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Educational aspects of nanotechnology

Facilitating teachers' development of nanoscale science, engineering, and technology content knowledge

Lynn A. Bryan[1,2,*], David Sederberg[2], Shanna Daly[3], David Sears[4] and Nicholas Giordano[2]

[1] Department of Curriculum and Instruction, Purdue University, 100 N. University Street, West Lafayette, IN 47907, USA, e-mail: labryan@purdue.edu

[2] Department of Physics, Purdue University, West Lafayette, IN 47907, USA

[3] College of Engineering, University of Michigan, Ann Arbor, MI, USA

[4] Department of Educational Studies, Purdue University, West Lafayette, IN 47907, USA

* Corresponding author

Abstract

As nanoscale science, engineering, and technology (NSET) becomes more integrated into precollege science curricula, it is crucial for teachers to develop coherent understandings of science principles (e.g., the structure of matter, size and scale, forces and interactions, and size-dependent properties) that allow them to coordinate these understandings from the macro- to the nanoscale. Furthermore, as teachers acquire new NSET content knowledge through professional learning opportunities, it is incumbent upon NSET educators to understand their developing content knowledge. To this end, we report results from a study in which we used a pre-/post-/delayed-posttest design to examine the change in 24 secondary (grades 7–12) science teachers' NSET content knowledge as a result of their participation in a year-long professional development program that consisted of a 2-week intensive course and academic year follow-up activities. Participants showed significant gains from pretest to posttest and significant gains on the delayed test compared to the pretest. We also present trends that emerged in teachers' open-ended responses that provided deeper insight into teachers' NSET content knowledge. Finally, we discuss issues related to the assessment of teachers' NSET content knowledge as well as the design of NSET professional development for teachers.

Keywords: nanoscale science, engineering, and technology (NSET) education; professional development; science teacher knowledge.

1. Introduction

In the United States (US), increasing attention is being placed on the quality of our nation's science teachers – particularly the depth and breadth of their content knowledge in science. This is evidenced by policies such as the US Department of Education's [1] *No Child Left Behind Act of 2001*, as well as a recent increase in funding for programs that provide content-focused professional development aimed at improving teachers' knowledge and skills for teaching science (e.g., US Department of Education's [2] *Race to the Top*, US Department of Education's [3] *Teacher Quality Program*, National Science Foundation's [4] *Math Science Partnership Program*).

Concomitant with an amplified focus on the quality of science teacher knowledge, nanoscience, engineering, and technology (NSET) is making its way into precollege classrooms. NSET represents both grand challenges and great opportunities for science education at the precollege level. It is a grand challenge in the sense that the interdisciplinary nature of NSET necessitates that teachers construct new science knowledge and skills, developing a more unified view of fundamental principles across the traditionally demarcated scientific disciplines. By contrast, NSET provides a great opportunity to reform and extend "traditional" school science into an exciting new scale of science. Capitalizing on this opportunity serves not only to empower teachers but also to provide students the educational, cultural, and social capital they will need to participate in the world developing around them [5].

The implications of rapid scientific advances in NSET require a commensurate response in the science education community to develop and provide science learning opportunities *across scale* – specifically, the resources and learning experiences necessary for a new workforce to understand the fundamental principles that govern behavior of materials from the macro- down to the nanoscale [6, 7]. This challenge has not gone unnoticed. Since President Clinton established the National Nanotechnology Initiative in 2000, the number of nationally funded nanoscience education opportunities for teachers has grown significantly (e.g., programs through the National Center for Learning and Teaching in Nanoscale Science and Engineering, NanoSense, NanoTeach, National Nanotechnology Infrastructure Network, Center for Nanotechnology Education and Utilization, Materials

Research Science and Engineering Center on Nanostructured Interfaces, Cornell Center for Materials Research). However, a paucity of research has been published to date on what and how teachers learn from these programs.

If NSET is to be meaningfully integrated into precollege science curriculum – specifically, secondary (grades 7–12) science curriculum – then it is crucial for teachers to develop coherent understandings of science principles (e.g., the structure of matter, size and scale, forces and interactions, and size-dependent properties) that allow them to coordinate these understandings from the macro- to the nanoscale [8]. Although many of the ideas we mention such as the nature of matter, forces and interactions, and size and scale are currently taught in secondary school, they are typically presented in a fragmented manner, lacking a unified perspective of science – that is, a cross-disciplinary, cross-scale perspective [9–11]. By contrast, nanoscience emphasizes a need for teachers to develop a unified understanding of these fundamental ideas and their interrelatedness.

