Content transformation for experimental teaching nanoscale science and engineering to primary teachers

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Abstract. This study is a response to the need to examine the educational perspective of the Nanoscale Science and Engineering field (NSE) in all grades of education. Specifically, we address to educate primary teachers about essential concepts, applications and phenomena of the NSE discipline. In order to do so, we first seek to establish, the salient concepts, principles and phenomena that should be introduced to primary teachers, as a result of the transformation of the content, to content appropriate for the target population. In addition, to address the challenges of making the formatted content structure accessible to primary teachers, a variety of experimental activities were designed, which we present in detail.

1. Introduction
Nanoscale Science and Engineering (NSE) is a modern field of research. It deals with the ability to manipulate matter at the nanoscale level, and exploit the unique properties and phenomena that occur at this scale in order new, revolutionary applications to emerge. An unprecedented rate of advancements is taking place ranging from biomedical applications, electronics and advanced materials (Jones et al. 2013).

The explosion of the NSE achievements requires a commensurate response by the education community. Trying to confront with this challenge, initiations regarding NSE education have been made across the world in all grades of education (Feather & Aznar 2011).

However, the inclusion of NSE to education seems to be a challenging task. Several issues emerge, such as the determination of the content to be taught, teacher training and the design of the experimental activities that would make the NSE content accessible to learners (Hingant & Albe 2010, Jones et al. 2013).

2. Theoretical background
Features of NSE discipline
There is no denying that NSE is an interdisciplinary field that focuses on the study and the manipulation of matter at the nanoscale, a realm below 100 nanometers approximately (Hingant & Albe 2010, Logothetidis 2012). The development of advanced techniques and sophisticated instrumentation, such as Electron Microscopy and Atomic Force Microscopes (AFM), has paved the way for the emergence of the NSE field, as they provided scientists and engineers with new capabilities for the imaging, manipulation and characterization of nanoscale materials (Murty et al. 2013, Jones et al. 2013). A large
number of applications has emerged ranging from electronics, advanced materials, medicine and so on (Hingant & Albe 2010).

The true foundation of NSE lies on the alteration of materials’ properties at this dimension (Murty et al. 2013). Indeed, most definitions articulating about NSE emphasize the remarkable properties that matter exhibit at the nanoscale (Ramsden & Freeman 2009, Hingant & Albe 2010). When the size of a bulk material is gradually reduced, its properties remain the same at first. Then some small alterations may occur, until, the material’s size reaches the nanoscale regime, where dramatic changes in properties can happen. For example, a macroscale chunk of gold is a familiar yellow metal. When this piece of metal is broken into smaller centimeter – long pieces, it will still appear yellow. However, if the pieces are broken down about million times, the tiny gold nanoparticles will vary in color, ranging from blue (50 nm in size) to orange (1 nm in size), depending on their dimension (Murty et al. 2013).

Why NSE in education?

Several types of argumentation justify the inclusion of NSE in education. The first one involves the shortage of appropriated skilled workforce in nano-related sectors. It has been estimated, that there will be a worldwide demand for 6 million workers in NSE fields by 2020 (Feather & Aznar 2011). Considering that elementary school students may constitute the future workforce of NSE, an as soon as possible interaction with this emerging field should be a primary focus (Lin et al. 2015). Moreover, teaching about careers in science is argued that it can offer new opportunities for the young students to expand the range of their aspirations (Osborne 2008).

The concern of ensuring a trained workforce may grow due to the documented decline of student’s interest towards STEM studies and related careers as well. This drawback may be attributed either to the fact that a looming gap exists between the science that students are learning in schools and their everyday life or because teaching students about modern scientific and technological advances is often underestimated (Kähkönen Laherto & Lindell 2011). On the other hand, it is argued that teaching students about NSE advancements can be a motivator to excite them in the classical fields of physics, chemistry and biology and direct them to pursue studies and careers in STEM (Healy 2009, Jones et al. 2013).

The second type of argumentation stems from the explanation of structure – property relation, which is a common theme to all grades of education. Traditional school curricula focus on macroscopic properties first and lead to explanations on the atomic level. However, many of the macroscale phenomena we experience in our everyday life demand explanations on the nanoscale level. For example the superhydrophobic property of some plants has its origin to the hierarchical nanoscale structures (Bhushan 2016). To conclude, not only the sub-nanoworld, which is characterized by atoms and molecules, has an impact to our lives, but also the nanoworld, can determine the properties of the macroscale materials that we manipulate.

