

## **Participating in Authentic Engineering Projects Improves Teachers' Ability to Teach the Design Process to Middle School Students**

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## Introduction

At the national, regional and local level, science, technology, engineering, (art) and math (STEM/STEAM) curricula and activities are receiving increased emphasis in schools. This instructional effort goes beyond including specific STEM-related content in instruction; STEM instruction incorporates multi-disciplinary approaches to problem solving, inquiry, and engineering design.<sup>[1]</sup> STEM standards such as The Next Generation Science Standards (NGSS) that embody “practices, cross cutting concepts, and core ideas” require cross-disciplinary, authentic science and engineering learning and thus influence STEM instruction.<sup>[2]</sup> The standards necessitate that teachers have not only understanding of content, but also of real-world application and practice. K-12 science teachers are increasingly pressured to include engineering design in their curriculum; however, there are relatively few engineering-focused professional development programs in comparison to those for traditional science and mathematics.<sup>[3][4]</sup>

Professional development can improve teacher practice,<sup>[5][6]</sup> especially if the programs are content specific,<sup>[7]</sup> inquiry-based, and learner-centered.<sup>[8][9]</sup> Successful professional development provides teachers with content, pedagogical knowledge, and training; training that includes guidance, support, feedback, and time for reflection and planning.<sup>[10][11]</sup> In addition, effective professional development approaches include peer support, teacher-developed research experiences, and hands-on curriculum development. Contrary to these best practices, professional development programs in engineering often focus more on tools, processes, and techniques than on learning or teaching pedagogy.<sup>[4]</sup> In addition, the programs are typically short term, such as three days or one week in length. Gerard *et al.* found, in a meta-analysis of 43 studies, that while most technology-enhanced science education professional development programs helped teachers elicit new ideas, they did not adequately support teachers in reflection, integration, or critiques of their ideas.<sup>[12]</sup>

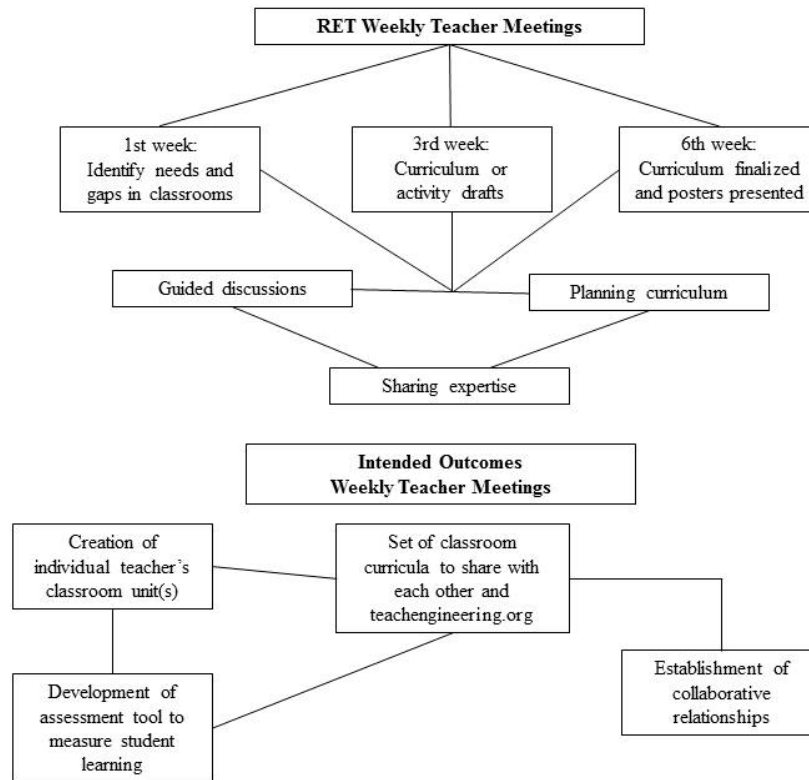
In this work, we present the structure and outcomes of an immersive integrated research and teaching experience for middle school teachers, developed as part of our NSF-funded Research Experiences for Teachers (RET) program. The program, based on the engineering design process, inspires inquiry and active learning in a structured manner; a process that fills gaps in professional development for middle school teachers of engineering. The RET program includes meaningful research experiences and curriculum development based on those experiences. As middle school students are most engaged by educational activities centered on active inquiry and on developing critical thinking skills,<sup>[13][14]</sup> we predict that our approach of providing teachers with authentic and reflective experiences translates into analogous practices in their classrooms that have a positive impact on student learning.