2. Purpose

In this paper, we report the findings from a recent study conducted as part of a 5-year initiative by the National Center for Learning and Teaching Nanoscale Science and Engineering (NCLT) to facilitate secondary science teachers' development of NSET content knowledge. In doing so, we aim to heighten awareness within the field of NSET of the necessity to provide quality professional development for teachers that facilitates their development of deep, transferable understandings of NSET concepts. Whereas a strong emphasis on content knowledge is particularly crucial for NSET professional development, there are additional aspects of designing professional development with which those who teach teachers should be familiar. To this end, we review specific recommendations from educational research about what factors engender the most effective professional development experiences for teachers and discuss salient issues that have arisen from our own experience in offering professional development for practicing high school science teachers.

3. Relevant literature

To situate our study and the broader discussion of teacher NSET knowledge, two bodies of scholarship predominantly informed our work: research on teachers' knowledge of NSET and research on the professional development of teachers.

3.1. Teachers' knowledge of NSET

To offer learning experiences for teachers that focus on deepening their NSET content knowledge and skills, one must first determine what the content *learning goals* should be. In other words, what NSET content do teachers need to know? Perhaps the most authoritative source to date that outlines what teachers should know about NSET is the *Big Ideas in Nanoscale Science and Engineering* [8]. The phrase "big ideas" refers to the important understandings, concepts, and organizing principles that are at the core of a discipline and have an enduring value [12]. More than a fact or skill, a big idea provides a conceptual anchor for students' construction of knowledge. Big ideas provide a focus, both to prioritize concepts and to provide a basis for teaching, learning, and assessment. Stevens et al. [8] identified nine big ideas in nanoscale science and engineering that clarify significant and developmentally appropriate learning goals for grades 7–12 nanoscience and engineering instruction: (1) size and scale; (2) structure of matter; (3) size-dependent properties; (4) forces; (5) self-assembly; (6) tools and instrumentation; (7) models and simulations; (8) nano and society; and (9) quantum mechanics.

In their description and discussion of each big idea, Stevens et al. [8] identified connections among these nine big ideas and current science curriculum, as well as new ways of considering traditional science content relevant to nanoscience and technology. The book was designed as a resource to support teachers' development of fundamental content knowledge and skills for teaching NSET in grades 7–12. Additionally, the *Big Ideas of Nanoscale Science and Engineering* serves as a reference for secondary teachers who wish to contemporize their existing science curricula with the integration of NSET and facilitate students' learning of the exciting new discoveries and novel applications from NSET research and development.

3.2. Studies focusing on teachers' NSET knowledge

As one might expect from a relatively new field such as NSET education, very little has yet been published about teachers' knowledge of NSET concepts and phenomena. A growing number of studies exist that examine various aspects of content knowledge among university professors, undergraduate students, precollege students, and even elementary children. There is also a plethora of publications that describe NSET professional development programs, courses, and instructional materials for teachers (e.g., see articles in *Journal of Nano Education*, Volumes 1 and 2; chapters in [13]). In addition, several studies that included teachers involved surveys of attitudes and/or risk perceptions about NSET (e.g., [14–16]). Although most of the focus in the literature has been on other aspects of NSET learning, we were able to find a handful of studies examining secondary teachers' content knowledge that have been published in recent years.

In particular, Blonder [17] reported on the influence that an Atomic Force Microscope (AFM) teaching model had on high school chemistry teachers' knowledge of the AFM and their attitudes towards using the AFM model in their classroom. Blonder analyzed four learning dimensions: (1) change in quantity of teachers' appropriate use of vocabulary; (2) depth of teachers' understanding of how the AFM works; (3) teachers' attitudes towards teaching AFM in their high school classrooms; and (d) teachers' metacognition as expressed in a personal meaning map [18]. Two groups of teachers participated in the study: one group of teachers who had previous knowledge of NSET and specifically the AFM, and one group of teachers who were NSET novices. Blonder found that teachers from both groups demonstrated significant changes in all four dimensions. Related to content knowledge, the teachers used richer vocabulary after instruction with the AFM teaching model and learned new and fundamental concepts regarding the AFM.

Another small study related to teachers' development of content knowledge was reported as part of a paper on the design and evaluation of an online nanoscience course for teachers. Tomasik et al. [19] administered pre- and post-instruction quizzes consisting of seven items, each addressing a different NSET topic. Their analysis revealed statistically significant differences in pre- and posttest scores, indicating that teachers demonstrated substantial gains in understanding NSET topics. The researchers also noted that the quality of teachers' responses improved such that teachers were able to provide "comprehensive and well-informed" responses after instruction.

