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Essential Concepts of Nanoscale Science and Technology for High School Students Based on a Delphi Study by the Expert Community

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Essential Concepts of Nanoscale Science and Technology for High School Students Based on a Delphi Study by the Expert Community

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Nanoscale science and technology (NST) is an important new field in modern science. In the current study, we seek to answer the question: 'What are the essential concepts of NST that should be taught in high school'? A 3-round Delphi study methodology was applied based on 2 communities of experts in nanotechnology research and science education. Eight essential concepts in NST were identified. Each concept is accompanied by its explanation, definition, importance and includes subcategories that compose it. Three concepts emerged in the Delphi study, which were not identified before: functionality, classification of nanomaterials, and the making of nanotechnology. Differences between the concepts suggested by the 2 communities of experts were found. The results of this study serve as a tool to examine different nanotechnology programs that were reported thus far and to make recommendations for designing a NST program for high school students that includes the essential concepts.

Keywords: *Nanoeducation; Delphi study; Community of experts; High school*

Introduction

Nanoscale science and technology (NST) is an important field in modern science. It deals with the ability to create materials, devices, and systems having fundamentally new properties and functions by working at the atomic, molecular, and macromolecular levels (Roco, 2001). These properties were utilized for developing new applications that affect people's lives and their daily needs in different domains (Menaa, 2011; Panyala, Pena-Mendez, & Havel, 2009; Petros & Disimone, 2010; Wagner, 2007).

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These revolutionary broader nanotechnology applications have made governments and industries around the globe recognize their impact and contribution to worldwide economic prosperity (Foley & Hersam, 2006). As a result, a great investment in NST developments has been made. The rapid developments in the NST field require a well-educated scientific and engineering workforce (Jones et al., 2013; Toth & Jackson, 2012). There is also a need to prepare future citizens to deal with NST. They will soon need to achieve a certain level of nanoliteracy in order to navigate the science-based issues related to their everyday lives and (Laherto, 2010) to intelligently question and understand the ethical and societal implications of this revolutionary technology (Toth & Jackson, 2012).

To properly prepare the next generation of scientists, engineers, and future NST-engaged citizens, effective educational programs in NST are needed and some efforts have been made (Bryan, Magana, & Sederberg, 2015; Jones et al., 2013). Most of these programs have focused on different developmental levels and aspects for teaching NST (Ambrogi, Caselli, Montaltic, & Venturic, 2008; Blonder, 2011; Blonder & Dinur, 2011; Blonder & Sakhnini, 2012, 2015; Bryan et al., 2015; Dori, Dangur, Avargil, & Peskin, 2014; Jones et al., 2013; Jones, Gardner, Falvo, & Tayler, 2015; Samet, 2009; Walters & Bullen, 2008)

Although NST is considered a motivating interdisciplinary scientific field, it cannot be easily dropped or integrated into an existing broad and condensed curriculum. In addition, the interdisciplinary nature of NST makes it difficult to determine (1) where and how NST should be integrated into the current curriculum in which scientific disciplines (e.g. chemistry, physics, biology) are separated, (2) what content should students need to know about this emerging field, (3) what concepts are important to be taught for better understanding NST, (4) what should be taught at different grade levels, and (5) how these concepts should be taught. These questions and others prompted educational researchers to study the challenges facing nanoscale science education before integrating nanoscale science into the school science curriculum.

Theoretical Background

Several studies and projects have been conducted to develop nanoscale science educational programs. In Germany, the Model of Educational Reconstruction (MER) was applied (Parchmann & Komorek, 2008). This model combines content analyses, empirical research, and the design of educational settings. The MER considers teachers' perspectives and experts' knowledge in order to develop a coherent educational program that takes into consideration scientific parameters as well as science education. Student teachers and experts in nanotechnology were chosen to analyze the learners' perspectives regarding nanoscience, to investigate preservice teachers' self-estimated knowledge, their expectations about teaching nanoscience at the secondary school level, and their beliefs about nanostructures and about techniques such as scanning tunneling microscopy (STM) and atomic force microscopy (AFM). Preliminary results of this research showed that student teachers are interested in gaining further knowledge and understanding, but that they do not yet feel confident about teaching nanoscience topics. Student teachers gave various reasons why teaching nanoscience could have positive effects on their teaching and students' learning. The experts offered additional insights into scientific topics, models and content for teacher workshops.

Another approach aimed at identifying and reaching a consensus on the 'big ideas' of nanoscale science and engineering (NSE) that would be appropriate for grades 7–12 was conducted (Stevens, Sutherland, & Krajcik, 2009). Thirty-three scientists and science educators were chosen to represent different scientific disciplines (e.g. chemistry, physics, and biology) that are involved in NSE research, in learning various sciences, and science education. The participants were brought together with two goals in mind: to develop a consensus on what the 'big ideas' are in NSE and to determine how these ideas might be introduced into the US science curriculum. Based on the workshops' results, Stevens et al. (2009) presented the final consensus of the nine big ideas for grades 7–12 that are important for understanding the NSE field: (1) size and scale, (2) the structure of matter, (3) forces and interactions, (4) quantum effects, (5) size-dependent properties, (6) self-assembly, (7) tools and instrumentation, (8) models and simulations, and (9) science technology and society.

Huang, Hsu, and Chen (2011) developed a questionnaire of 'The Core Concepts of Nanotechnology' and conducted a Delphi survey in which 28 experts were asked to evaluate the importance of each concept. These experts included professors from the college of science and engineering, professors from science education, and elementary school teachers. Through three rounds of the survey, Huang et al. (2011) identified five main concept categories of nanotechnology for elementary school science. The categories included 'nanotechnology definitions', 'nanoscale features', 'nanophenomena in the natural world', 'nanomaterials', and 'the development of nanotechnology', each included several sub-concepts. Within this list, they identified one sub-concept of nanotechnology that should be taught in elementary schools in the lower grades, fifteen sub-concepts for the middle grades, and 33 sub-concepts for the higher-grade elementary school students. According to the results, they established the concepts map of nanotechnology as a reference for future curriculum design for nanotechnology in elementary school.