## **Methods**

### Description of the professional development program

Each program year, middle school teachers from the Worcester Public School system and surrounding districts applied to our RET program at Worcester Polytechnic Institute (WPI), and six to ten teachers were selected to attend. For 6-weeks each summer, the teachers participated full time in authentic independent design projects in bioengineering research labs and developed design-based inquiry curriculum units for their classes. The teachers' research projects help to solve or investigate real-world, practical biomedical problems. Based on the engineering design process, the teachers' research projects and approach to curriculum development were collaborative.

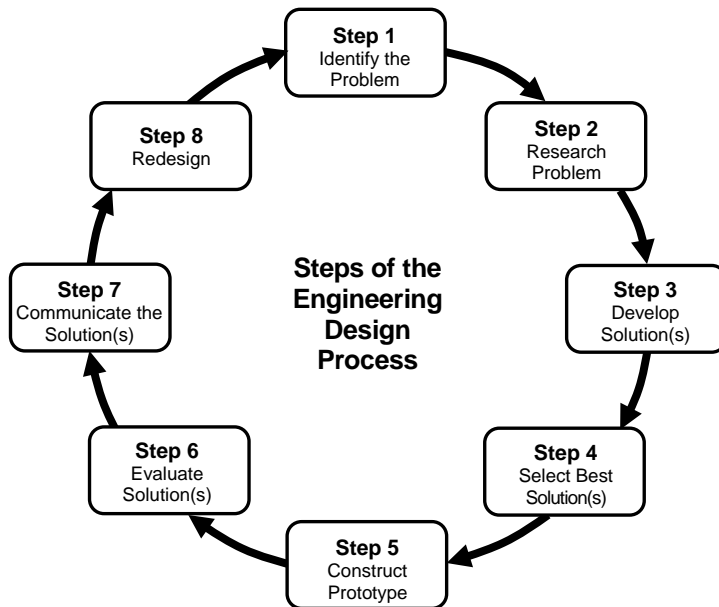
Throughout the research and curriculum creation process, the middle school teachers had a number of opportunities for training, development, and mentoring (Figure 1 and 2). Each middle school teacher paired with another teacher, and each pair was assigned a faculty research advisor and a graduate student mentor who actively supported and aided the teachers in their research. Examples of support included meeting at least weekly with faculty advisors, meeting daily with graduate students, and ongoing email contact. In addition to their own research, while the teachers worked they were able to see the cutting-edge work of many other researchers due to the open-lab format at the institution. They had extensive contact with undergraduate and graduate students, as well as the faculty mentors. The teachers followed the engineering design process (EDP) for the creation and execution of their research projects. Examples of the teachers' projects included designing a device to hold threads made from tissue proteins in a precise configuration for chemical treatment; designing a custom harness for a service dog, and design of a device to more efficiently add therapeutic cells to a novel cell-delivery device.



**Figure 1.** Overview of expectations and outcomes for weekly teacher meetings focused on the development and implementation of inquiry-based curricula. The teachers provided feedback to each other based on their experiences rather than be ‘taught’ by an expert how to incorporate the engineering design process in their classrooms.

