AC 2011-2046: MAKING SENSE OF NANOSCALE PHENOMENA: A PROPOSED MODEL OF KNOWLEDGE AND THINKING

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Making Sense of Nanoscale Phenomena:
A Proposed Model of Knowledge and Thinking

Abstract

New curricula are needed to meet the challenge of producing the trained scientists, engineers and technicians that will be needed to fuel the nanoscience revolution. Instructors of nanoscience and engineering will need to combine both content knowledge and effective pedagogical methods to create effective curricula. The objectives of this study are to begin to identify the (1) content knowledge and (2) pedagogical content knowledge (PCK) of experienced researchers and instructors in nanoscale science and engineering. It is hoped that these results can be used to inform curriculum design in nanoscience and technology. Our participants were seven senior researchers at a large Midwestern university. We employed qualitative research methods to identify the concepts, ideas, and ways of thinking for understanding nanoscale phenomena and to identify how nanoscale scientists and engineers convey nanoscale related concepts and ideas to their students and apprentices. Respondents spoke about the need for learners to "go deep" in their understanding of the phenomena involved in their respective content area. Depending on the focus of the research, very deep conceptual understanding of biology, chemistry, and/or physics is required in addition to knowledge of their respective engineering field. Knowledge of quantum mechanics is also vital. Interdisciplinary collaboration is essential since research in nanoscience requires extensive knowledge in several domains. Respondents also mentioned the importance of computational and complexity thinking. These findings have implications that relate to a) the advancement of effective nanotechnology education in higher education and b) the use of PCK as a theoretical framework to investigate aspects of teaching in engineering education.

Introduction

The ability to explore the physical world at the nanoscale has opened up a wealth of research opportunities. New marvels of design seem to appear each day and the potential of nanoscale devices to improve human life is staggering. In the last twenty years nanotechnology has revolutionized technological devices and has impacted medicine, biotechnology, electronics, and has contributed to the creation of innovative tools and materials. The promise of nanotechnology is enormous, but producing enough trained scientists, engineers and technicians to fuel the transition from macro- to nano-engineering will be a great challenge [1].

One of the initial steps for the development of new curricula is a clear notion of the key concepts or habits of mind that will remain with a learner long after the actual learning experience has ended. Wiggins and McTighe have coined the term "enduring understandings" for these essential, long-term outcomes [2]. However, enduring understandings should not be the only focus of effective curricula; effective pedagogical methods and learning strategies that help learners make sense of such concepts must also be incorporated. These pedagogical methods and learning strategies that are specific to a domain is known as pedagogical content knowledge (PCK). Therefore, the development of quality curriculum in nano-education should begin by uncovering practitioners' pedagogical content knowledge (PCK)[3] of nanoscale science and engineering. This goal is the long-term objective of the authors' research agenda. As an avenue to uncovering enduring understandings and corresponding pedagogical methods, we start by identifying instructors' understanding of nanoscale concepts and investigate the methods they use to help themselves and their students understand these concepts. Our rationale is that in order to fully understand nanoscale phenomena we need to identify the knowledge and ways of thinking for making sense of such phenomena. Therefore, we used pedagogical content knowledge (PCK) as an analytical framework to investigate how experts' transform content knowledge into a more conceptually understandable version for students. This research study explores the following research questions:

1. **What are the concepts, ideas, and ways of thinking for understanding nanoscale phenomena?**
    - **This research question explores the "enduring understandings" needed to learn about nanoscale phenomena.**

2. **How do nanoscale scientists and engineers make sense of and convey nanoscale related concepts and ideas to their apprentices?**
    - **This research question investigates the pedagogical content knowledge (PCK) that helps instructors convey the enduring understandings to their students.**

Literature Review

What is already known about how people come to understand nanotechnology? As one would expect from such a new field, the literature in this area is limited. The expansion in nanotechnology research has not been coupled with an expansion in knowledge about the conceptual requirements needed to understand the nanoscale world. Not only are nanoscale researchers confronted with the logistical difficulties of creating products at a very small scale, they also must grapple with a conceptual hurdle: the world at nanoscale is very different from the macroscopic world of our everyday experience. At the nanoscale physical properties may be size-dependent, quantum effects may be seen, and there is constant motion. For students to grasp nanotechnology principles, they must be able to understand concepts that are abstract, difficult to visualize and describe, and often counter-intuitive [4, 5]. Furthermore, the students must also understand complex systems which, even at the macroscale, are challenging for people to understand [6].