In addition to the above-mentioned studies that aimed at mapping nanotechnology concepts for school science, other studies focused on the undergraduate level. Wanson et al. (2009) developed a broad curriculum framework for degree programs in NSE, based upon a set of big ideas. The framework linked four essential areas in NSE: processing (how nanomaterials are fabricated), nanostructure (how the structure of nanomaterials can be imaged and characterized), properties (the resulting size-dependent and surface-related properties of nanostructured materials and devices), and applications (how nanomaterials and nano devices can be designed and engineered for the benefit of society). The researchers argued that the linkage between these four areas serves as a tool for program and course construction and for evaluation in higher education. The resulting framework was used to evaluate nanotechnology programs in different academic institutions. It was found that research universities tend to emphasize nanostructure property relationships, with less attention given to processing or applications (Wanson et al., 2009).

Although these studies and projects resulted in an organizational framework for nanotechnology programs, and the main concepts comprising nanotechnology at different developmental levels, there is still a need for research based on a thorough examination of the question in order to broaden the scholarly sources, particularly non-US central sources, and to pursue viable alternative perspectives that will contribute to the development and growth of knowledge in NST education.

Research Goals and Questions

The goals of the current study are to map the essential concepts of NST that should be taught in high school science, as well as to learn about the differences between the two communities of experts that participated in the study (nanotechnology researchers and teachers) regarding the perceived importance of these concepts.

Based on the Delphi study, our research questions are as follows:

(1) What are the essential concepts in NST that should be taught in high school science?
(2) What are the differences in how the two different communities of experts (nanoscience researchers and science teachers) perceived the importance of these concepts?

Methodology

Instruments and Data Collection

The method chosen for eliciting the expert community's views was a three-stage Delphi study (Murray & Hammons, 1995). It is based on anonymous group interactions and responses involving a multiple-iterations process to collect and distill the anonymous judgments of experts, interspersed with feedback, using a series of data collections and statistical analyses (Delbecq, Van de Ven, & Gustafson, 1975). The Delphi methodology is well suited as a research instrument when there is incomplete knowledge about a problem or phenomenon (Custer, Scarcella, & Stewart, 1999; Skulmoski, Hartman, & Krahn, 2007) and it is useful for consensus building by using a series of questionnaires (Dalkey, 1969; Dalkey & Helmer, 1963; Lindeman, 1981; Linstone & Turoff, 1975; Martino, 1983; Young & Jamieson, 2001). This approach is used for gathering data from respondents within their domain of expertise without face-to-face interactions (Hsu & Sandford, 2007).

An adopted representation of a typical Delphi process (Skulmoski et al., 2007) was applied, as presented in Figure 1 and will be further explained next.

Usually, the minimum number required for a Delphi panel is 10 (Cochran, 1983). However, Delbecq et al. (1975) maintained that few new ideas are generated in a homogeneous group once the size exceeds 30 well-chosen participants.

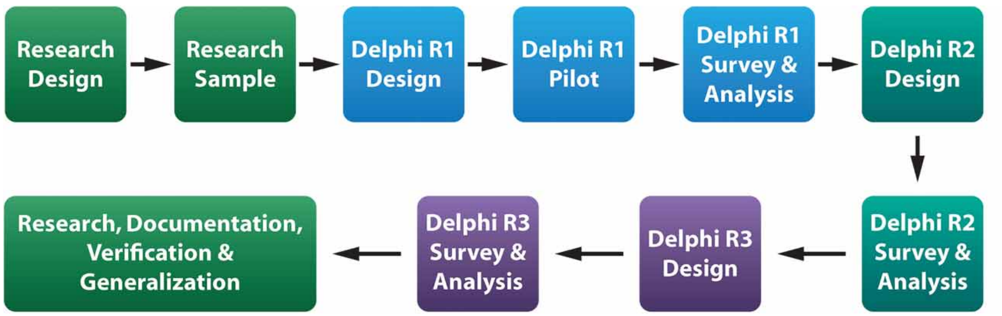

Figure 1 Delphi process, based on Skulmoski et al. (2007).

Delphi Process Design

The Delphi process begins with an open-ended questionnaire in the first round (Figure 1). The open-ended questionnaire (Appendix 1) serves as the cornerstone for exploring specific information about a content area from the Delphi subjects (Custer et al., 1999). After receiving the subjects' responses, investigators convert the collected information into a Likert-type questionnaire. This questionnaire is used as the survey instrument for the second and third rounds of the data collection.

Participants

The first-round Delphi questionnaire was sent to 82 participants ($n = 82$), from two groups of experts. Twenty-one researchers who are experts in nanotechnology ($n = 21$) out of 41, and 21 teachers ($n = 21$) out of 41 science teachers who have knowledge in nanotechnology replied to the first-round Delphi questionnaire, is shown in Figure 2.

The first group of experts included NST researchers in Israeli universities and industries. They represented several scientific backgrounds (applied physics, chemistry, materials and science engineering, physical chemistry, polymer physics, and physical organic chemistry). All the researchers who participated in the study hold Ph.D. degrees. Thirteen of them are full professors in their field, and three researchers work in companies involved the nanotechnology industry.

The second group of participants consisted of experienced high school science teachers who teach different science disciplines (chemistry, biology biotechnology, and physics). They all have a solid background in NST from different sources; some of them underwent a thorough course about NST and were defined as nanoliterate (Blonder, 2011). These teachers possessed strong content knowledge in NST and strong pedagogical content knowledge. Other teachers were involved in developing an NST curriculum or modules in Israel from different science disciplines (chemistry, biology, bio-nanotechnology, and physics). Some of these teachers also had taught the nanoethics module, whereas others had taught nanobiotechnology; there were some teachers who had only informal experience