Concurrent with their research projects, each teacher developed a design-based lesson or unit based on their research or another aspect of biomedical engineering. A unique contribution of the RET program was the requirement to develop a curriculum unit using the engineering design process (Figure 2).<sup>[15]</sup> As such, teachers began with a statement of “client” (students’) needs and researched the problem. They investigated several alternative designs (solutions) for their lessons and selected the best approach to “prototype”. Teachers matched their curricula with their State and school district standards and evaluated their “prototyped” solution with the help of their peers, and they communicated their solutions to the group. The cyclic nature of the design process was stressed, with teachers repeating steps in the process and “redesigning” until they came up with an instructional unit that they believed would meet their students’ and their own needs. The engineering design process provided a framework and the tools to develop a curriculum unit and at the same time gave teachers additional experience in using the process itself. Teachers met weekly for four hours in group peer discussion and assessment meetings facilitated by the external evaluator. Teachers presented their progress towards development of curricula and discussed all aspects of it with their peers. Peers offered suggestions for improvement or resources for development. The teachers were required to implement their

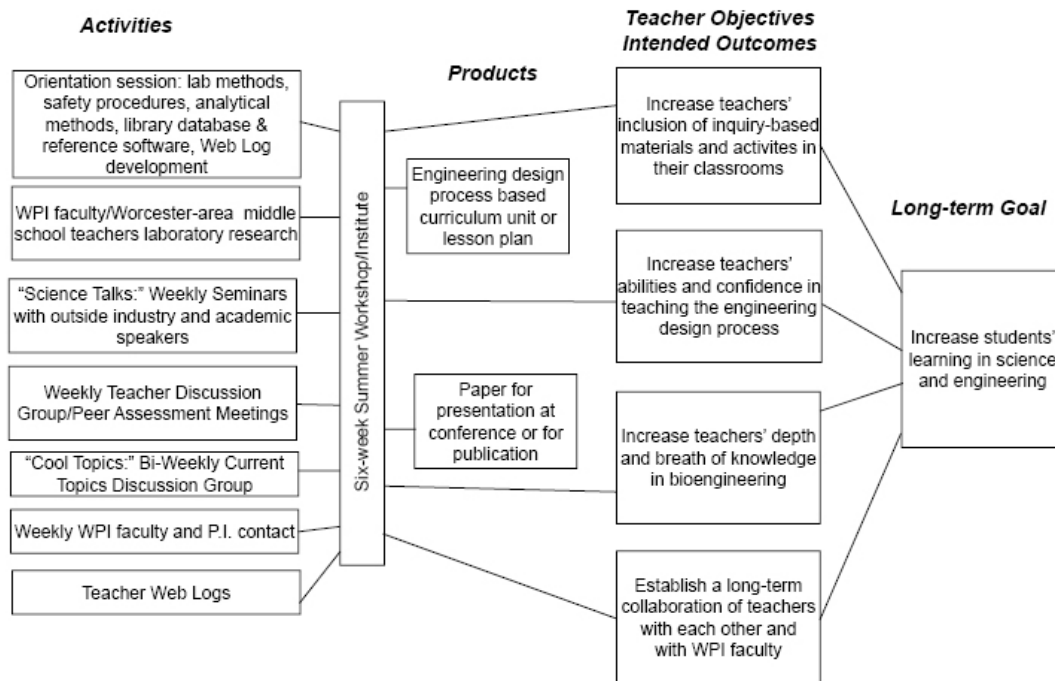
curricular unit in their classrooms in the successive academic year. They were invited back to WPI to give follow-up presentations during the next academic year, at which time teachers shared successes and issues with implementation of their units.



**Figure 2.** The steps of the engineering design process. Note that each step can also cycle back to previous steps as needed, e.g., after researching the problem, the identified need is often refocused. Adapted from <http://www.doe.mass.edu/mcas/>.

To meet the broader goals of the RET program (Figure 3), in addition to their research and curriculum activities, teachers participated in an orientation session covering lab safety, the design process, research methods, and software. They also participated in weekly “Science Talks” or seminars describing current, cutting-edge bioengineering topics. The teachers gave an oral presentation of their research to the public at the end of the project. Also, at the end of the program, teachers presented a poster of the development of their curriculum units or lessons.

## Six-Week Summer Institute Component of RET Project



**Figure 3.** Overview of activities, products, outcomes, and goals related to the RET program.

### Evaluation of the program

During each of the program years, teachers completed surveys at the beginning and end of the summer. Surveys included structured and open-ended questions. Throughout the year, teachers wrote about their experiences in response to weekly prompts. Each Friday, during curriculum planning, teachers had the opportunity to offer formative feedback. The external evaluator also made unannounced observations at the labs and common planning areas and served as a participant observer during most science professional development sessions.