In 2006, Hsi and colleagues stated that there was minimal research available on how people learn about nanotechnology and the core concepts of this field had yet to be identified [7]. At the time Hsi's article was published, researchers could look to the limited literature about how people learn about complexity as a way to extrapolate about learning in nanotechnology. Learning about complexity was seen as relevant because nanotechnological systems are dynamic and highly interconnected. But even here researchers were just beginning to explore the learning issues associated with complex systems [8, 9]. Hmelo-Silver & Azevedo [10] argued that learning about complex systems requires metacognitive and reasoning skills as well as motivation. Jacobson and Wilensky [9] proposed that the concept of emergence, where patterns emerge from the interaction of parts of a system, is central to understanding complex systems, and several studies have found that emergence is a difficult concept for students to understand [6, 11, 12].

Our research team recently searched major databases and conference proceedings using *nanotechnology* or *nanoscience* and *education* as keywords. This search returned 120 articles and conference papers about nanoscale science and engineering education. The themes of the 120 articles ranged from papers: a) describing the content and development of specific curricular materials, b) position papers describing the importance of well-trained future scientists and technicians in nanotechnology, c) assessment papers focused on evaluating the impact of specific curricular materials and d) research papers focused on how students learn specific concepts related to nanoscale science and engineering. However, more than 100 of the 120 papers,did not discuss *how* nanoscale concepts are learned. Exceptions are the work of research groups at Northwestern [13, 14-16], North Carolina at Chapel Hill , University of Louisville [17, 18, 19], and Michigan State University [20, 21]. These groups have published a set of conference papers, journal publications, and books that highlight the fundamental topics related to nanoscale science and engineering. For example, Stevens, Sutherland and Krajcik [21], identified the *Big Ideas of Nanoscience* at the 7-12 levels. However, these "Big Ideas" may not be applicable to post-secondary nano-education.

A few research studies have recently commenced to identify the core concepts of nanotechnology in the undergraduate curriculum. For instance, Wansom et al.,[16] informed by academic course/degree program analyses and university research faculty, constructed a rubric for post-secondary degree programs in nanoscience and nanotechnology. This rubric focused on identifying "what students need to know to be successful in those fields" (p.616). Similarly, Uddin and Chowdhury [22] described an interdisciplinary curriculum integrating basic sciences, engineering sciences, information sciences and their application to nanotechnology. A different approach was taken by Sweeney and Seal [23], who compiled a set of articles ranging from: a) research studies to the description of curricular materials and classroom implementations of curricular materials and b) grade levels k-12 to undergraduate education and general public education and awareness. Although these efforts have been crucial to the advancement of nanotechnology undergraduate education, very few of them have integrated the identification of concepts, skills, ways of thinking and the appropriate pedagogical methods following a rigorous research process. An example of an effective research and implementation process is the one followed by Light and his colleages[13, 14] who first identified how students learn nanoscale science and engineering concepts (i.e. size and scale, self-assembly) and then implemented curricular materials employing effective pedagogical methods (see [15]) based on their findings.

Our study complements existing research by not only identifying important nanoscale science and engineering concepts, but also by investigating potential pedagogical methods and learning strategies that may help learners grasp these concepts.

Methodological Framework

Our methodological framework is informed by a construct Shulman called *Pedagogical Content Knowledge* (or PCK). PCK is knowledge instructors have about how to help their students learn domain-specific material. PCK provides us with an analytical frame for organizing and collecting data on experts' cognition [24]. It also allowed us to identify specific expert's knowledge that could allow an engineering instructor to transform content knowledge into a more conceptually understandable version for students by blending content knowledge with pedagogical methods [3].