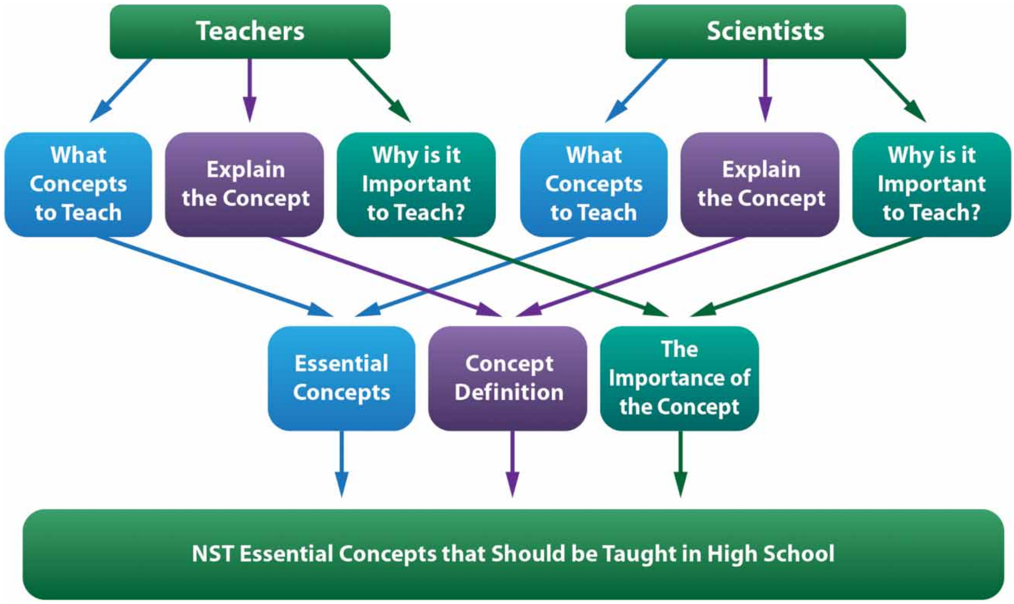

Figure 2 The process for reaching a consensus about NST essential concepts that should be taught in high school.

in teaching NST. Four of the teachers who participated in this research hold BSc degrees, 13 hold MSc degrees, and 4 of them have PhD degrees in science or science education. All of the teachers have at least 15 years of teaching experience.

The aim of choosing these two different groups of participants was to combine those factors that, in our opinion, play a fundamental role in developing the NST education field from different aspects (e.g. research, education).

Data Collection and Analysis

Delphi Pilot Study

A pilot of the Delphi study was conducted to examine (1) whether the responses in the pilot are influenced by the way the questionnaire was constructed and (2) whether the phrasing of the questions is sufficiently clear for the participants so that the researchers can obtain suitable responses from the questions. In this stage, the researchers decided on the questions that will appear in the questionnaire (the original questionnaire is given in Appendix 1). In the open-ended questionnaire, the participants were asked to suggest essential concepts in NST that are important and should be taught in school science. The participants suggested clear descriptions of the concepts and justified their importance. In the pilot stage, three researchers and three teachers filled in the open-ended questionnaire used in the first round. The pilot study showed that the questionnaire was clear and useful and provided a wide variety of participants' answers. Therefore, we decided to use it in the first Delphi round with no modifications.

Delphi Round 1

As a result of the Delphi pilot study, we contacted the remaining Delphi participants using the same procedure mentioned in Figure 1. The questionnaire was sent to them by mail. We used a content analysis methodology that included the following steps: (1) carefully reading the information, and then (2) identifying, (3) categorizing, and (4) validating the emerging NST concepts. This process enabled us to place those phrases having similar themes into categories for further analysis (Chi, 1997; Glaser & Strauss, 1967). While categorizing, the researcher did not interfere with or change the wording that the participants used. Even most of the categories' names were derived from the participants' words, sentences, and phrases. The process of identifying the emerging categories included discussions between the first author and the second author (an expert in nanotechnology and in science education) that led to reshaping the categories. The content of the categories was again validated together with an external nanotechnology expert; the obtained agreement was higher than 90% and in cases of disagreements, minor changes were made in organizing of the subcategories until agreement was reached.

Upon completing the content analysis process, a chi-square test was used to compare the relative frequencies of each category in the two communities of experts comprising the Delphi panel (research scientists and science teachers) and to examine the overall agreement regarding a specific category among all the participants in the first round.

Delphi Round 2

The second-round questionnaire (Appendix 2) presented the titles of the emerging concepts together with representative anonymous definitions obtained from individuals in the first round. In the second round, experts were asked to rate the importance of each concept on a 5-point Likert-type scale, with a score of 5 representing the highest degree of importance. In addition, they justified their rating, and commented on the accuracy of the title and wording of the concept reflected their understanding of a specific concept. The participants commented on and responded to the representative supporting statements. Means and variances for each concept (using the rating given in the 5-point scale) were calculated.

Delphi Round 3

The third and final questionnaire of the Delphi study presented the concepts along with their definitions, and representative anonymous statements from the previous round that support or reject the importance of each concept and the percentage of participants who found each concept to be important. Participants commented and responded to the representative supporting statements and rated each concept's importance again.

The participants (1) rated again the importance of each concept on a 5-point Likert-type scale, with a score of 5 representing a high degree of importance, based on the premise that it should be explicitly taught, (2) justified their rating, and (3) commented on ways by which the wording of the concept might be improved to reflect the essence of each concept, and (4) suggested any potential difficulties while teaching each of the concepts.

It should be mentioned that according to the research literature on the Delphi method, the third and final round of the Delphi questionnaire should not be lengthy and detailed, so that the participants will not become tired at the end of the Delphi process, which would consequently affect the research results (Judd, 1972). Therefore, the researchers of the current study decided not to include the subcategories of each concept in round 3 of the study. In rounds 2 and 3, online questionnaires were used (Turoff & Hiltz, 1995). In order to present information concerning the collective judgments of the respondents (Hasson, Keeney, & McKenna, 2000) in the Delphi rounds, different descriptive statistical tests can be used (Hsu & Sandford, 2007). We decided to use the mean for presenting the importance of each concept, and the variance for presenting the consensus (Murray & Jarman, 1987; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003). A consensus regarding the importance of a concept is considered to be reached (Hasson et al., 2000) when the participants rate a concept with a mean $\geq$3.5 on the Likert scale and the variance is $\leq$1. If a concept's mean is $<$3.5 and the variance is $<$1, then a consensus is obtained regarding the unimportance of the concept. If the concept's variance is $>$1, then no consensus is obtained concerning the importance of the concept and another stage is needed in order to reach a consensus. A *t*-test was used in the second and the third rounds to compare the mean score of each concept, by each of the two research communities (research scientists and science teachers) comprising the Delphi panel.

Advantages and Disadvantages of Using the Delphi Study Methodology

The Delphi technique allowed participants to reflect on their initial judgments (Ludwig, 1994), review the comments of other participants in additional reviews (Hsu & Sandford, 2007), and reduced the effect of dominant individuals on the process. Moreover, statistical analysis ensured that the opinions generated by each subject of the Delphi study were well represented in the final iteration (Hsu & Sandford, 2007).