In addition, a third type of argumentation is relevant to the scientific – technological literacy, or nanoliteracy (Jones et al. 2013). Nanoscale materials have already been penetrated to products that we utilize in our everyday life. For example, nanoscale metal oxide nanoparticles are already used in diverse applications such as sunscreens and antimicrobial coatings (Ramsden 2009). However, it is questionable whether nanoparticles can be a menace for the human body when they digested or released to the environment (Bhushan 2016). An informed citizenry is needed to appreciate risks and put them into context.

This study deals with the above issues. Especially, we focus on training Primary Teachers (PTs) about this modern field. A major consideration is to establish the content structure for instruction and build upon related activities. In order to do so, we first sought to map the core concepts of NSE discipline across all levels of education, and with content transformation process to form the content to be taught to PTs. We aim to answer to the following question:

Which of the fundamental NSE concepts can form a content structure for educating PTs and what laboratory activities can be built upon to develop NSE content learning?
3. Methodology
As a first step, we sought to detect through the literature, the fundamental ideas that construct the NSE discipline, across all levels of education, from elementary school up to undergraduate level. We followed this route because it is noted that teachers need to develop understanding about the fundamental concepts in order to learn NSE (Jones et al. 2013). Especially, we searched for studies that were conducted with the definite aim to determine the NSE concepts that should be introduced to a particular grade level of education.

Major data sources were books and journals, which we collected with several ways. We examined web pages of journals whose area of focus was educational, e.g. Journal of NanoEducation. The key words written to the search engines of these journals included terms as nanoscience, nanotechnology, primary/secondary/post-secondary, nanoscale, fundamental/essential/core concepts, engineering nanoeducation and combinations, e.g. k-12 nanoeducation. By writing the above terms, we searched for relevant material into electronic data sources such as scienceDirect, ERIC (The Education Resources Information Center), GoogleScholar, and google. Furthermore, we examined the references of the studies collected, gathering more articles, until no new study was found.

Blonder & Sakhnini (2016) and Sakhnini & Blonder (2015) published results concerning a similar research. However, the distinction of our research is that we do not seek for differences and similarities among concepts that emerged from separate studies concerning the same grade level (e.g concepts within the secondary level), but only among different grade levels. For this reason, we integrated the concepts that came from different investigations but were addressed to the same educational level. In addition, we weren’t interested in comparing the items that were included under the umbrella of each concept. Instead, the included items served as a tool to recognize the underlying essential concept. For example, “size and scale” was explicitly identified as a core concept for secondary and tertiary education. While this concept is not explicitly mentioned as such in the primary education, the included items of the core concept “nanoscale definitions” (Huang, Hsu & Chen 2011) led us to “correspond” the latter concept with the concept “size & scale” (table 1).

We traced four studies that satisfied the criterion we have established: one for the academic level (Wansom et al., 2009), two for the secondary level (Stevens et al. 2009, Blonder & Sakhnni 2016) and one for the primary education (Huang et al. 2011).

The second step after identifying the basic concepts of the NSE discipline is to form the content structure to be introduced to the PTs. In order to do so, we had to take into consideration not only solely the above identified NSE concepts, but also the students’ and teachers’ perspectives about the particular content as well (interests, difficulties in understanding, preexisting knowledge, etc.) (Duit et al. 2012).

4. Results
In the following, we present the fundamental NSE concepts that may form a content structure as well as the related intended aims for educating PTs (table 1). In parallel, we focus on the laboratory activities that can support the introduction of the NSE content.

Concept 1: Size and Scale (Lesson 1 & 2)
Size and Scale is considered as fundamental for the comprehension of all of the NSE concepts (Delgado et al. 2015). Size refers to the actual extent or amount of something, and nanoscale can be defined by the size of the objects that NSE focuses on. As size and scale change, not only the properties of matter change, but the models, the tools, or the dominant forces that underlie these changes may alter (Stevens et al. 2009). To illustrate the significance of the particular concept, Jones et al. (2013) stress: “If teachers lack a fundamental knowledge of the size and scale of nanometers, it is not clear how they can understand and teach students about how materials behave differently and how tools and techniques differ when working at this small scale” (p. 11).

