a list of criteria and constraints aligned to the problem statement, an evaluation matrix, descriptions and drawings for three possible solutions, and an explanation of why the chosen design was deemed the best. Reflection questions were intended as a metacognitive activity for the teachers to prepare how to instruct the EDP to their students. The final report and presentation were designed to demonstrate the teachers' understanding of the EDP and solar energy concepts and to assess their plans for using EDP in their class.

Mastery grading: Course products were graded using a Mastery approach. Each assignment had three or four objectives (Appendix A). All work was marked as unsatisfactory, approaching mastery or mastery. Teachers were permitted to resubmit course products multiple times or to extend the timeframe needed to complete the course products. After each submission, the instructor provided feedback along with the grade.

Methods

In our single-case pilot study, course products, NOE perceptions, and teacher reflections were assessed. All data were assessed by the first two authors (both engineers and educators) collaboratively and shared with other authors. When a disagreement occurred, authors referred back to the teacher responses and rubrics (Appendix B), discussed their reasoning, and reached a consensus to score the participant's NOE responses for each aspect. The pilot study involves one teacher (pseudonym: Nathan) who participated in the teacher PD during fall 2016. He is a first year high school science teacher with a science undergraduate degree but no prior experience with the engineering design process or engineering education. Nathan teaches physics and chemistry at a charter school.

Nature of Science (NOS) is a well documented research area in science education literature [12, 15]. NOE and NOS aspects are similar to each other; therefore, NOE aspects can benefit from well-established NOS research. We modified and used Views of Nature of Science Version C (VNOS-C) in our study to assess teachers' NOE aspects. The NOE pre/post assessment [18,19] consists of seven questions covering six aspects of the nature of engineering: demarcation, engineering design process, tentativeness, creativity, subjectivity, and social/cultural embeddedness (Appendix C). Questions were reviewed by a panel of expert engineers (n=6) and iteratively revised to its final form.

The teacher was required to use Google Docs to create the course products. A unique and useful feature of Google Docs is the option to look at revisions over the entire time of document creation, much like reviewing a videotape of a class lesson. The authors exploited this feature to observe changes and get a sense of how the teacher's understanding changed. In particular, authors could see how the course product evolved during group discussion versus independent work and what changes the teacher made after receiving feedback from the instructor. To the authors' knowledge, using Google Docs to "record" understanding in a PD is a novel approach.

Data analysis and discussion

Results of NOE assessment**:** In general, Nathan had high NOE scores for both the pre-test and post-test (Table 1). In terms of the demarcation aspect, Nathan held a fully informed view at the onset. He not only made a clear distinction between engineering and other fields but also described how engineering relates to other disciplines. Nathan's pre- and post-test responses included key details, such as "systematic design process" and "application of basic knowledge." Regarding his view of the engineering design process, Nathan did not specifically explain the 3 phases in his pre-test, but the ideas of the EDP (e.g. systematic process, finding solutions, feedback oriented) were included in his response. In the post-test, he presented all the steps in detail, which demonstrates that he learned the EDP stages during the course. For the tentativeness aspect (i.e. no set order to the steps and changes to the design as it develops), Nathan's response suggested a fully informed view that a design does change during the EDP, but his response lacked an example despite an explicit request for an example in the question. In the post-test, he provided a fully informed view, as well as a concrete example of the aspect. Specifically, Nathan wrote "The students would build these structures, then test them. There were some designs that failed to stand and as a result, the students went back and redesigned the structures to best meet the goal." In the creative aspect of NOE, Nathan provided a fully informed explanation supported with examples in both his pre-test and post-test. One reason he gave for the necessity of creativity was that "there might not be prior solutions to a problem." In regards to the subjectivity NOE aspect (e.g. there is no single best design), it appeared at first that Nathan's understanding decreased. During the pre-test, he provided a well-articulated answer that no single solution exists and his response mentioned that criteria and constraints influence the optimal design. However, his post-test response was rated as partially informed because it failed to acknowledge constraints as influencing the design. To further analyze his understanding of the subjectivity aspect of NOE, the teacher was contacted with a follow-up question, "What influences the design? Select an option and explain: criteria only, constraints only, or both criteria and constraints." Nathan provided a detailed explanation that meets the requirements of well articulated response with a concrete example. It raises the importance of including interviews in open-ended assessments to have a better understanding of teachers' views to interpret easier. Lastly, for the social and cultural embeddedness aspect of NOE, Nathan provided consistent pre- and post-test responses. His responses were fully aligned with the description of NOE (i.e. sociocultural factors influence engineering design). Although he mentioned that political and cultural values affect ideas behind engineering designs, he did not provide concrete examples for the social embeddedness aspect. Overall, Nathan demonstrated a slight increase in his understanding of NOE. Prior to intervention, he did not have misconceptions about NOE. His initial responses were all at the level of fully informed or fully informed with concrete examples, which only left room for small improvement.