Whereas the previous studies examined aspects of practicing teachers' NSET content knowledge, Kumar [20] conducted a study of prospective teachers' general knowledge of NSET. Volunteer prospective teachers (n=109) who were enrolled in an undergraduate science teacher preparation course at a southeastern university in the US completed a 10-item, multiple-choice format Nano Quiz from the National Institute of Standards and Technology. The average score was 6.13 out of 10 (SD=1.34). However, what this means about prospective teachers' knowledge about NSET is unclear. The quiz consisted of questions about simple definitions (e.g., "What is a qubit?", "What is a flying qubit?", "What is a Bose-Einstein Condensate?") and discreet facts ("The prefix 'nano' comes from the Greek word meaning…"). In addition, some of the distracter choices seemed fairly obvious ("What is a nanonewton?" Choices included "a new kind of cookie", "a miniature pop singer", etc.). In our opinion, the Nano Quiz is not an assessment of *conceptual* knowledge, and any findings from its use should be interpreted with skepticism.

Overall, it is clear that the field of NSET education has barely "scratched the surface" in terms of examining secondary teachers' NSET knowledge development. Professional development opportunities for teachers in NSET education are growing; yet, we have little evidence of what content knowledge teachers have about NSET, what NSET content knowledge teachers are able to develop through professional development experiences, and what assessments can measure those differences. Because teachers will play a pivotal role in the integration of NSET in secondary science curricula, it behooves the NSET education community to understand how teachers conceptualize and understand NSET content.

4. Teachers' professional development

An integral part of any profession is an expectation that professionals will continually enhance their knowledge and skills. The teaching profession is no exception. Professional development plays a vital role in teachers' learning throughout their career trajectory. Over the past 25 years, a considerable amount of educational literature has amassed that focuses on teacher knowledge, teacher learning, and teacher change. As a result, characteristics of effective professional development have emerged as a topic of study and review.

Historically "traditional" professional development of teachers has been bemoaned as a weak, ineffective, and "incoherent and cobbled-together non-system" ([21], p. 174) that has little to no effect on teachers' instructional practices (e.g., [22–25]). The phrase "traditional professional development" encompasses workshops, programs, and seminars of short duration, single instance learning experiences that often have a bag-of-tricks or tool-box orientation. These experiences often do not require any follow-up or accountability of implementing the content of the learning experience in practice.

However, there appears to be a changing face of professional development – one that calls attention to the importance of high standards, coherence, and comprehensive learning opportunities for teachers. Researchers have begun to synthesize the literature on what constitutes effective and high-quality professional development, resulting in a portrait of consensus about the principles of effective professional development. In Table 1, we summarize these characteristics and frame them as *professional development design principles* that are most relevant to designing learning experiences for high school science teachers in NSET.

4.1. Methods

We measured the change in grades 7–12 science teachers' content knowledge about NSET as a result of their participation in a year-long professional development program that consisted of a 2-week intensive course and academic year follow-up activities from 2009 to 2010. Specifically, we used a pre-/post-/delayed-posttest design to analyze test responses.

4.2. Context

In 2004, the multi-institutional NCLT was created to focus on "learning and teaching though inquiry and design of nanoscale materials and applications" ([7], p. 1). With an emphasis on nanoscale science and engineering capacity building in grades 7–12, NCLT initiatives aimed to provide a strong impact on national science, technology, engineering, and mathematics (STEM) education. A major component of the NCLT was a national professional development program for secondary science teachers. An interdisciplinary team of scientists, science and engineering educators, assessment specialists, graduate students, and high school "master teachers" collaborated on the design and implementation of an NSET professional development program that we will henceforth refer to as NCLT-PD. Each year from 2006 to 2010, the NCLT-PD program involved both a summer institute (80 contact hours) and academic year sustained contact activities

Table 1 Principles of effective professional development for teachers.