Recommendations regarding the conceptualization of “size and scale” suggest five levels of thinking (Magana et al. 2012): a) categorizing, involves grouping together objects that have similar sizes
Concept 2: Tools (Lessons 1-5)

Research has revealed that learners meet challenges regarding the above conceptualizations (Delgado et al. 2015). For example, undergraduate students classified several objects in two categories according to their visibility (Magana et al. 2012). This may hinder their understanding about the objects that NSE focuses on. In order to confront with this challenge, we decided to introduce the concept of “tools”.

The different tools that scientists utilize when they study objects of several scales, can be implemented as a criterion for grouping several objects into the scales. Although the idea “tools” has been characterized as inadequate to teach students about the properties of materials at the nanoscale (Jones et al. 2015), we decided to include it to the to be taught content, as it can be implemented as a “stepping stone” for the discrimination of the three scales (e.g. macroscale-naked eye, microscale – optical microscopes, nanoscale – electron microscopes) (Stevens et al. 2009). This treatment of the concept “tools” led us to neglect introducing to PTs how the tools at different scales operate (especially at the nanoscale), or the different kind of non – optical microscopies (e.g AFMs, SEMs) that are utilized for studying the nanoscale objects.

Regarding lesson 1 & 2 we designed activities in order to train teachers considering size & scale – tools. Teachers had to complete the task that can be seen to image 1. The image shows a diagram, which is called Scale ladder. The black arrows point the absolute sizes of specific landmark objects, the white circles the tools that render these objects visible, and the three large frames (with three different colors) indicate the three scales: the macroscale, the microscale, the nanoscale. PTs watched two videos that introduced the nanoscale via macroscale and microscale. For example, one video presented the absolute size of a human being, then of a bacterium and then of a DNA, and the tools that are used for observation. Teachers were assigned to write next to the appropriate arrow, the object, and into each circle, the tools that are utilized. Then they had to name the colored boxes as macroscale, microscale, nanoscale. PTs were encouraged to refer to and complete the scale ladder with several objects that would encounter during the following lessons (e.g nanobumps – lesson 6-7, nanopores – lesson 9) in order to enrich the macroscale, microscale or nanoscale areas.

Fig. 1. The Scale ladder, which was used as a tool in order PTs to develop understanding about size and scale – tools

Concept 3: Model (Lessons 3-9)

One of the main reasons, that learners encounter difficulties for developing understanding about NSE, is the lack of intuition (Xie & Pallant 2011). A higher level of thinking is acquired, which will not only be implemented just for knowing facts, such as how small a nanometer is or what the structures
of some nanomaterials look like, but, even more importantly how materials behave at the nanoscale or how nanoscale systems are engineered. The nanoscale world is foreign to the learners as it is the world that is governed by electromagnetic forces and quantum mechanics, and the phenomena that occur at that scale are often counterintuitive (Xie & Pallant 2011, Jones et al. 2013). In order to make nanoscale accessible to Pts, we turned our attention to the concept “models” (Stevens et al. 2009, Wansom et al. 2009). Indeed, it is acknowledged by scientists, engineers and educators, that models and modeling can be a valuable tool for learners in order to develop understanding of the phenomena and processes that take place at the nanoscale (Schonborn et al. 2016).

However, models are approximations of reality and as such, they can provoke misconceptions about the targets they represent (Turkoglu & Oztekin 2016). For example, it has been noted that often when students think of microscopic objects, they recall pictures from textbooks they have seen. In this case, students may develop macroscopic conceptualizations of microscopic objects (Tretter et al. 2006). Such a way of thinking may prevent learners to develop a firm grasp of the concept “size and scale”.

For this reason, we considered that aspects about the nature and role models should be introduced to PTs. In particular, we were based on the overview by Oh and Oh (2011) who identified important aspects about models such as the meaning of a model, purposes of modeling, multiplicity of scientific models, change in scientific models and uses of models in the science classroom. In addition, we prompted teachers to build models to represent nanoscale entities and phenomena, as it is documented that the process of creating models can improve the understanding about the nanoscale phenomena (Daly & Bryan 2010). For example, teachers constructed their own models to represent the structure of nanoscale objects (virus or DNA) & outline the viral infection (image 2).