Research has identified that the acquisition of PCK is essential for instructors to provide proper instruction and help improve students' conceptual learning [25]. In this study PCK was used as a way to conceptualize experts' content knowledge and the learning strategies (e.g. analogies, mental models and representations, etc.) they have employed to make sense of such understandings. By identifying experts' PCK, we were able to identify appropriate pedagogical methods for conveying such concepts.

Because PCK was originally conceived as a framework to be used in science education, we have made some adaptations to study expert knowledge. Table 1 describes Miller's [26] assumptions of PCK and the adaptations done for this study.

Table 1. Adaptation of PCK to research expert knowledge.

Teacher knowledge (Miller, 2007)	*Expert knowledge (adapted by our research team for this study)*
Teachers become experts in a specific subject area through construction of specific knowledge that informs them of superior teaching methods for that subject.	Experts in nanoscale science and engineering construct specific knowledge that informs them of learning strategies for making sense of that subject.
Instruments can be devised to identify and measure PCK	Instruments can be devised to identify and measure PCK
PCK can be shared with other science educators for use in their classrooms	PCK can be shared with other science and engineering educators for use in their classrooms.
Articulations by teachers about beliefs and knowledge mirror teacher practice in the classroom.	Articulations by experts about beliefs and knowledge mirror their research practice and training of their apprentices.

Therefore, PCK provided us with a starting point for collecting and analyzing concepts and learning strategies that not only can inform a new curriculum in nanoscale science and engineering, but also lays a pathway to find improved pedagogical methods for teaching such concepts.

Methods

Baxter and Lederman [27] identified multiple data collection techniques (e.g. interviews and observation techniques, convergent and inferential techniques, visualization techniques and multi-method evaluation) as effective for identifying PCK constructs and classroom applications. Following the adaptation of PCK depicted in Table 1, we selected interviews as the data collection method. We interviewed researchers at a large nanoscale engineering research center in the Midwest to uncover their ideas about the prerequisite knowledge needed to understand nanoscale engineering concepts.

Participants. Seven researchers volunteered to participate in this study. All participants held the rank of full professor at the time of the interview. Participants' research backgrounds ranged from theoretical to experimental, in areas of applications ranging from science and engineering. Researchers' current research agendas focused on the study or development of a) self- assembly of functional nanomaterials, b) novel nanocomposite materials for applications in solid-state lighting, direct conversion of heat to electrical power, and thermoelectric refrigeration, c) the physics and technology of nanoelectronic devices through theory, modeling, and simulation, d) the abilities of electron and ion microscopes to document nucleation and growth processes in nanoscale systems in real time and at high spatial resolutions e) modified nucleic acids for use as biochemical tools, diagnostic probes, and therapeutics and f) multiplex mechanistic sensing and quantification of molecular markers, genetic material, DNA modifications, and drug localization in biological systems.

Data collection method. Semi-structured interviews were used to probe participants' ideas about what knowledge is needed to truly "understand" nanoscale engineering concepts and to identify pedagogical methods and learning strategies employed to make sense of such concepts. Interviews are the most common and dominant method of discovery. Interviewing permits an in-depth exploration of a particular topic or experience and, thus, is a useful method for interpretive inquiry [28]. Sample interview questions are:

To investigate necessary content knowledge:

- What do you consider are the key concepts in your discipline that are related to nanotechnology?
- Are any of these concepts new in your field? How are these concepts different from other concepts?
- Why do you think these concepts are important?
- Why are these concepts important to you?

To investigate PCK:

- How did you learn about these concepts?
- How did you make sense of them?
- What models of thinking/mental models have you used to help yourself understand them (concepts)?
- How do you help your students learn it?
- How do you know they are getting it?

- Why do you think these concepts are difficult for students? What is making these concepts difficult and how do you help your students to overcome such difficulties?

These interviews were recorded, transcribed and coded.

Data analysis method. Grounded theory was used to analyze the data. Grounded theory is a theoretical framework in which themes and findings emerge directly from the data [28]. Strauss and Corbin [29] describe it as a systematic approach of data collection and analysis where theory is inductively derived from the study of the phenomenon it represents. The process of inductive analysis consists of a process of identification of differences and similarities in the data, resulting in a set of categories or themes and their properties and interrelations [30]. In particular, we sought to determine commonalities existing among specific concepts and ideas related to nanoscale phenomena and strategies these experts employed for making sense of such phenomena. Human subjects' procedures were followed to protect participants' privacy and confidentiality.