Principle	Description	Resources
Subject matter knowledge	Effective professional development provides numerous and varied opportunities for teachers to build in-depth subject matter knowledge. Research in education, and more specifically science education, clearly has demonstrated positive effects on student achievement outcomes for teachers who participate in professional development programs that have a strong focus on subject matter knowledge. In addition, research supports the intuitive notion that a deep, flexible, and coherent understanding of subject matter is prerequisite to the development of knowledge for how to teach the subject matter. Subject matter knowledge enables the science teacher to design conceptually coherent lessons, lead dynamic and in-depth discussions about science explanations, and relate content to meaningful and authentic situations.	[26–34]
Pedagogical knowledge/ pedagogical content knowledge	Merely knowing science content is not sufficient for teaching science. Science teachers must have knowledge about learners, curriculum, instructional strategies, and assessment to transform their science content knowledge into effective teaching (i.e., pedagogical content knowledge or PCK). A significant component of professional development must include the expansion and elaboration of pedagogical knowledge and pedagogical content knowledge. Professional development learning activities must not only model the instruction advocated in reforms but also help teachers reflect on the nature of the discipline and their epistemological beliefs vis-à-vis their own experiences as learners and teachers.	[21, 26, 28, 31, 32, 35–39]
Program coherence	When a professional development program consists of a coherent set of opportunities for learning, it is more likely to result in enhanced knowledge and skills for teaching. Coherence of a program concerns not only the extent to which activities reinforce and build on one another but also the extent to which the professional development experiences align with local, state, and national standards and assessments. Effective professional development programs show teachers how to connect their work to specific standards for student performance.	[26, 28, 31, 32]
Sustained contact	Just as learning science takes time and experience, learning to teach science occurs over a developmental trajectory. Professional development needs to take into account that teachers must be given time to learn new content and pedagogy, adapt their instruction to reflect what they have learned, and analyze the outcomes of their new/refined knowledge and practice (e.g., student learning). Programs that support teacher learning over time with coherent, sustained contact experiences acknowledge the complexity of teachers' development of knowledge and skills for teaching science.	[28, 31, 40, 41]
Professional relationships	Effective professional development provides opportunities for teachers to interact and collaborate with each other and experts in the processes of learning and teaching, both in and out of school contexts. Professional communication and colleagueship has been shown to sustain motivation for enacting reform. When professional collaborations are developed skillfully they can lead to sharing of knowledge and expertise; working together to address common concerns; developing a better understanding of goals for student learning; alleviating teacher isolation, and numerous other benefits. In addition, effective professional development supports teachers in developing professional relationships in the context of leadership roles, for example, as teachers of other teachers and promoters of reform.	[21, 26, 28, 31, 37, 41, 42]
Continuous assessment and evaluation	Just as teachers are expected to implement what they learn in professional development, those designing professional development should implement what they learn from the teachers. Continuous assessment and evaluation should inform all components and drive the focus and priorities of professional development efforts. Effective professional development is "information rich" ([28], p. 142) in that multiple sources of information on teaching and learning processes and outcomes contribute to an iterative design and implementation cycle.	[26, 28, 31, 41]

(>20 contact hours). The instructional goals of the NCLT-PD program were to:

- provide grades 7–12 science teachers with enhanced content knowledge of NSET;
- enhance teachers' understanding of the connections between NSET and the traditional sciences of chemistry, physics, biology, earth science, and mathematics;
- enhance teachers' knowledge and skills for using inquiry-based methods (such as the role of evidence and explanation in inquiry) for teaching NSET;
- promote reflection on salient issues involving NSET teaching and learning; and
- support integration of NSET lessons by grades 7–12 science teachers by helping them adapt materials from a collection of suitable lessons for classroom use.

4.2.1. NSET content in the NCLT-PD program The *Big Ideas of Nanoscale Science and Engineering* [8] provided a framework for the content knowledge teachers learned during their participation in the NCLT-PD summer institute. Because a 2-week institute provides the opportunity to address in depth only the most salient NSET concepts, we chose to address content that we believed secondary teachers could most easily integrate into their existing science curricula. They engaged in a suite of NSET lessons (see Appendix 1) that included investigations, modeling activities, demonstrations, readings, and discussions. The science lessons were designed not only for the teachers to experience as science learners but also for teachers to adapt and utilize with their secondary science students. All NSET content lessons were designed to be closely integrated with science inquiry skills and aligned with national [41, 43, 44] and state [45] academic standards. Pedagogical discussions and activities were woven throughout the NSET content lessons. Finally, in addition to participating in investigation-based instruction, participants heard from scientists and engineers about current NSET research.

During the academic year follow-up activities of the NCLT-PD program, we introduced only one new NSET lesson (intermolecular forces). Instead, the majority of follow-up activities were aimed at assisting teachers in the integration of NSET content into their existing curricula. Teachers designed at least one NSET lesson from content in the summer institute using a generative learning model format [46] and a backward design approach to planning [12]. They were required to teach at least one inquiry-based NSET lesson in their secondary science classroom and collect data on students learning from the lesson. Project staff travelled to teachers' classrooms to assist with lesson implementation and provide instructional resources that teachers requested. Additionally, as part of the academic year activities, teachers completed a lesson implementation analysis report that included evidence-based conclusions about what students learned from their NSET implementation. Finally, teachers met for a 2-day seminar in which they presented their academic year work, engaged in pedagogical discussions, learned a new NSET lesson, and attended a presentation on current NSET research.

4.3. Participants

The teacher participants comprising the sample used in this study consisted of 24 middle and high school teachers. Twelve teachers were female and 12 were male. Seven teachers (29.2%) taught science at the middle school level and 17 teachers (70.8%) taught science at the high school level. Twenty-three teachers (95.8%) had a bachelor's degree in a science field, and one teacher (4.2%) had a bachelor's degree in science education. Thirteen teachers (54.2%) had a graduate degree – eight had a graduate degree in a science field, and five had a graduate degree in an education-related field. The primary subject areas in which teachers taught were chemistry (45.8%), biology and life science (20.8%), and physics and physical science (16.7%). The remainder of the teachers taught ICP (integrated chemistry and physics) and general science courses (16.7%). Years of teaching experience ranged from 2 to 40 years with a mean of 10 years.