Several disadvantages of using this technique are mentioned in the literature and were taken into account while designing our study. The first is the selection of the participants. Choosing appropriate subjects is the most important step in the entire process because it directly relates to the quality of the results generated (Jacobs, 1996; Judd, 1972; Taylor & Judd, 1989). Therefore, we chose NST experts (researchers and teachers) who represent a variety of expertise, as described in the 'participants' section. The second is the number of participants. Delbecq et al. (1975) suggested that 10–15 subjects are sufficient if the background of the Delphi subjects is homogeneous. In contrast, if various reference groups are involved in a Delphi study, more subjects are generally needed. In the current study, 42 participants were selected from different scientific disciplines, backgrounds, and expertise, including 21 participants from each group. The third drawback is the time frame needed for conducting and completing a study. A Delphi study can be time consuming. Specifically, when the instrument used in the Delphi study in the second and third rounds consists of numerous statements, the participants need to devote a lot of time to complete the questionnaire. The use of an online questionnaire in the second and third rounds of the Delphi study provided a convenient platform that prevented delayed responses. The fourth disadvantage is related to the possibility of a low response rate. If a certain percentage of the subjects discontinue responding during various stages of the Delphi process, the quality of information obtained could be discounted or at least critically scrutinized (Ludwig, 1994). However, this problem was not found in our study. The response rate in the first round was 50%, and no dropouts in the second and third rounds were recorded.

Results

In this section, we present the research results in the following order: First, we present the main results of the study, namely the eight essential concepts of NST, their definitions according to the entire Delphi process and quotations of the participants' explanations regarding the importance of each concept and for some of the sub-concepts. Then, we describe how we obtained these concepts by providing the results from each of the rounds. We also present the differences between the two expert groups regarding the importance of each of the emerging concepts. Note that the resulting list of essential concepts of NST is based on the overall Delphi study.

Essential Concepts of NST and Their Definitions That Emerged from the Delphi Study

(1) Size-dependent properties. In the nanoworld, the properties of materials change as a function of the material's size. This effect does not exist in the macroscopic world. This concept includes the following:

(a) *The surface area-to-volume (SA/V) ratio*: When you go down in size to the nanoscale, the SA/V ratio increases dramatically. As a result, a greater percentage of the atoms are on the surface and there are more atoms on the surface as compared to internal atoms in the matter. This turns out to be a very effective factor for many of the materials' properties (e.g. color, catalysis, the effects of intermolecular forces, and roughness).

(b) *Quantum properties*: Unique properties, based on the wave nature of the electron. These properties appear at the nanoscale.

(c) *Optical properties*: Near-field is a relatively recent theory in optics, which explains optical properties at the nanoscale. In near-field optics, a small light source (e.g. 50 nm size) is brought close to the inspected object (a few nanometers). This distance is much less than the diffraction limits and thus, it is called the Near-field.

(d) *Defects*: Nanomaterial structures have a small number of atoms. Therefore, the chance of finding defects in these structures is very small, which is why nanomaterials have very high mechanical properties compared with macro materials, which have defects.

It is clear that there are additional properties that dramatically change at the nanoscale; however, the size-dependent properties previously presented, which were suggested by the Delphi participants, received high mean scores and received a consensus.

The participants explained why the concept of size-dependent properties is important to be taught: 'To demonstrate how many opportunities one can get with each single nanomaterial'; 'To show the strength and importance and the uniqueness of nanotechnology'; 'To show the "freedom degrees" provided by the nanotechnology that show new properties'.

(2) Innovations and applications of nanotechnology. The potential applications and innovations of nanotechnology include the following:

(a) *Current and future applications*: Innovative implementations of nanoscience and nanomaterials into current and future technologies and products for everyday use.

Why is it important to be taught: 'Showing and demonstrating potential applications as early as possible will motivate the students to learn and to understand the basics of the NST'. It is also important for 'Illustrating the real, unmet need for multidisciplinary approaches'.

(b) *Mimicking nature*: Mimicking nature, which involves devising motors, machines, and surface nanostructures, is based on single molecules or collections of them for many tasks such as energy harvesting and transfer, motion, cleaning surfaces, and replication.

Why is it important to be taught: 'Gives increased awareness about the world around and within us; helps students imagine how nano can be used to perform complex tasks with ease'.

(c) *Risks and benefits of nanotechnology*: Is nano dangerous? One should understand that the benefits of being small can also be harmful to our health and environment. The socio-scientific issues concerning nanotechnology should be explored.

Why is it important to be taught: 'To recognize the potential disadvantages of nanotechnology for human health and/or the environment'; 'To recognize that advance in nanotechnology applications is fine, unless they are not used ethically'; 'To introduce the students to other factors when they design a nanotechnology-based system'.

(d) *Tailoring nanomaterials to the application*: Constructing complicated systems (e.g. due to the size-dependent properties of the nanomaterials) to meet the needs of a certain application.

Why is it important to be taught: 'To illustrate new approaches of thinking and implementation, which rely on a "tailor-made" approach for constructing complicated systems, which will motivate the students to learn science'; 'Students will be able to understand the relationship between chemistry, materials science, and nanoengineering.'

(3) Size and scale. Size is defined as the extent or amount of an object. Scale is defined as a comparison of the size of an object to a reference object.
Why it is important to be taught:

> This topic will introduce (probably for the first time) the need for miniaturization as well as the advantages of miniaturized systems beyond the microscale. It will justify the need to learn about nanoscale science and to use 'nanotechnology'; 'Size and scale are important for getting an idea about the size of objects around us in the world and realizing the actual size of molecules that we teach about in chemistry lessons'; 'Students have difficulties in imagining the nanometric scale, because it is abstract for them. The understanding of the size and scale concept is essential for understanding other nanotechnology concepts like size-dependent properties.'

(4) Characterization methods. Tools for observing, imaging, studying, and manipulating the nanomaterial's size, along with techniques for characterizing nanomaterials.

(a) *SPM* (Scanning probe microscopy) and mostly STM and AFM.

(b) *EM* (Electron microscopy), which includes TEM (Transmission electron microscopy) and SEM (Scanning electron microscopy).