Results

Several themes emerged from the data. Some of these themes went beyond topics discussed in the "Big Ideas" of nanotechnology paper (see [21]) and other concepts related to engineering education (see [31]). Respondents spoke about the need for learners to "go deep" in their understanding of the phenomena involved in their respective content area. Depending on the focus of the nanotechnology research, very deep conceptual understanding of biology, chemistry, and/or physics is required as well as knowledge of the researcher's respective engineering field. Knowledge of quantum mechanics is also vital. Because no one researcher will have all the necessary knowledge in all the required domains, interdisciplinarity is a must. Respondents also mentioned the importance of computational and complexity thinking.

Research Question 1: What are the concepts, ideas, and ways of thinking for understanding nanoscale phenomena?

There was consensus among researchers that a strong background in Physics and Chemistry are the required prior knowledge for understanding nanoscale phenomena. In the following excerpts scientists describe how having fundamental knowledge of physics, chemistry, math and, if required, biology is a must.

Smith:

> … the real challenge … to work in this area [is] to have [a] really strong underpinning in chemistry and physics and even biology if that's the application area. It's real hard to do anything without that [strong foundation].

Other important subject matter areas described by researchers were solid-state physics (Kingston and Summers) and quantum mechanics (Woodson, Summers, Kingston and Smith).

Kingston:

> …[well if] they've taken all the quantum mechanics courses, they've learned about solid state physics, at the very end of their Ph.D. program they might have now a course on what in physics you might call quantum statistical non-equilibrium quantum mechanics, which is like putting statistical mechanics, quantum mechanics, openness and non-equilibrium all into once package, and then you say, "Well, that's what you need to know for nano."

Summers:

> …the primary tools … for nanoscience [are] a good strong math background; you need to have a good fundamental physics background; and in particular the field of solid-state is a key one, and quantum mechanics is a key one. Because for electrical, optical, magnetic and thermal properties, those are all quantum mechanical and solid-state ideas, that are being manipulated.

Woodson:

> … any student who wants to think about a career in nanoscience and technology …ought to start with quantum mechanics first … because quantum mechanics is fundamental to what nanoparticles do. … You want to start with the basics and quantum mechanics is the basis.

Although many of the concepts related to nanotechnology are the same basic concepts that have been introduced in the curriculum in the past (i.e. physics, chemistry, etc.), researchers have identified that the particular quality for understanding nanotechnology is to understand how those concepts and principles interact as a system. Here Bailey described his view about how the concept of complex systems has been integrated in the curriculum:

Bailey:

> … coming back to this idea of concepts, nanotechnology, at least … at the undergraduate level, doesn't really involve new fundamental concepts; the same fundamental concepts apply. It's just now how to think about a system. … So I think that sort of the courses that people could benefit from… are things like systems biology [and] systems engineering.

Because nanotechnology involves the understanding of complex phenomena, it has become a need to have expertise in multiple fields. This expertise can be accomplished through seeking collaborations that can provide the expertise that a researcher or research group may require. Bailey made this point explicit during the interview.

Bailey:

> So it's basically a field that's evolved in such a way that it absolutely requires that you bring together people with top-down experience and wed them in some way to the people who have the bottom-up experience.

Bailey also pointed out that in order to be able to participate in nanotechnology research, a person needs to "think outside the box" and be open to work on other disciplines:

Bailey:

> Chemists become the organic chemists…they're always focused on small molecules. And it's forced them to think outside the box, if they want to participate in nanotechnology, because now they have to think not only in terms of their particular research activity, but other people's research activities.

Ingham, posed an example demonstrating how, when his research group does not possess the expertise, the only possible way to accomplish their research goal is by seeking the expertise outside his group.

Ingham:

> …[In research, there] are …different components that you should be thinking about. …In some cases, [the] expertise [we need] is already here [in our group]….[But] in some cases, we need… [other expertise, so we need to] collaborate with somebody else.