We recognize that these 24 teachers may not be representative of the larger population of grades 7–12 high school teachers. Although we solicited applications from the larger population, it is probable that the teachers most likely to apply are "reform-minded", and as such, are "hungry for continuing education that provides novel ways to address content" ([47], p. 27). Our primary goal was to measure teachers' change in NSET content knowledge as a result of their participation in the NCLT-PD program, rather than generalizing these findings to a broader population of science teachers. We also hope to provide "transferable" findings – that is, our results will be applicable and helpful to similar studies in similar contexts.

4.4. Data collection

The data in this study were teachers' responses to a written paper and pencil instrument created to measure teachers' knowledge of NSET content before and after participation in the NCLT-PD 2-week institute and after 8 months of academic year follow-up activities. The instrument and the corresponding scoring rubric were designed by the NCLT-PD team, who also authored the lessons. The instrument consisted of 11 questions, each with two or more subquestions for a total of 24 items. The 24 pre-, post-, and delayed-posttest items consisted of free response, matching, fill-in, and multiple choice questions, as well as questions asking for the construction of diagrams, graphs, or models, with supporting arguments of evidence or rationale. Test items addressed each of the NSET principles of our lessons: (a) defining and describing the nanoscale (material properties and behavior); (b) size and relative scale; (c) tools of the nanoscale (scanning probe microscopy); (d) size-dependent properties (optical, magnetic); (e) structure and design of materials (allotropes, fullerenes, self-assembly); and (f) models and modeling.

The assessment instrument was administered as a pretest prior to the beginning of the NCLT-PD program, as a posttest at the culmination of the summer institute, and as a delayed-posttest at the end of the academic year lesson implementation (8 months after posttest). Although carryover may typically be a risk in cases of repeated measurements, this was not a concern for several reasons. First, the content relevant to NSET is so distinctly different from the traditional sciences that we believed it would be unlikely that the teachers would retain more than a vague familiarity at best of the nature of the pretest questions. Second, we are not attempting a reliability factor of multiple measures of a static condition where familiarity with the testing instrument will bias future performance; it is our intent to produce and measure an intervention effect. Lastly, there was no "pressure" on the participants to score well in either case; no grade or privileges were correlated to their test performances.

4.4.1. Test reliability The rubric for scoring the participant responses to assessment instrument items was developed and piloted in earlier work [48]. The assessment instrument showed adequate reliability both in terms of inter-rater agreement and in terms of internal consistency. The 24 items that were related to knowledge of NSET were rated by two members of the research team. As part of the process to check inter-rater reliability, an independent rater who was not part of the NCLT-PD team (but trained in the use of the rubric) coded half of the pretests and posttests. Each item on the pre-, post-, and delayed-posttest was scored as 0, 1, or 2 points by respective level of accuracy and sophistication. The highest score possible for the assessment instrument was 48 points. A copy of both the instrument and the rubric is available at http://web.ics.purdue.edu/~dsederbe/NCLT_InstrumentRubric.pdf. Inter-rater reliability was adequate, with 90.6%, 83.3%, and 91.5% agreement across all three administrations of the test. The internal consistency of the posttest and delayed posttest was also adequate, coefficient α values=0.767 and 0.772, respectively.

4.5. Data analysis

Analysis was performed using paired t-tests. The expected outcome of this study was that teachers' knowledge of NSET content would increase as a result of their participation in the 2-week institute. Our dependent variable was teacher content knowledge of NSET. In this study, the null hypothesis states that there will be no difference between the mean value of the scores of the pre- and post-assessments, H_0: $mean_{pre}=mean_{post}=mean_{delayed\text{-}post}$.

4.6. Results

Twenty-four participants completed the pretest and posttest, and 20 participants completed the delayed posttest. Analyses are presented for the 20 participants who completed all three tests; however, results from pretest to posttest were similar whether the sample of 20 or the sample of 24 was analyzed. Fourteen participants provided the written lesson plans that they taught in their classrooms between the posttest and delayed posttest. The lesson topics and related learning goals that the teachers identified in their lesson plans allowed us to compare their performance on taught vs. non-taught topics.

As shown in Figure 1, participants showed significant gains from pretest (mean±SD: 11.15±4.48, out of 48) to posttest (32.50±6.76), $t(19)=18.4$, $p<0.001$. Eight months passed between posttest and delayed test, and participants still showed significant gains on the delayed test (27.85±9.95) compared to the pretest (11.15±4.48), $t(19)=13.4$, $p<0.001$.