(c) *Resolution*: Resolution, as used in science, can be defined as a measuring value to resolve things. It is associated with different areas such as picture resolution, pixel resolution, and audio. In the nanoworld, resolution involves measuring the size or the distance of objects. In practice, it is a tool used for determining whether the object is considered nanoscale.

Why is it important to be taught: 'To recognize the tools used for characterizing and monitoring the properties of nanomaterials and/or nanosystems'; 'To illustrate to the students that "nano" is NOT science fiction, rather, it is reality (people tend to believe what they see!)'; 'It will be hard to explain any of the nanoscale concepts without understanding at a basic level how we view and measure them.'

(5) Functionality. Functionality can be defined as a property that is provided for a material or for a specific area in it. This property endows the material with a specific activity or endows it with bonding ability. Functionality transforms nanoscience into nanotechnology.

Why is it important to be taught: 'To have functionality we bind functional groups, for example, groups that can be attached to a carrier, which will attach the particle to a receptor and react with a certain molecule.'; 'The functionality is very important for nanotechnology because it transforms nanomaterials from just matter to something that is part of technology.'

(6) Classification of nanomaterials. Nanomaterials can be categorized according to the following characteristics:

(a) *Type of nanomaterials*: Categorizing nanomaterials according to their chemical composition (e.g. carbon nanocompounds, inorganic NP, and organic nanocompounds).

(b) *Electrical conductivity*: Categorizing nanomaterials according to their electrical conductivity (semiconductors, conductors, and insulators).

(c) *The origin of the nanomaterial*: Categorizing nanomaterials according to their source: Natural nanomaterials, organic molecules, and synthetic nanomaterials.

(d) *Dimensionality*: Dimensionality in the context of NST can be defined as the number of dimensions in which a nanostructure expands beyond 100 nm (0D, 1D, 2D, 3D). Nanomaterials can be classified according to their dimensionality.

Why is it important to be taught: 'To recognize the different categories of nanomaterials and the pros and cons of each'; 'To understand that in nanotechnology the properties are determined not only by the substance and molecules that are used to fabricate the material but also by the dimensions of the particles that determine the electronic properties.'

Mostly, the teachers provide explanations regarding the importance of teaching the concept of classification of nanomaterials: 'To distinguish different types of materials according to their characteristics, and to adapt these characteristics to the desired application. For example, between metals and semiconductors and insulators'; 'It is similar to the Periodic Table, which classifies chemical elements according to their properties, which helps teaching the general patterns in chemistry'; 'Using categorizations help to link nanomaterials to different categorizations that are used in chemistry, which the students are familiar with, like electrical conductivity'.

(7) Fabrication approaches of nanomaterials. A wide variety of options can be used for fabricating nanomaterials. For example, there are top-down vs. bottom-up approaches for fabricating nanomaterials as well as a self-assembly fabrication approach. Self-assembly is the leading example of a bottom-up approach: the ability of molecules to arrange themselves into ordered structures 'on their own' to satisfy the laws of thermodynamics.

(a) *Top-down vs. Bottom-up approaches for fabricating nanomaterials.*

Top-down: Locating each component of the material from the top, in a way in which the arrangement of the material is determined by an external intervention (e.g. lithography) at the scale of the resulting nanomaterial.

Bottom-up: Molecules or atoms, in the gaseous phase or in a solution, are arranged for producing a defined set of structures and their directionality, sometimes on a specific platform. This process does not require a nanoscopic external intervention.

(b) *Self-assembly approach for fabricating nanomaterials.*

Self-assembly is the leading example of a bottom-up approach: The ability of molecules to arrange into ordered structures 'on their own' to satisfy the law of thermodynamics.

Why is it important to be taught: 'To recognize the tools used for fabricating the naomaterials and the pros and cons of each technique'; 'To illustrate the wide variety of options that the students can use for fabrications (something that could help in the tailor-made approach mentioned above)'; 'Self-assembly is the heart of many fundamental processes at the nanoscale including biological function, and growth of quantum structures. Since it is spontaneous, it holds great promise for making relatively complex things happen with minimal intervention and effort.'

(8) The making of nanotechnology. Uncovering the mystery of nanotechnology, or in other words, how nanoscience research is performed and how innovations are transformed into applications.

(a) *Multidisciplinary science and technology*: Combining knowledge that is derived from different backgrounds and from different disciplines of science and technology.

Why is it important to be taught: 'This topic will unify the knowledge of those students that have different backgrounds (schools, classes) and/or that were trained in different disciplines'; 'This topic will introduce to the students not only the advantages, but also (and mainly) the disadvantages of the reality in which nanotechnology is being developed'; 'To demonstrate the synergetic effect in the multidisciplinary approach (mainly, the combination of the knowledge they have acquired in all scientific courses they have learned beforehand), using concepts that the students ALREADY know from their present or past experience'.

(b) *Team work*: Collaboration among chemists, physicists, biologists, electrical and material engineers.

Why is it important to be taught:

> It is important that students will work in groups. Each student in the group will bring a different content knowledge (e.g., biology, chemistry). Students will overcome their knowledge gap, they will have an opportunity to complete their knowledge in a specific phenomenon from other students in the group.

(c) *Development of nanotechnology*: The chronological development of NST research and applications.

Why is it important to be taught: 'To expose the students to the developmental thinking that led to the NST research and industry'; 'The development of nanoscience and technology is a great platform for making students learn and understand how scientific research is done, and the way its ideas are transformed to be applications.'

Next, we present the results of the first and the second rounds, which led to what we consider to be the essential concepts of NST (the third round) that should be taught in high school.

Round 1

The average number of concepts that were suggested by each participant in the two groups (teachers and researchers) is presented in Table 1. No significant difference was found between the two groups ($P = .05$) concerning the average number of the suggested concepts. However, the teachers suggested on average more concepts than the researchers did.

Table 1. The average number of NST concepts that were suggested per participant for each of the groups in the first round

	Teachers	Researchers	*P*
Average number of concepts (SD)	5.75 (1.92)	4.65 (2.01)	.05

Nine concept categories were identified in the first round of the Delphi study (Table 2). The nine main concept categories had subcategories. The definitions of the whole essential concept categories and subcategories and their importance to be taught at high school science level were derived from the questionnaires (that are presented in Appendices 1–3).