Doing research in nanotechnology requires having a strong background in a particular discipline and the ability to transfer that knowledge to some other discipline to an extent.

Ingham:

> … if the student is working in a certain field, then they will have to know that particular field very well…They first need to understand the concepts involved in their own discipline first. And then, [after] you learn this knowledge in your field,…you work in …a similar field where you directly apply [the knowledge from your primary discipline].

Smith provided the example of Charlie Lever, a scientist who has been able to apply what he has learned in Chemistry to advance research in the semiconductor area.

Smith:

> I went to a lecture last night [by] Charlie Lever, [a] famous nanoscientist. He …gets credit for …getting the excitement going with nanowire structures, especially semiconductors. And it was … fun listening to him, because … he started off more as a chemist or

> materials person and has gradually [over a couple of decades] become more of a semiconductor device person. And it's …interesting to see that…he now thinks differently about what he's doing than he did say 15 years ago, because he's picked up some new perspectives… from the semiconductor side. He can still use everything he learned about chemistry and nanomaterial synthesis, but now he has to worry about what happens at the surface [differently, because what happens at the surface] has a huge effect on the behavior of a semiconductor.

This broad understanding of a secondary discipline is required to make the collaboration experience more productive.

Ingham:

> … the knowledge in chemistry would be very useful, and then … if you want to solve a biological problem, …you need to know something about the problem. You don't have to be an expert, but you have to know something [about biology], because…if you collaborate with somebody in the field of biology, [it] becomes a more productive experience.

Sometimes that understanding of a secondary discipline should be accomplished while the research is going on. This means that the collaboration becomes a learning process itself.

Bailey:

> [Members of the research team now] need to …understand and learn more. Not that they'll necessarily do more experiments, but they'll interact with other people. So they need to understand how their research [is] contributing to the overall project. …They may have to take some time to learn what the other person is doing, so they can figure out how to integrate their part of the project [into the research].

Bailey: I don't see anything really different about the concepts [in nanoscience and technology]. I think [they are] still the same fundamental concepts. …[But] because of these collaborations involving multiple people, that we can make certain molecules and … devices.

Models and simulation are also an important part for understanding complex systems and in particular phenomena at the nanoscale. Here, Kingston described the importance of computation not just for nanotechnology, but for any field. And Smith described how, by means of computation, he could really understand the shape of a material:

Kingston:

> Model building … is critical when we can't … build these things, but we have to model them first and understand them in the conceptual

> sense, and …have [those models] hopefully be close to reality. But that's not fundamentally different from any other field. You can argue that in any of these decoupled fields that if you want to build something you end up… better off if you can "build" it on a computer first….[To build anything, even your garden shed, you want to model it first.]

Smith:

> It's related to the presence of the boundary conditions and the shape [of a particular material…They don't grow in perfect squares; they grow in these very faceted structures. And there's a [researcher] whose whole work is to do multi atom simulations that capture the true shape, and look at how those give you real answers.

Research Question 2: How do nanoscale scientists and engineers make sense and convey nanoscale related concepts and ideas to their apprentices?

The researchers we interviewed also spoke about how they helped their students understand the nanoscale phenomena. They are able to blend their content knowledge with their instructional expertise to make their Pedagogical Content Knowledge (PCK) explicit.

Two researchers (Smith, Kingston) spoke of ways they try to make their thinking transparent to their students.

Smith:

> I think all you can kind of do is model [your thinking]. …When we're talking about an experiment … I try to verbalize what I'm thinking or how I'm thinking about it.

Kingston:

> I personally prefer sort of pictorial diagrams that indicate how something [behaving.] … I mean, you can sort of pictorial-ize it, and those are the concepts I have in the back of my head.

Another pedagogical strategy is connecting concepts to things students already know.

Kingston:

> I think one can develop educational material that embrace these concepts in a more open-minded way, … intuitive way. [For example,] I can draw analogies to a classical guitar. …There is an acoustic wave that's sitting in your guitar body, so to speak, and it's exciting the… acoustic waves in it. And there is actually another resonator that's close to it. Those are the strings. [And] the strings actually excite the resonator body, and the sound decays. It doesn't ping there forever.