In the final years of the program (2013 and 2014), the teachers, with the facilitation of the external evaluator (author J.H.), developed a common measure to assess their middle school students' understanding of the design process (pre and post instruction). Based on statistical and formative feedback from the first administration of the test, the teachers revised the measure during the final year. This tool provides a common measure of understanding of student learning.

### Statistical analysis

To assess student learning, we analyzed the pre and post percent correct scores teachers submitted. Item and reliability analyses were performed for students' knowledge tests. Descriptive statistics, tests for homogeneity, and '*t*'-tests were conducted using SPSS statistical software (IBM). To assess teachers' responses to survey items, we used descriptive and nonparametric statistics such as Wilcoxon Signed Ranks.

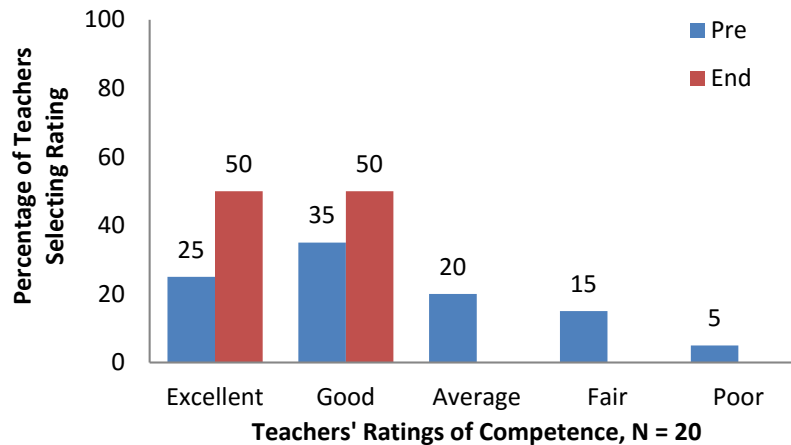
## Results and Discussion

The RET program was provided each year from 2009 to 2011 and again each year from 2013 to 2015. Similar programming was included in each cohort; however, substantial changes were made for the second grant period including team-based projects, mandatory submission of curricular units to [teachengineering.org](http://teachengineering.org), metrics for middle school student learning, and assessment questions. For simplicity in presenting quantitative data, we focus on the second cohort of teachers (2013-15). During this time, training was provided to 20 teachers. Seven teachers were repeat teachers who attended earlier program offerings. Forty-five percent of the teachers were female and 15% were black. While all of the teachers taught 6<sup>th</sup> through 8<sup>th</sup> grade prior to entering the program, two teachers had their assignments changed during their summer of participation. One teacher was moved to fourth grade, while the second teacher was moved to 9<sup>th</sup> and 12<sup>th</sup> grade science. While most (75%) of the teachers taught science, a fifth (20%) taught engineering and/or technology; one teacher (5%) taught robotics.

Twenty-seven curriculum units were created. The units were aligned with Massachusetts and national STEM frameworks or standards, such as NGSS. These units were shared with others via the WPI website, within school districts, and nationally at conferences. In addition, all teachers were asked to submit their curricular units to [TeachEngineering.org](http://TeachEngineering.org) and over a third were accepted for publication. Sample titles of accepted lessons include “E.G. Benedict’s Ambulance: Teaching Engineering through Transportation Technology and Patient Safety,” “Wrist Watch for the Visually Impaired: Teaching Engineering through Assistive Devices and Product Design,” and “Sensory Toys Make Sense! Design a Toy for Sensory Integration for Children with Developmental Disabilities.”

### Teachers’ increased competency in the design process

Teachers reported a significant increase in their competency to teach the design process. While teachers rated themselves from poor to good competence at the beginning of their RET, all teachers rated themselves as having good or excellent competence at the end of their RET (Wilcoxon signed ranks  $Z = 2.994, p < .01$ ) (Figure 4).