Table 1. Nathan's pre-test and post-test scores for Nature of Engineering assessment

NOE Aspect	Demarcation	Engineering Design Process	Tentativeness	Creativity	Subjectivity	Social and cultural
Pre-Test	4	3	3	4	4	3
Post-Test	4	4	4	4	2 (4)	3

Number in parentheses is the score after a follow-up question

***Understanding of the engineering design process*:** The available data for the teacher's understanding of EDP is limited to phase one and two assignments created as Google documents. In Nathan's first attempt to define the problem, he successfully wrote a problem statement that described the situation without proposing a solution and he identified several criteria and constraints relevant to the problem. There were a couple deficiencies in his work, including: an improperly written criterion (e.g. suggesting a particular piece of equipment to measure water temperature difference), and not correctly distinguishing between criteria and constraints. These deficiencies were resolved on Nathan's second attempt after receiving feedback from the course instructor. There was considerable discussion with the instructor and prompting in order for

Nathan to achieve mastery on this assignment. In developing the evaluation matrix, Nathan began by placing the criteria in the table and describing the actions that corresponded to different scores (i.e. achievement levels). As recommended, he identified the endpoints first and then the middle levels. Overall, he correctly created an evaluation matrix containing his criteria and delineated levels of achievement for each criterion. One problem that stands out in one of Nathan's early iterations is having gaps or overlaps in the achievement levels (i.e. not having appropriate scaling). For example, solar panel adjustability was blocked into four levels: adjusted 80 degrees, 60-80 degrees, 30-60 degrees, not adjustable. Nathan did not notice the discontinuity until the instructor questioned him about the appropriate score for 60 or 20 degrees. Then Nathan observed the discontinuity and altered the achievement levels to eliminate gaps and overlap (i.e., 80 degrees or more, 60-79 degrees, 30-59 degrees, <30 degrees). In struggling with this phase of the design process, Nathan realized that this would be a potential pitfall for his students and he noted in his reflection questions that he would have to scaffold this process heavily for the students' first experience. Generating solutions proved difficult for Nathan both as an independent and collaborative process; however, he was adept at evaluating the solutions. With prompting from the instructor, Nathan developed three solutions. He successfully evaluated them on his own and determined the best solution. Although Nathan could clearly state the parts of the engineering design process, as evidenced in his NOE post-test responses, he struggled to execute the steps. As NOE research is emerging, there is not sufficient information to determine if NOE understanding and ability to perform EDP should be correlated.

Future Work and Changes

This pilot project study was developed concurrently with implementation of the teacher professional development. As a result, there are several areas of improvement for the full research study, such as: 1) including explicit-reflective instruction, 2) the timing of the pre-test, 3) conducting interviews, and 4) investigating the correlation between ability to perform EDP and a teacher's understanding of NOE. First, NOS literature recommends that students should be introduced to NOS ideas in an explicit-reflective format because research shows that implicit only exposure to scientific inquiry does not improve students' nature of science views [20]. Drawing a parallel between NOS and NOE instruction, teachers may not be able to understand NOE aspects in an implicit format, such as through an engineering design challenge (i.e. building a solar water heater). Therefore, in the second iteration of the PD, NOE aspects will be included in an explicit-reflective manner and the high school teachers will reflect on these NOE aspects throughout the engineering design challenge. For example, the researchers will facilitate a group discussion where teachers will be asked reflective questions, such as "Did you use creativity in your design process?" or "Is it possible to have two different design solutions for a problem?" Through this approach, teachers will experience explicit-reflective NOE instruction rather than the implicit instruction in the pilot study. Second, the NOE pre-test was given late; it was already three weeks into the semester. This may be one of the reasons that Nathan's NOE views were high in pre-test. For the future paper, the pre-test will be given at the beginning of the first class prior to instruction. Third, pre/post NOE assessments will be followed by semi-structured NOE interviews to elicit teachers' ideas fully and provide more detail into their open-ended responses to the NOE assessment. Lastly, a future research goal is to check the correlation between participants' ability to perform EDP and understanding of NOE. The researchers do not yet have a plan for accomplishing this goal.