Summers:

> I …show pictures…and movies from when my students have grown those [structures], and use that as a way to say, "See, these structures are real." And then use that as a way to describe why you would want to understand mathematically how small size scales affect electrons. And say, "And now people are using these in advanced transistor ideas, where you can give discrete choices to the electrons, and then use that to improve the properties." So I try to incorporate that into teaching as a modern example, and a modern example that strongly motivates the fundamental [concepts].

Woodson and Summers mentioned using quantum dots to explain important concepts.

Woodson:

> Well, … one of the things you can do with quantum dots, is you can make them fluoresce. …By carefully tailoring the size of quantum dots in some materials you can make them emit different colors of lights by shining light on them.

Summers:

> But by being able to now say, "Oh, and we're making these things, with small size scales, to interrogate this." I can use those as examples. We can discuss what we call quantum dots. … They're called that because they're so small that if you look at the electrons in that cluster, they're again aware of the boundary conditions; they give you different energy levels. And thus you can do different things with the electrons. You can make different transition action out of them." …I have a whole lecture where I … describe the growth of quantum dots.

Two interviewees (Woodson and Kingston) mentioned a celebrated colleague, who we call Professor Davis, who uses a "bottom up" rather than a "top down" approach to teaching about the nanoscale.

Woodson:

> [Professor Davis] … starts with an atom and [then] adds a few [more, and] builds more and more up and watches what happens to the properties. So at some point in … that way of teaching he gets to the nanoscale. So … he can teach students what goes on to the nanoscale. ...You start from single atoms and build things up from that. … I think that's how you should teach students in the future because if nanotechnology is going to go anywhere you'll need to understand how [it] works from bottom up.

Kingston:

> But then there is another way of looking at this…For example Professor Davis is … teaching these concepts from the bottom up. Quantum mechanics is an element of the teaching at the nanometer scale, but it's not the sole purpose. So he starts with relatively simple systems that have all of these categories of being open, being discrete in quantum mechanical things and being out of equilibrium, and he connects them to real devices even in an undergraduate course.

Discussion and Implications

The findings of this study have implications that relate to a) the advancement of effective nanotechnology education in higher education and b) the use of PCK as a theoretical framework to investigate aspects of teaching (and potentially teacher training) in engineering education.

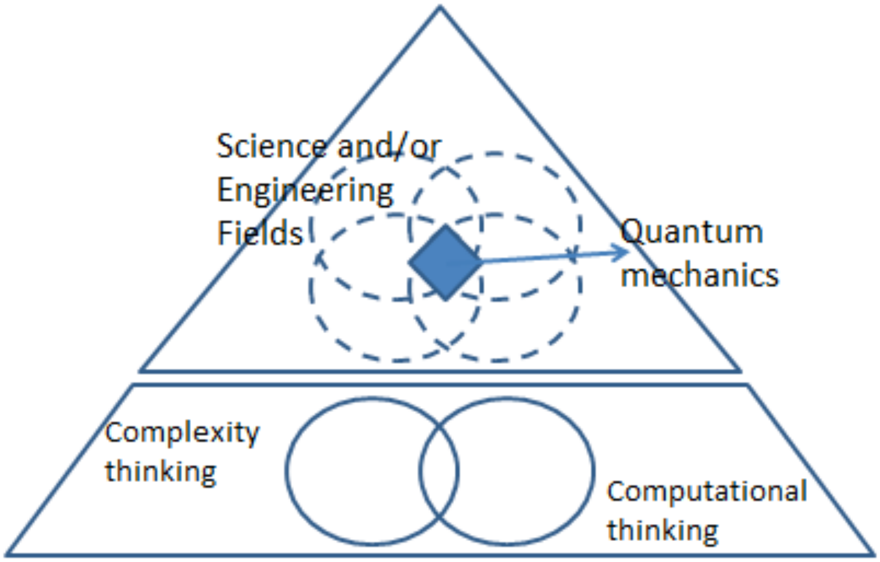

Figure 1. Proposed model of the knowledge and thinking needed to conduct nanoscale engineering research