During the validation process of the first round, eight of the nine concepts were decided to be considered NST essential concepts. The category 'prerequisite knowledge', which was mentioned by the participants, should not be considered an essential NST concept. This category included basic scientific knowledge: atoms and molecules, molecular orbitals, types of chemical bonds, waves, light, spectroscopy, the color of molecules and matter, organic and inorganic chemistry, polymers, energy and entropy, metals, semiconductors, insulators, and biomaterials. Therefore, it was

Table 2. First Delphi round: suggested NST concepts, percentage of participants (out of the overall number) who suggested each concept and the differences between the teachers and the researchers, using the chi-square test

Concept categories	Percentage of participants (%)	Teachers (%)	Researchers (%)	χ^2 *(P)*
1. Size-dependent properties	77	75	78	0.06 (.80)
2. Size and scale	61	95	31	18.7 (<.0001)
3. Fabrication approaches of nanomaterials	61	45	74	3.74 (.05)
4. Characterization methods	54	60	48	0.64 (.43)
5. Innovation and application of nanotechnology	44	45	44	0.01 (.92)
6. Classification of nanomaterials	42	60	22	6.55 (.01)
7. Functionality	7	5	9	0.23 (.64)
8. The making of nanotechnology	7	5	9	0.23 (.64)
9. Dimensionality	7	0	13	2.80 (.09)

removed from the list of concepts and was not incorporated in the round 2 questionnaire.

'Dimensionality', which was one of the subcategories of the concept 'Classification of nanomaterials', was suggested (by the external nanotechnology expert) during the validation process to be considered as an independent concept because of its great importance in NST. Table 2 presents the concepts that emerged from the first round, the consensus percentage among the participants, and the differences between teachers and researchers concerning the importance of the suggested concepts.

A significant difference was found between teachers and researchers regarding two concepts: (1) size and scale ($P < .0001$) and (2) classification of nanomaterials ($P < .05$), as presented in Table 2. Teachers considered size and scale a more essential concept for high school science than researchers did. Sixty percent of the teachers suggested the concept 'Classification of nanomaterials' as an essential concept, but only 22% of the researchers did. In addition, the concept 'Fabrication approaches of nanomaterials' was suggested by more researchers than teachers were ($P = .05$).

Round 2 Results

In the second round, participants from the different research communities rated the importance of each concept, which emerged from round one (on a 5-point Likert-type scale). In addition, they justified their rating and commented on how accurately the title and wording of the concept reflected their understanding of a specific concept. The participants commented on and suggested changes to the wording of each concept and the sub-concept names and definitions that emerged from round one. The means, variances and *t*-test results for each concept are presented in Table 3.

Eight concepts received a mean higher than 3.5, five of which were rated by the participants as very important (≥ 4), with variance ≤ 1, indicating a high level of consensus among the participants regarding the importance of these concepts; the other three concepts were rated as important ($3.5 \leq \text{mean} \leq 4$); however, the variance for two of them was higher than 1 ('Classification of nanomaterials' and 'The making of nanotechnology').

The concept 'Dimensionality' was not rated as important (mean = 3.38), but its total variance was <1; therefore, a consensus was reached regarding the unimportance of this concept. We therefore decided to exclude this concept from the list of the essential concepts and to return it to be a subcategory in the concept 'Classification of nanomaterials'.

The variances in the researchers' group were higher than those of the teachers' group for the nine concepts, indicating low homogeneity between the researchers' group. For most of the concepts, the researchers' variances are >1, whereas the teachers' variances are <1 for the nine concepts.

Only one significant difference ($t = 2.17$, $P < .05$) was found between the researchers' and teachers' groups, regarding the concept 'Functionality'. Both groups rated

Table 3. Delphi round two: means and variances of the NST concepts and a comparison between the teachers and researchers

Concepts	Total		Teachers		Researchers		
	Mean	Variance	Mean	Variance	Mean	Variance	t^a
1. Innovation and application of nanotechnology	4.67	0.33	4.76	0.19	4.57	0.46	1.08
2. Size-dependent properties	4.48	0.6	4.6	0.36	4.38	0.85	0.80
3. Characterization methods	4.36	0.53	4.38	0.45	4.33	0.63	0.21
4. Functionality	4.29	0.79	4.57	0.46	4.00	1.00	2.17*
5. Size and scale	4.22	0.56	4.19	0.46	4.24	0.69	0.20
6. Classification of nanomaterials	3.98	1.05	4.1	0.59	3.86	1.53	0.75
7. Fabrication approaches of nanomaterials	3.83	0.83	3.86	0.63	3.81	1.06	0.17
8. The making of nanotechnology	3.55	1.03	3.72	0.71	3.38	1.35	1.06
9. Dimensionality	3.38	0.88	3.29	0.61	3.48	1.16	−0.65

[a] $t < 0$ indicates that the concept's mean of the researchers is higher than the mean of the teachers' group.

*$.01 < P < .05$.

this concept as very important, but the researchers' group variance was higher than the teachers' group variance.

As a result of Delphi round 2, and according to the participants' comments and the validation stage with the NST expert, only a few of the wordings and definitions of several concepts' subcategories were removed. For example, the subcategory 'Dynamic light scattering' (DLS) technique of the concept 'Characterization method' was removed from this concept category because of the low score it received in the second round (mean = 2.93). Another change was the addition of two subcategory in the concept 'Classification of nanomaterials': 'The origin of the nanomaterial' and 'Dimensionality'.

Round 3 Results

The third-round Delphi questionnaire included the eight essential NST concepts without their subcategories, as was described before. For each concept, representative anonymous statements were included in the questionnaire. These statements, which support or reject the importance of each concept, were obtained from the participants, in the second round. The percentage of participants from Delphi round two who found each concept to be important were also presented in the questionnaire (Appendix 3).