Based on the topics and learning goals stated in the lessons that the teachers provided, the lesson topics taught were matched with the test items that were most likely to be covered in those lessons. On average, participants reported teaching lessons related to three of the 24 test items covered in the professional development workshop (median 3, range from 2 to 11). Importantly, the teachers chose different topics to

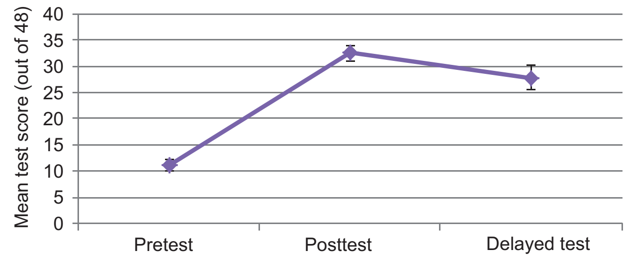

Figure 1 Mean scores for pretest, posttest, and delayed posttest (error bars represent standard error).

present to their students. Twenty-three of the 24 items were related to lessons taught by at least one teacher, and no more than 6 of the 14 teachers reported teaching lessons related to any given item.

Regarding performance on taught vs. non-taught items, all scores were converted into percentages to make performances comparable despite different numbers of items being taught by each teacher. Surprisingly, as shown in Figure 2, performance did not differ significantly on the delayed test on taught (65.5±28.5%) vs. non-taught items (52.5±17.4%), $t(13)=1.5$, p=0.166. Performance on those same items at pretest (19.4±23.1% taught vs. 20.0±10.7% non-taught), $t(13)=-0.1$, p=0.939, and posttest (75.1±21.1% taught vs. 64.0±16.9% non-taught), $t(13)=1.7$, p=0.116, also showed no significant differences. In other words, the teachers did not show a systematic bias towards teaching topics they found either particularly easy or particularly difficult during the workshop.

5. Discussion

Taken together, the findings suggest that the NCLT-PD program was successful not only in supporting teachers' development of NSET content knowledge but also in promoting durability of content knowledge. Overall, teachers demonstrated large gains in understanding important "big ideas" and concepts of NSET. However, we are cautiously optimistic about the findings as the scores themselves do not tell the whole story. Although the complete qualitative analysis is beyond the scope of this report, there were a few trends

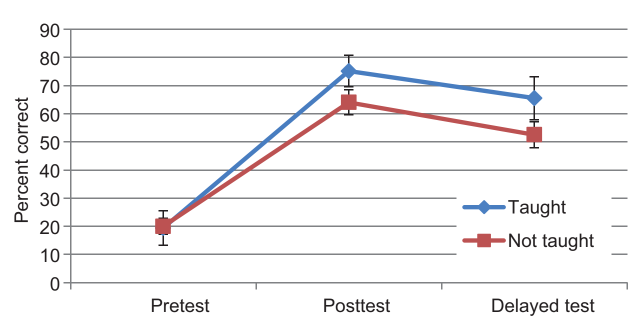

Figure 2 Comparison of taught vs. non-taught items (error bars represent standard error).

that emerged from repeatedly reading teachers' open-ended responses during the scoring process that provided deeper insight into teachers' content knowledge.

Not surprisingly, the most prevalent trends in teachers' open-ended responses involved specificity of descriptions, mechanism in explanations, and language use. For example, there were many instances in which teachers provided responses that lacked specificity in describing fundamental NSET ideas such as how science and engineering at the nanoscale is different and distinct from the micro- and macroscales, such as the responses of Teachers 2, 9, and 19:

Separate/distinct set of properties: Materials have different properties at nano level than macroscopic scale (Teacher 2).

Nanomaterials have different properties: Gold can be red and iron can be paramagnetic at nanoscale (Teacher 9).

Material properties: The properties of nanoscale materials are very different than the bulk materials properties (Teacher 19).

Based on the NSET learning goals and lessons that we taught in the summer institute, we anticipated that teachers would be able to list and explain multiple distinguishing characteristics unique to the nanoscale. On the posttest, we expected teachers to recognize, for example, that (a) at the nanoscale extreme changes in properties can be affected by small changes in size, thus enabling the "tuning" of specific properties and related phenomena; (b) bottom-up fabrication (e.g., self-assembly) has significant applications in the development of nanoscale materials and devices; (c) tools and instrumentation, used to visualize and manipulate matter at this scale are different from those used at other more familiar scales (e.g., scanning probe and atomic force microscopes); (d) extreme aspect ratios (e.g., surface area to volume) at the nanoscale offer novel properties and applications; and (e) forces which are consequentially insignificant at larger scales often become a dominant force at the nanoscale (e.g., Brownian motion and van der Waals forces). However, each of these distinctions was reported in fewer than 20% of the responses.