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Appendices

Appendix A. Mastery Grading Objectives for Engineering Design Process

Engineering Design Phase	Objectives
Define (2 assignments)	Define the Problem ● Listed criteria and constraints appropriate to the design ● Correctly categorized each item as a criterion or constraint, thus demonstrating an understanding of how criteria and constraints differ ● Provided sufficient detail to help someone understand each criterion and constraint Evaluation Matrix ● Created a consistent framework/matrix using criteria and levels of achievement ● Appropriately scaled level of achievements across each criterion ● Clearly delineated the level of achievements for each criterion
Develop Solutions	● Generated three distinct solutions that meet the established constraints ● Described each solution, as well as how the solutions differ ● Evaluated how well the solutions meet the established criteria using a matrix ● Justified the achievement scores for each solution
Optimize	● Successfully build a functioning solar water heater ● Explain why design changes were needed ● Explain why these changes improved the design

Appendix B. NOE Aspects Scoring Rubric

Description	Point
No answer, incomprehensible or irrelevant answer, or an answer could not be categorized	0 points
An answer that is not aligned with the description of NOE aspect	1 point
An answer that is partially aligned with the description of NOE aspect	2 points

An answer that is fully aligned with the description of NOE aspect	3 points
An answer that is fully aligned with the description of NOE aspect. The view is well-articulated and/supported with relevant example(s)	4 points

Appendix C. Descriptions of Nature of Engineering (NOE) Aspects

NOE Aspect	Description
Demarcation criteria (What is engineering? What makes engineering different from other disciplines?)	Engineering is systematically engaging in the practice of design to achieve solutions for specific problems. Engineers apply their understanding of the natural world (scientific knowledge) to design solutions for real world problems. This endeavor results in new technologies. In the K-12 context, "science" is generally taken to mean the traditional natural sciences: physics, chemistry, biology, and (more recently) earth, space, and environmental sciences… We use the term "engineering" in a very broad sense to mean any engagement in a systematic practice of design achieve solutions to particular human problems. Likewise, we broadly use the term "technology to include all types of human-made systems and processes-not in the limited sense often in schools that equates technology with modern computational and communications devices. Technologies result when engineers apply their understanding of natural world and of human behavior to design ways to satisfy human needs and wants. (NRC, 2012, pp. 11-12)
Engineering design process	The core idea of engineering design includes three component ideas (NGSS Lead States, 2013): Define, Design, and Optimize A. Define: Defining and delimiting engineering problems involves stating the problem to be solved as clearly as possible in terms of criteria for success and constraints or limits.

	B. Develop Solutions: Developing solutions to engineering problems begin with generating a number of possible solutions. These potential solutions are then evaluated to assess which ones best meet the criteria and constraints of the problem. C. Optimize: Optimizing the design solution involves a process in which solutions are systematically tested and refined and the final design is improved by trading off less important features for those that are more important.
Empirical basis	Engineers optimize their design solutions and compare alternative solutions based on evidence obtained from test data. They use assumptions to produce simplified models that does not contain the variables that the problem are insensitive to.
Tentativeness	Phases of engineering design process do not always follow in order, any more than do the “steps” of scientific inquiry. At any phase, a problem solver can redefine the problem or generate new solutions to replace an idea that is just not working out.
Creativity	Creativity and imagination of engineers play a major role during the engineering design process. The role of creativity and imagination is not limited to any specific phase of the engineering design process.
Subjectivity	There is no unique solution to an engineering design problem. While there can be many solutions to the same problem, some of these solutions may be more suited to meet the criteria and constraints of the problem.
Social aspects of engineering	Engineering is not a solitary pursuit. Engineering design solutions are constructed through social negotiation. Despite their individual differences, members of an engineering community share common understandings, traditions, and values. This social dimension enhances the quality of engineering design solutions.
Social and cultural	Engineering is a human activity. There is a continued interaction between engineering and society. Sociocultural

embeddedness	factors influence the engineering design process, and in turn, engineering influences the society. These social and cultural factors include social composition, religion, worldview, political, and economic factors.