The participants (1) rated again the importance of each concept (on a 5-point Likert-type scale, with a score of 5 representing a high degree of importance), based

Table 4. Delphi round three: means and variances of the essential NST concepts and a comparison between the teachers and researchers

Concepts	Total		Teachers		Researchers		
	Mean	Variance	Mean	Variance	Mean	Variance	t[a]
1. Size-dependent properties	4.62	0.58	4.43	0.86	4.81	0.26	−1.65
2. Innovation and application of nanotechnology	4.41	0.39	4.57	0.26	4.24	0.49	1.77
3. Size and scale	4.29	0.84	4.48	0.56	4.10	1.09	1.36
4. Characterization methods	4.1	0.77	3.91	0.79	4.29	0.71	−1.42
5. Functionality	3.72	1.04	3.62	1.05	3.81	1.06	−0.60
6. Classification of nanomaterials	3.57	0.98	3.72	0.81	3.43	1.16	0.93
7. Fabrication approaches of nanomaterials	3.5	0.70	3.62	0.45	3.38	0.95	0.92
8. The making of nanotechnology	2.88	1.33	2.76	1.29	3	1.40	−0.67

[a] $t < 0$ indicates that the concept's mean of the researchers is higher than the mean of the teachers' group.

on the premise that it should be explicitly taught, (2) justified their rating, (3) commented on ways by which the wording of the summary might be improved to reflect the essence of each idea about NST. Table 4 presents the mean, variance, and t-test value (on a 5-point Likert-type scale) for each concept.

A detailed description of the essential NST concepts, including their subcategories, are presented at the beginning of the Results section. Seven of the concepts had a mean of ≥3.5, as presented in Table 4. Four of these concepts were rated by all the participants as very important (≥4) with variance ≤1, indicating a high level of consensus. The other three concepts were rated as important (3.5 ≤ mean ≤ 4), two of which with variance <1 (Classification of nanomaterials and Fabrication approaches of nanomaterials), and the third concept 'Functionality' had variance = 1.04. An additional stage is needed to decide whether the concept 'The making of nanotechnology', which received a mean ≤3.5 and a variance >1, should be included in the list of essential concepts. This concept did not reach a consensus at this stage of the research.

A t-test was conducted to identify differences between the two research groups (research scientists and science teachers) and no significant differences were found.

Discussion

The following discussion focuses on the two research questions, respectively:

(1) *What are the essential concepts in NST that should be taught in high school science?*

Eight nanoscale science, and technology concepts that should be taught in high school science level are listed in our study. Seven were found to be essential and were reached consensus by the Delphi study experts: (1) Size-dependent properties,

(2) Innovation and application of nanotechnology (3) Size and scale, (4) Characterization methods, (5) Functionality, (6) Classification of nanomaterials, and (7) Fabrication approaches of nanomaterials. An additional concept (8), the making of nanotechnology, emerged in the study, but it did not reach a consensus concerning its importance (mean < 3.5 and variance > 1) at this stage of the study. The essential NST concepts are built from the subcategories and together provide a comprehensive mapping of NST.

When we compare the resulting NST essential concepts to other studies and projects, we can learn about the contribution of the current study to the field of NST education. The overlapping and the differences between the essential NST concepts and the NSE big ideas document (Stevens et al., 2009) are presented in Table 5.

The big ideas document of Stevens et al. (2009) was partly guided by US science education reform, which might have influenced what the authors assert as an appropriate solution for the question of NSE big ideas. Furthermore, the big ideas include many science fundamental concepts that are critical for building general science literacy and for the connection of the new field to existing US science curricula. The current research, attempted to find what are the essential concepts of NST, that high school students (grades 10–12) need to understand. We included only those concepts that are unique for NST and are not general scientific concepts. The results of the study are based on two groups of experts, the NST experts who bring with them the comprehensive understanding of the NST, and the group of the teachers who bring their expertise in teaching high school science. However, we included only the concepts that are domain-specific, namely only those that are unique for NST. For example, the ideas, structure of matter or forces and interactions (Table 5), were not considered as NST essential concepts, although they are important scientific concepts, since they are not NST domain-specific, but rather general to scientific understanding.

Huang et al. (2011) identified five main concepts of nanotechnology for elementary school science. The categories included 'nanotechnology definitions', 'nanoscale features', 'nano-phenomena in the natural world', 'nanomaterials', and 'the development of nanotechnology'. The 'nanoscale features' and 'nanotechnology definitions' concepts include the understanding of size and scale and size-dependent properties that constituted the first and the third essential NST concepts in our study. The concept 'nano-phenomena in the natural world' (Huang et al., 2011) is a subcategory of the second concept 'Innovations & applications of nanotechnology' in our study. Huang et al. (2011) included the concept of nanomaterials as a stand-alone concept that describes two nanomaterials (C60 and carbon nanotubes). In our study, this concept is included in the sixth NST essential concept 'Classification of nanomaterials'. Finally, the concept 'The development of nanotechnology' of Huang et al. (2011) is included in the eighth essential concept of our study that describes the 'making of nanotechnology'. The NST essential concepts that were framed in the current study include all the concepts suggested by Huang et al. (2011) and present a wider perception of the NST field.

Table 5. Comparison between the essential concepts of NST and the big ideas of Stevens et al. (2009)

Essential concepts	Big ideas (no. in the big idea's document)[a]
1. Size-dependent properties:	Size-dependent properties (no. 5)
• The surface-area-to-volume ratio	–
• Quantum properties	Quantum effects (no. 4)
• Optical properties	–
• *Defects*	–
2. Innovation and application of nanotechnology:	–
• Current and future applications	–
• Mimicking nature	–
• Risks and benefits of nanotechnology	Nanoscience, technology and society (no. 9)
• Tailoring nanomaterials to the application	–
3. Size and scale (includes a modern definition for scale)	Size and scale (no. 1)
4. Characterization methods:	Tools and instrumentation (no. 7)
• SPM	–
• EM	–
• Resolution	–
5. Functionality	–
6. Classification of nanomaterials:	–
• Type of nanomaterials	–
• Electrical conductivity	–
• The origin of the nanomaterial	–
• Dimensionality	–
7. Fabrication approaches of nanomaterials:	–
• Top-down vs. bottom-up	–
• Self-assembly	Self-assembly (no. 6)
8. The making of nanotechnology:	–
• Multidisciplinary science and technology	–
• Team work	–
• Development of nanotechnology	–
Prerequisite knowledge (not an essential concept)	Structure of matter (no. 2) Forces and interactions (no. 3)
How to teach the essential concepts (this section is not presented in the current paper and is not considered an essential concept)	Models and simulations (no. 8)

[a]Some of the big ideas implicitly include in their description other subcategories of the NST essential concepts.