Related to specificity of responses was our concern about teachers' understanding of mechanism – when teachers did not indicate in their response a process or means by which an effect was produced, even when prompted by the assessment item. For example, we anticipated that on the posttest teachers would contrast the effects of an increased ratio of surface area to volume and a thermal energy effect of the surface atoms of nanoscale particles compared to larger objects. However, the teachers were more likely to identify the conditions that accounted for the observed phenomenon than to offer a mechanistic explanation. The assessment item stated:

An iron bar, iron nail, and tiny iron filings can all be magnetized and stay magnetized. Pieces of iron that are nanosize, however, are magnetized near a magnet, but cannot stay magnetized. Explain in as much detail as you can why nanoscale pieces of iron do not stay magnetized.

This question elicited relatively few responses attributing the loss of magnetism to thermal energy and alignment of domains. Among them, for example, Teacher 2 wrote: "The ambient temperature, the random kinetic motion of the particles is enough to jostle the domains of the magnetic particles, preventing them from staying aligned. Only aligned domains will remain magnetic." By contrast, the majority of responses cited the size of the magnetic particles as the reason why nanoscale ferromagnetic materials do not stay magnetized without explaining how size is responsible for the phenomenon. For example, Teacher 18 stated, "Not enough material" and Teacher 21 responded, "Too small to have domains." Teacher 17's response also lacked a mechanistic explanation and essentially restated the question: "Because of their size, their magnetic force is weak. So when taken away from a magnet, it becomes unmagnetized."

Similarly, teachers' explanation of how color is produced in quantum dots revealed teachers' general understanding that properties may be size-dependent, but few teachers demonstrated an understanding of why color is size-dependent. Sophisticated responses to the question "How is color produced in quantum dots?" included a discussion of the relationship between energy, color, and the emission of light, as in Teacher 15's response: "Through electrons moving between the conductive zone and the valence shell in what are called band gaps. This movement is expressed in the form of light and is based on particle size." However, many responses simply indicated that "size" was the reason that quantum dots produced different colors, similar to Teacher 5's statement: "The size of the dot determines the light that is emitted/fluoresced."

Finally, language use in descriptions and explanations emerged as an issue related to teachers' content knowledge. Teachers tended to use the words such as element, atom, molecule, material, substance, and particle interchangeably without regard to specific context. For example, when describing allotropes, approximately 33% of teachers interchangeably used the term molecule and element, as did Teachers 11 and 14:

Different arrangements of pure carbon molecules (Teacher 11).

Allotropes are substances composed of different arrangements of the same element which display unique properties (Teacher 14).

It is probable that some teachers were unclear about the distinction between molecule, atom, and element. Using words interchangeably, such as atom, molecule, and element blur the distinctions among the scales of atoms (atomic scale), molecules (which can be included in the nanoscale), and elements (the bulk scale). The use of appropriate scientific language is an important part of communicating ideas and concepts of science; this is especially true for teachers whose students will rely on their use of terminology to build their own understandings.

6. Implications

Indeed, teachers demonstrated significant growth in their understanding of NSET concepts as a result of participating in the program. Our discussion is not intended to minimize this point. Furthermore, we bear in mind that some of the concepts teachers were learning in the program were among the most abstract ideas of instruction (e.g., quantum effects) and concepts with which teachers' have little if any prior knowledge and experience teaching.

The issues raised above provide reason to reflect upon the process of teacher learning and our expectations as instructors when designing and administering assessments of content knowledge. As with any written assessment, the lack of specificity in descriptions, mechanism in explanations, and accepted language use in responses may be a consequence of the way in which we worded the assessment items. There also is the possibility that respondents experienced test fatigue, especially when being asked to construct multiple detailed drawings and explanations throughout the test, or they simply did not wish to take the time to craft answers that revealed the depth of their knowledge. These types of technical issues highlight the fact that assessments of content knowledge are far from simple to create and require an iterative development process.

However, the test response trends discussed in this section may also suggest that teachers, like any other learner, need time and varied learning opportunities to develop robust, coherent understandings of new scientific concepts and phenomena [26, 29]. We view learning as a generative and revisionary process in the sense that learners have existing understandings, beliefs, and experiences that influence how they interpret new experiences and information. In addition, they must expend the mental effort to build understanding of new concepts, ideas, and experiences for themselves. This building and revising process of knowledge development takes time, effort, motivation, and repeated learning opportunities [46, 49, 50], which is why sustained contact activities are so important to NSET professional development programs.

The pretest provided a reasonable indication that the teachers attending the NTCL-PD program entered the program with little exposure to NSET concepts. However, this does not mean that the teachers came to the NSET learning experience without scientific knowledge that would influence their learning. Teachers indeed will enter NSET professional development programs with varying degrees of content knowledge from science disciplines. However, that knowledge may be fairly discipline-specific and lacking the cross-disciplinary, cross-scale perspectives that are important for understanding NSET. Moreover, it is probable that if teachers' knowledge of how physical objects move and interact is framed by Newtonian physics, then understanding the concepts and physical laws that govern the behavior of matter and interactions at the nanoscale may be a challenge. Hence, it is incumbent upon NSET educators to design learning experiences with a strong content focus that is unified and coherent. Ultimately, teachers must be able themselves to develop coherent, detailed descriptions and explanations of science concepts and phenomena if they are to design and enact meaningful instruction that leads their students to develop coherent, detailed descriptions and explanations of science concepts and phenomena.