**Figure 4.** Teachers’ ratings of competence in teaching the design process

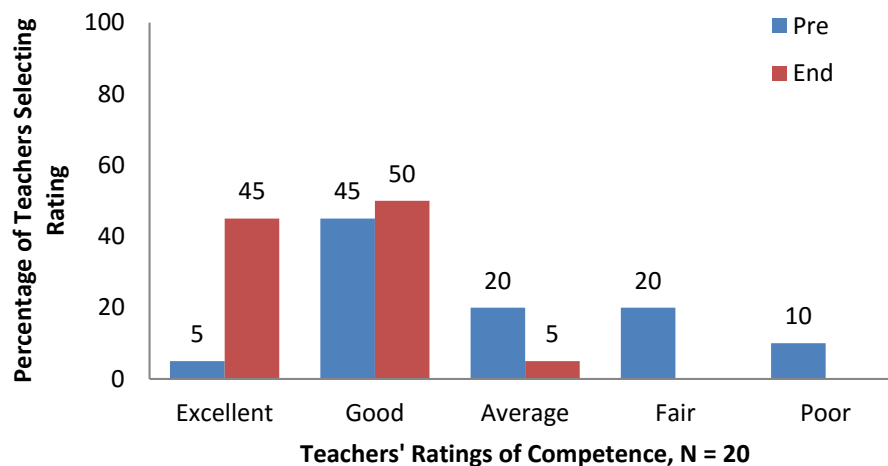
These ratings are in agreement with teachers' agreement at the end of program that the program increased their ability and their confidence to teach the EDP. For both items, 70% of the teachers strongly agreed and 30% agreed. Three teachers stated that participation in the program for longer than one year helped to improve and refine their ability to teach the EDP.

The following comments from one repeat teacher reflect feedback from other RET teachers. *"I wanted to take a minute to thank you for running such an amazing program. The RET has literally changed my life (as corny as that sounds.) I never thought I would stop teaching life science, yet I find myself teaching an Engineering & Technology course. I cannot imagine going back to teaching in a traditional science classroom. The RET has given me so many opportunities to thoroughly develop engaging lessons and work with a variety of teachers that I never would have met. I have a greater understanding of biomedical engineering and have worked on fascinating projects."*

### Teachers' knowledge in engineering increased

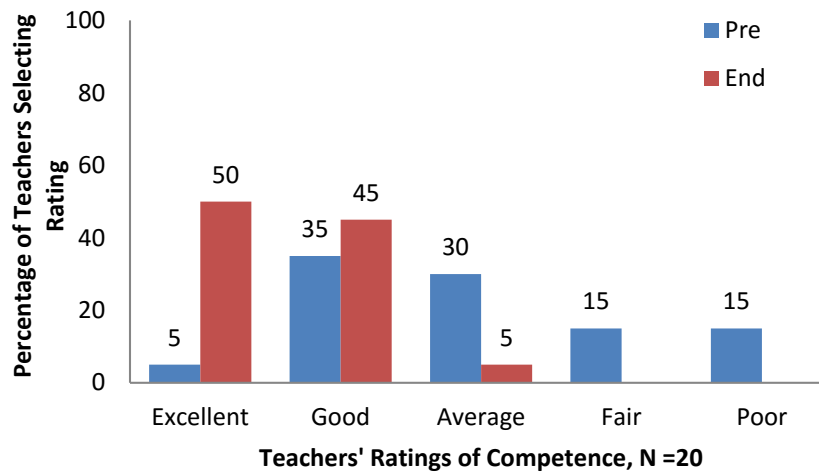
Teachers' knowledge of engineering was also assessed directly through pre and post-test responses covering biomedical engineering and the engineering design process. The beginning percentage correct for the teachers was  $58.7\% \pm 17.3\%$ , and the ending percentage correct was  $79.4\% \pm 11.8\%$ . This difference is statistically significant ( $t'_{df=19} = 6.19, p < .01$ ).