![Fig. 2. A model of viral infection which was built by one group of teachers. The viruses are represented with ball and stick models and the cells by the yellow plastic dishes](image)

In general, the content of models was woven in parallel with the NSE content (table 1). To be specific, aspects about the nature of model were introduced to PTs gradually as they mentally made the transition among scales.

**Concept 4: Size dependent properties (Lessons 6-8)**

Across literature, it is stressed that much of the advances of the NSE field have become a reality, because of the unique phenomena and the remarkable properties that emerge at the nanoscale. It is argued that the statement “a material’s properties may change with size” consists the essence and foundation of the NSE discipline (Hochella 2002). At the same time, most of the articulated definitions of NSE emphasize the unique properties that materials exhibit at the nanoscale (Ramsden & Freeman 2009).

Accordingly, it seemed incumbent to introduce the concept of “size dependent properties”. A material’s properties can be size dependent either because quantum effects begin to dominate in the nanoscale regime (e.g. quantum confinement), or because of the dramatic increase of the ratio surface area to volume (S/V ratio). Research concerning the negotiation of this concept, has revealed several issues. In particular, it seems that learners encounter difficulties when they attempt to explain why a material’s properties change at the nanoscale. For example, secondary science teachers are inade-
quate to explain the size dependency of the quantum dots color (Bryan et al. 2012). In addition, it is acknowledged not only by NSE educators but even from secondary teachers, that implementing quantum physics to explain the occurrence of nanoscale phenomena is a challenging task and may be inappropriate even for the secondary level (Laherto 2011). Taking into account that “quantum mechanics is an extremely complex subject that requires extensive experience in both mathematics and science, and its counterintuitive predictions are difficult to grasp even for expert scientists” (Stevens et al. 2009, p. 33), we chose not to negotiate at all, to the PTs, properties that emerge due to quantum effects.

Continuing the above discussion, we placed our attention to properties that can be explained in terms S/V. However, it is reported in the literature that students’ from elementary up to undergraduate level and teachers’ applications of surface area to volume relationships in several contexts is problematic. For example elementary school teachers have trouble understanding the S/V beyond its mathematical calculation (Swarat et al. 2009). Similar remarks have been reported in other ratios. For example, in the case of density which is defined as the mass per unit volume, the difficulties, that student encounter, are mostly qualitative and conceptual rather than quantitative (Spyrtou et al. 2008). Bryan et al. (2012) assumed that secondary students may not have yet developed the mental skills to apply S/V relationships in NSE contexts.

To confront the above challenges, we introduced the S/V ratio qualitatively avoiding using the relevant mathematical ratio. We took into consideration that the amount of S/V may define the contact area of two surfaces. That is, for the same volume, the smaller the size of a material the more increased exposed surface area will be created, which in turn will increase the amount of contact between two surfaces. For example (image 3), we present in the context of the lotus effect, the decreased surface contact area between a spherical water droplet and the surface of the lotus leaf. Furthermore, PTs quantitatively measured in situ on printed images depicting plant leaves, the contact angle between a water droplet and a surface using a protractor (image 4). In addition, via gecko effect, we demonstrated the impact of the increased surface contact area to adhesion (lesson 8).

![Fig. 3](image3.png) A video simulation that shows the small surface contact area between a water droplet and the nanoscale structures of the lotus leaf

![Fig. 4](image4.png) One of the printed images that was used in order PTs to draw and measure the contact angle by a protractor

**Concept 5: Applications (Lessons 5-9)**
Sakhnini & Blonder (2016) argue that NSE applications can form a platform for the inclusion of several core concepts, such “as size dependent properties”. Introducing NSE applications to school classrooms that are meaningful to student’s everyday life may motivate them and increase their interest towards NSE learning (Lin et al. 2015). This approach to introduce NSE concepts via applications has been proposed by several researchers in the nanoscale field education (e.g. Lin et al. 2015 primary education, Delgado et al. 2015 secondary education).