Finally, we note that while we were planning the NCLT-PD program and creating its instructional materials, we searched for existing NSET content tests and concept inventory items to use as resources to develop an assessment relevant to our program. Not surprisingly, few resources existed and those that did consisted of brief multiple choice items that would provide little insight into what teachers understood about NSET concepts. The development of systematic, reliable, and valid assessments to measure the impact of NSET programs and to allow comparable measures across programs has not kept pace with the development of the programs themselves. Undeniably, the development of such assessments necessitates a great deal of time and resources. It will require the collaboration of scientists, science educators, assessment specialists, and teachers to systematically develop and validate assessments or banks of questions in various formats that researchers and educators can use to measure content knowledge. Valid and reliable NSET assessments will provide a vital resource that will enable significant advances in grades 7–12 teacher and student learning of NSET concepts.

7. Conclusions

Science, engineering, and technology at the nanoscale level have significant implications for the future of precollege science education. As scientists and science educators seek ways of helping teachers integrate NSET into existing science curricula, it becomes clear that we must design learning experiences to enhance teachers' content knowledge for teaching NSET concepts that reflect the most basic principles of effective professional development. Realizing the need for effective teacher professional development, we also must not overlook the necessity to examine and measure teachers' knowledge as they learn about NSET. There are a growing number of NSET professional development programs, workshops, and activities. Yet, very few have reported what teachers' are learning in these experiences, despite conventional wisdom that teachers must have a strong command of content knowledge to be able to facilitate students' learning. If we can ensure that teachers are prepared to address the linchpin ideas in NSET, then students will also have the potential to develop deep, transferable understandings. Ignoring teachers' development of content knowledge belies its importance to science teaching and learning to teach science.

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Appendix

Appendix 1 Suite of NCLT-PD lessons for grades 7–12 vs. big ideas in nanoscience.

	Size, scale, and geometry	Size-dependent properties	Forces and interactions	Self-assembly	Tools and instrument	Nano and society	Models and simulations
How small is nano?							
What's the smallest thing I can "see"? Relative size							
It's all in the way you're put together: allotropes of carbon							
Energy, force, and magnetism: thresholds at the nanoscale							
That's a dot of a different color: quantum dots							
How can lead and anthrax be detected? Biosensors							
Why do some things stick while others fall? IM forces							
How can I design something to build itself? Self-assembly							
How do you know it's there if you can't even see it? SPM							
Where's the nano? Nano in every-day life							
Models and modeling							

Darkly shaded cells denote that the corresponding big idea was a primary learning goal for the lesson. Faintly shaded cells denote that the corresponding big idea was a secondary learning goal for the lesson.

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Lynn A. Bryan is a professor and current head of science education at Purdue University. She holds a joint appointment in the Department of Curriculum and Instruction and the Department of Physics. Her research focuses on teachers' development of knowledge and skills for teaching in instructionally innovative settings involving novel curriculum reform and technology-enhanced environments. From 2006 to 2010, Professor Bryan served as co-director of professional development programs for the National Center for Teaching and Learning Nanoscale Science and Engineering (NCLT).

David Sederberg is a doctoral candidate in the Department of Curriculum and Instruction and the Director of Outreach in the Department of Physics at Purdue University. From 2006 to 2010, he served as a curriculum developer and co-instructor for the NCLT professional development programs. His research interests include instructional design and teacher professional development in nanoscale science education and children's mental models of magnetism across scale.

Shanna R. Daly is an assistant research scientist at the University of Michigan in engineering education. She earned her doctorate from Purdue University's Engineering Education program in 2008. From 2006 to 2010, she served as a curriculum developer and co-instructor for the NCLT professional development programs. Her research focuses on factors that support innovation, design ideation, and creative processes within engineering, outside of engineering, and cross-disciplinarily.

David A. Sears is an assistant professor in the Department of Educational Studies at Purdue University. He holds a BA. in Psychology from Reed College and a PhD. in Educational Psychology from Stanford University. His research examines instructional practices for promoting learning and transfer in individual and group contexts with a focus on the STEM disciplines.

Nicholas R. Giordano is the Hubert James Distinguished Professor of Physics at Purdue University with research interests in nanoscience, musical acoustics, and neuroscience. He has written textbooks *Computational Physics* (with Hisao Nakanishi) and *Introductory College Physics*. From 2006 to 2010, Professor Giordano served as co-director of professional development programs for the National Center for Teaching and Learning Nanoscale Science and Engineering.