Teachers reported a significant increase in their broad understanding of biomedical engineering and in explaining the details of one topic in bioengineering. At the beginning 5% of the teachers rated their understanding of biomedical engineering as excellent and 45% rated it as good (Figure 5). At the end, 45% rated their understanding as excellent and 50% rated it as good (Wilcoxon Signed Ranks  $Z = 3.344, p < .01$ ). Similarly, at the start of their program, 5% of the teachers rated their ability to explain details of one topic in bioengineering as excellent and 35% rated it as good (Figure 6). At the end of the RET, 50% of the teachers rated their ability as excellent and 45% rated it as good. This difference is statistically significant (Wilcoxon Signed Ranks  $Z = 3.58, p < .01$ ).



**Figure 5.** Teachers' ratings of competence in broad understanding of bioengineering





**Figure 6.** Teachers’ ratings of competence in explaining the details of one topic in bioengineering

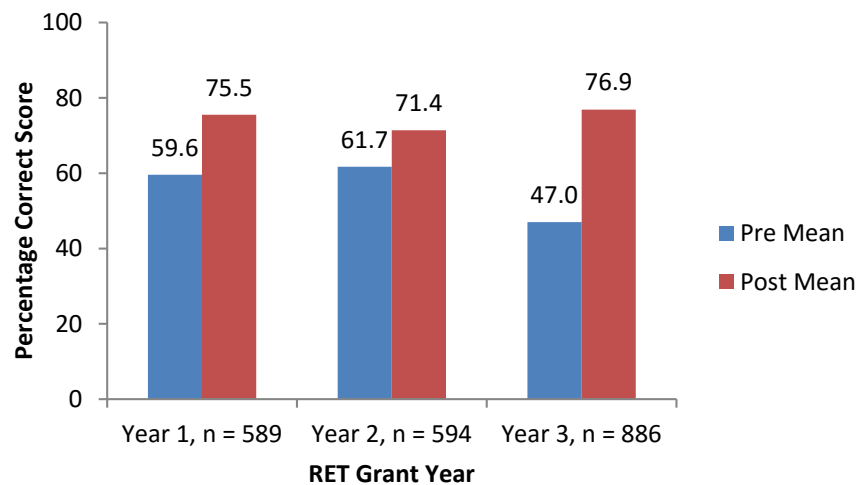
Most of the teachers strongly agreed (65%) or agreed (30%) that the program helped them learn how real-world research works. One person (5%) neither agreed nor disagreed. Faculty mentors to the teachers reported similar agreement. Sixty percent (60%) strongly agreed that their mentees developed an appreciation of the daily work of scientific research and 30% agreed. One faculty mentor disagreed (5%) and one had no opinion (5%).

#### Teachers’ learning transferred to the classroom

All teachers stated that participation influenced the way they teach, either “a great deal” (60%), “moderately” (20%), or “somewhat” (15%). Open-ended survey notes, journal entries, and focus group comments provided information about the nature of teachers’ changes in their teaching. Because of their exposure to biomedical engineering research and creation of an instructional lesson or lessons with a bioengineering emphasis, all teachers reported adding new content to their classes. Several teachers explained that they not only have a better understanding of the engineering design process, but that the program “*increased my creativity as well as my willingness to allow my students to be creative.*” Teachers noted that they will incorporate “*more hands-on instruction*” and “*inquiry-based learning*” in their classes. A few teachers wrote that they now allow for failure, because as one teacher commented, “*learning happens when students are able to make mistakes.*”

Teachers in the three-year grant cycle taught their RET curriculums to over 2,500 middle-school students. Two of the grant cohorts tested their students with an assessment instrument created during the summer. Specifically, for 2,069 of the students, we received pre and post percentage correct scores from tests of the engineering design process. Reasons for missing scores included absences, time constraints, piloting their lessons, and technical issues such as losing computer files and errors in printing assessments. In the three years, only one of the teachers did not provide information on classroom teaching of the RET-developed unit.