Based on the above consideration, we wove applications with the concepts of “size and scale” and “size dependent properties”. For example, after PTs established knowledge about size and scale, they contextualized this knowledge within a viral infection case, in which a nanoscale object (virus) affects
the microscale (cells) and the macroscale (human) (image 2). This taught content is associated with the aim PTs to understand that “the nanoscale may impact our everyday world (lesson 5) which is considered as a key concept in NSE education (Delgado et al. 2015). Concerning the size dependent properties, PTs related the mechanism of the gecko adhesion with applications in everyday life, such as gloves.

5. Discussion
We consider that certain fundamental NSE concepts have the potential to form a suitable content structure for PTs. “Size & Scale” and “tools” may help teachers to realize the realm of the nanoscale, “applications” provide examples about how the nanoscale can affect our macroscale, “size dependent properties” may be very motivating due to the unexpected behavior of matter at the nanoscale and “models” can bridge the gap between the nanoscale and the macroscale. The above justifications are encountered in similar approaches reported in the literature (e.g. Jones et al. 2015).

Table 1. Essential concepts and content structure per lesson

| Lesson | Essential concepts | Content Structure | The aim was PTS to |
|--------|--------------------|-------------------|--------------------|
| 1 & 2  | Size & Scale       | • 5 levels of thinking  
• objects and tools of the macro- micro- nano- scale | define the nanoscale by its size range, the landmark objects that includes, the tools that render the objects visible |
|        | Tools              |                   |                    |
| 3      | Size & Scale       | • Macroscale       
• PTs create and evaluate their own models  
• Nature and role of models | realize that the macroscale includes objects with different properties  
acknowledge that the naked eye is the tool for studying macroscale objects  
understand that models represent properties of macroscale objects |
|        | Tools Models       |                   |                    |
| 4      | Size & Scale       | • Microscale       
• PTs create and evaluate their own models  
• Nature and role of models | realize that the microscale includes objects with different properties  
acknowledge that the optical microscope is the tool for viewing microscale objects  
understand that models can represent properties of microscale objects |
|        | Tools Models       |                   |                    |
| 5      | Size & Scale       | • Nanoscale        
• PTs create and evaluate their own models  
• Nature and role of models: representations of nanoscale entities  
• The viral infection case | realize that the nanoscale includes objects with different properties  
acknowledge that electron microscopes can be used for viewing nanoscale objects  
realize that models can be used to obtain information about inaccessible targets  
understand that the nanoscale may impact our everyday world |
|        | Tools Models       |                   |                    |
|        | Models Applications|                   |                    |
| 6 & 7  | Applications       | • Lotus effect – applications  
• PTs create and evaluate their own models  
• The less the surface contact area between surfaces, the more decreased the adhesion | understand the super hydrophobic and self-cleaning property of the lotus leaf and the importance of the surface contact area  
understand that the nanoscale may impact our everyday world  
enhance their understanding that models represent aspects of nanoscale phenomena |
|        | Size & Scale       |                   |                    |
|        | Models Size dependent properties |                   |                    |
| 8      | Applications       | • Gecko effect – applications | understand the strong adhesion property |
To avoid the emergence of misconceptions and to enhance NSE content learning, not only we encouraged PTs to use models but also we addressed several aspects of the nature of models in parallel with the NSE content. In addition, the lab work we set consisted of a lot of model building activities. Despite that there are some NSE teacher’s training courses that implement model building practices (e.g. Bryan et al. 2012), it seems that the interlacement of the NSE content with the content of the nature of models, is an approach that is underestimated in the related literature. On the contrary, we are strongly aligned with the relevant Science Education suggestions which highlight the fact that introducing learners, aspects about the nature of models and modeling can foster learning from models (Oh & Oh 2011).

Some first remarks regarding the effectiveness of the approach reveal that PTs showed a significant deal of enthusiasm and anxiety to participate in the lab activities we designed. They argued that these activities could be suitable for their classes also, with some alternations in order for their students to develop understanding. Moreover, they willingly suggested designing their own experimental activities that would be implemented to their classes. From our point of view, our primary focus is to examine the PTs level of understanding regarding the taught NSE content. The results will point out the modifications to the content structure and to the experimental activities as well.

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