With a goal of using these findings to advance postsecondary nanotechnology education, we propose a model (see Figure 1) of the knowledge (i.e. concepts and ideas) and thinking (i.e. learning strategies) required to make sense of nanoscale phenomena. The top level of the pyramid represents the kinds of knowledge that are needed. The circles represent deep conceptual understanding of basic science and engineering concepts. Identifying these concepts will inform curriculum development. Four circles are presented as a way to illustrate that there are multiple domains. Understanding quantum mechanics is central and thus is at the center of the diagram. The boundaries of the system are represented as dotted lines because this kind of work requires researchers to bridge domains. Identifying these concepts (the top of the pyramid) will inform curriculum development.

The bottom of the pyramid describes learning strategies and kinds of thinking necessary, e.g. computational thinking and the ability to handle complex systems. The bottom part of the pyramid may inform pedagogical approaches.

Implications of the use of PCK as a theoretical framework to conduct research in engineering education relate to a) the need for better integration between content and pedagogy that is informed by and reflects what practitioners do, b) the difficulty of eliciting practitioners to reflect on and talk about their pedagogical methods, and c) the use of PCK as an instructor tool to more effectively integrate pedagogical methods into their teaching. The adoption of a holistic integration between content and pedagogy has become an essential kind of knowledge needed for a novice teacher to mature into an expert [26]. Therefore, the teacher education community continues to call for studies that devise methods for measuring PCK[26]. Because PCK is a complex form of teacher knowledge, PCK has been difficult to isolate and study, and this particular study was not an exception. For example, participants of this study focused the majority of their responses on the knowledge acquisition or prerequisite knowledge piece of the learning. That is, much of the data collected in response to the first research question represents traditional ways of thinking regarding curricula and student learning. It was very difficult for the interviewer to be able to elicit strategies employed by instructors to model cognitive processes, communicate understandings through visual representations, explore concepts through larger scale analogs, etc. Therefore, we identified potential limitations of the domain experts' responses to identify and uncover their pedagogical knowledge. We concluded that a more effective data collection method to better identify and isolate PCK would be through classroom observation, document analyses of researchers' textbooks and lecture notes and the use of visualization techniques.

Finally, we explored the use of PCK as an instructor tool to promote and facilitate more intentional integration of effective pedagogical methods into their teaching. We propose the use of PCK as a framework to analyze the degree and type of reflection college instructors devote to teaching (see [32]). Instructor reflection is important because this practice can help them "calibrate" their knowledge and the pedagogical methods they employ to convey that knowledge. In his book, *The Reflective Practitioner: How Professionals Think in Action,* Schön [33] argued that practitioners' reflection can serve as a corrective to over-learning. That is, through reflection, instructors can "surface and criticize the tacit understandings that have grown up around the repetitive experiences of a specialized practice, and can make new sense of the situations of uncertainty or uniqueness which he may allow himself to practice"(p. 61). For example, one of the participants in our study commented at the end of the interview that having been interviewed helped him clarify his ideas about how to approach writing his own textbook.

Conclusion

In this paper, we have identified the need for research studies that integrate content knowledge and pedagogical knowledge in engineering education. We have conducted a preliminary study aiming to identify higher education instructors and researchers' pedagogical content knowledge in nanoscale science and engineering. Integrating content knowledge and pedagogical knowledge can shed light onto ways in which nanoscale science and engineering can effectively be integrated into undergraduate engineering curricula. Although investigating PCK is an important kind of teacher knowledge, it still poses some limitations as a research approach due to its complexity. We therefore suggest the utilization of multiple data collections coupling interviews with classroom observation, document analyses of researchers' textbooks and lecture notes and the use of visualization techniques to be able to triangulate multiple sources of data collection.

By employing PCK we have also proposed a model to stimulate continued discussion of what it takes to make sense of nanoscale phenomena. This discussion could lead to uncovering what Wiggins and McTighe [2] called the "enduring understanding" of a content area together with potential effective pedagogical approaches. This model could ultimately lead to integrating the enduring understandings needed to make sense of nanoscale phenomena with effective pedagogical methods. We hope that this model might become a framework for the design of nanoscale science and engineering curricula.

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