During the first year, the teachers submitted pre and post percent correct scores from tests (specific to teacher) for 589 students. The post score ( $75.5\% \pm 20.5\%$ ) was significantly higher than the pre score ( $59.6\% \pm 25.6\%$ ;  $t_{df\ 588} = 17.71, p < .001$ ). The first administration of the teacher-developed engineering design process test (year two) yielded 594 student scores. The pre score was  $61.7\% \pm 23.7\%$  correct and the post score was  $71.4\% \pm 22.2\%$ . During Year 3, teachers submitted scores for 886 students who took the revised design process test. The pre score was  $47.0\% \pm 24.8\%$  correct, while the post score was  $76.9\% \pm 20.4\%$  correct. The differences during both years were statistically significant ( $t_{df\ 593} = 11.6, p < .001$ ;  $t_{df\ 885} = 36.1, p < .001$ ). Klein-Gardner and colleagues' phenomenological study of NSF Research Experiences for Teachers programs suggested the importance of supportive time for curricular development and research experiences with faculty. [16] Our quantitative data support the positive student outcomes reported in the aforementioned study obtained from anecdotal evidence from the teachers.



**Figure 7.** Students' mean percentage correct scores on pre and post instruction tests of knowledge of the engineering design process.

While the mean post score was not as high as teachers would have liked, it usually represented a short-term lesson or activity. The number of classes periods in which lessons were taught ranged from 3 to 12, with a mean of 7. The average class time was 50 minutes (ranged from 45 to 60 minutes). In addition, many of the classes in which the teachers taught their lessons were not required and students were not graded. A few students, especially those in the first test administration year, had prior exposure to the engineering design process.

Teachers reported that they also assessed their students with authentic measures such as portfolios of progress toward the engineering design process, presentation of their products, and collaborative work. Many teachers developed rubrics for the competencies. The additional measures were often included in their teachengineering.org submissions and shared at follow-up meetings. Because of the variability in content, administration and scoring, these measures were not used for comparison.

## Conclusions

Based on our detailed evaluation, we conclude that the WPI RET program was successful for four main reasons. First, our program, though run prior to publication of the ASEE standards for professional development for K-12 engineering teachers, embodied the elements of the standards.<sup>[17][18]</sup> Not only the design process, but also collaboration, teamwork, careful documentation, and communication were significant components of the program. Second, the design approach to both the teachers' research and to the development of their curricula corresponded to desired teaching practices.<sup>[11]</sup> Teachers were engaged in complex thought and reflected on how their research applied to their classrooms. They identified appropriate curricula, instructional materials, and assessment methods. Alignment with state and NGSS was a strong thread throughout curricula development. Third, the program was longer than traditional 3-day or 1-week workshops. Teachers were actively and fully engaged for six weeks during the summer. Repeat teachers told us that a second year or more in the program was vital to their understanding and processing of the design process and understanding of biomedical engineering. Fourth, teachers said that going through the design process both in their research and curriculum development helped them to see learning from their students' perspectives. *"By doing research and walking through the design process, I am experiencing challenges and struggles that my students feel."* Teachers talked about how that experience helped them to plan better and to increase the amount of inquiry-based learning in their content and methods. Teachers were encouraged to take risks, make mistakes, and to learn from their failures. Several teachers noted that this experience showed them the value for their students to make mistakes when going through the design process to create a product or meet a need.

All of the teachers gained a great deal of experience in inquiry-based learning and the engineering design process. They learned not only specific skills in a particular area of biomedical engineering, but they also learned how to apply the engineering design process to any of the science topics they are already covering in their classroom activities. Our data demonstrate that our RET program aided in increasing teachers' knowledge of engineering concepts and in their confidence to teach the engineering design process to their students. The program also facilitated the development and teaching of inquiry-based lessons which were effective in helping over 2,500 students learn engineering concepts. Many of these lessons were submitted to [teachengineering.org](http://teachengineering.org) for broader dissemination and impact. Developing STEM lessons that address students' needs and provide developmentally and pedagogically appropriate content within classroom constraints is a continuous challenge for K-12 teachers. Programs that combine authentic engineering research and curriculum development, such as the one described herein, are critical for aiding K-12 teachers in educating and motivating the next generation of technologically literate students.

## Acknowledgements

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