The results of the current study provide a detailed and comprehensive evaluation of the NST field. They serve as a supporting pillar and a framework that links four areas in nanotechnology, mentioned by Wanson et al. (2009): Processing (how nanomaterials are fabricated), Nanostructure (how the structure of nanomaterials can be imaged and characterized), Properties (the resulting size-dependent and surface-related properties of nanostructured materials and devices), and Applications (how nanomaterials and nano devices can be designed and engineered for the benefit of society). The study of Wanson et al. (2009) resulted in an organizing framework for NST programs for undergraduate students. The essential NST concepts that resulted in our study provide the students with primary understanding of all four nanotechnology areas.

(2) *What are the differences in how the two different communities of experts (nanoscience researchers and science teachers) perceived the importance of these concepts?*

To study the differences between teachers and researchers concerning the suggested concepts, a chi-square test was obtained after round one of the Delphi study. Table 2 presents the concepts that emerged, the consensus percentage between the participants, and the differences between teachers and researchers concerning each suggested concept.

In the first round, this test measured the difference between the frequency at which a certain concept was suggested (and not its rate of importance) by each of the research groups. According to the Round 1 results, a significant difference was found between teachers and researchers, related to three concepts: (1) Size and scale ($P < .0001$), (2) Classification of nanomaterials ($P < .05$), and (3) Fabrication approaches of nanomaterials ($P > 0.05$), as presented in Table 2. Almost all teachers (95%) considered the size and scale concept as an important NST concept to be taught in high school, whereas only 31% of the researchers did. Teachers realize that it is not trivial for high school students to understand this concept, as reflected from the explanation of one of the teachers: 'Students have difficulties in imagining the nanometric scale, because it is abstract to them.' In contrast, the researchers 'live' in the nano dimension and therefore did not consider it to be an essential concept. However, it was found that they relied on this concept regarding their suggestions for other concepts, as a needed background.

Sixty percent of the teachers suggested the concept 'Classification of nanomaterials' as NST concept, but only 22% of the researchers did. Teachers emphasized this concept because of pedagogical and didactical reasons: it is common to use generalizations and classifications in science education (e.g. the Periodic table) as expressed in the following statement: 'It is similar to the Periodic Table, which classifies chemical elements according to their properties; this helps in teaching the general patterns in chemistry.'

Seventy-four percent of the researchers and 45% of the teachers suggested the concept 'Fabrication approaches of nanomaterials'. This difference between the two communities was almost significant ($P = 0.05$). The researchers prepare and work with nanomaterials in their labs. However, teachers hardly work or even see nanomaterials, and NST lab work is not part of the teachers' repertoire. These differences between the two communities highlight the importance of integrating the two communities of experts in the current study. Whereas the researchers actually work with nanomaterials, the teachers are concerned with pedagogical issues. The integrated results include both perspectives (Hsu & Sandford, 2007).

In the second round of the Delphi study, as represented in Table 3, one significant difference between the researchers and teachers was found concerning the importance of the concept 'Functionality' ($P < 0.05$). Both groups rated this concept as important (mean > 4), but the researchers' variance was higher than the teachers' variance, indicating heterogeneity in the researchers' group concerning the importance of the concept. In contrast, one can see the teachers' homogeneity concerning the importance of the concept. In the third round, however, no significant differences were found between the two expert groups.

The research results indicate the consensus achieved (by the Delphi study participants) regarding the nanoscale science and technology essential concepts that should be taught in high school. A consensus was obtained for seven of the eight concepts that emerged from this study (as shown in Table 4). Seven concepts had a mean of ≥3.5. Four concepts were rated by all the participants as very important (mean ≥ 4) with variance ≤1, indicating a high level of consensus for these concepts, and three concepts were rated as important (3.5 ≤ mean ≤ 4) two of which are with variance ≤1, and the third (Functionality) is with variance = 1. The eighth concept (The making of nanotechnology) did not reach a consensus at the end of the Delphi study (mean ≤ 3.5 and variance > 1). An additional step is needed to determine whether this concept should be considered in the list of the essential NST concepts that should be taught at the high school level.

Implications

Mapping the essential concepts of NST that should be taught in high school science has several educational implications: (1) the list of the essential concepts serves as a tool for analyzing existing nanotechnology programs intended for the high school level. Using this analyzing tool, one can evaluate any nanotechnology program in order to identify the missing concepts. This content analysis of educational programs will help nanoeducators become more aware of the content included in the program. (2) Including these essential concepts in a program will lead to developing a comprehensive nanotechnology educational program that will support students' understanding of the field of nanotechnology and its implications on their life. (3) Nanoeducators can join together to create a collaborative teaching environment that supports the teaching of the eight essential concepts of NST. The teaching environment can include laboratory experiment for each concept, classroom activities, and visualizations. This approach will advance the nanoeducation field.

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References

Ambrogi, P., Caselli, M., Montaltic, M., & Venturic, M. (2008). Make sense of nanochemistry and nanotechnology. *Chemistry Education Research and Practice*, *9*, 5–10.

Blonder, R. (2011). The story of nanomaterials in modern technology: An advanced course for chemistry teachers. *Journal of Chemical Education*, *88*, 49–52. doi:10.1021/ed100614f

Blonder, R., & Dinur, M. (2011). Teaching nanotechnology using student-centered pedagogy for increasing students' continuing motivation. *Journal of Nano Education*, *3*, 51–61.

Blonder, R., & Sakhnini, S. (2012). Teaching two basic nanotechnology concepts in secondary school by using a variety of teaching methods. *Chemistry Education Research and Practice*, *13*, 500–516.

Blonder, R., & Sakhnini, S. (2015). The making of nanotechnology: Exposing high-school students to behind-the-scenes of nanotechnology by inviting them to a nanotechnology conference. *Nanotechnology Reviews*, *4*(1), 103–116. doi:10.1515/ntrev-2014–0016

Bryan, L. A., Magana, A. J., & Sederberg, D. (2015). Published research on pre-college students' and teachers' nanoscale science, engineering, and technology learning. *Nanotechnology Reviews*, *4*(1), 7–32. doi:10.1515/ntrev-2014-0029

Chi, M. T. H. (1997). Quantifying qualitative analyses of verbal data: A practical guide. *The Journal of the Learning Sciences*, *6*, 271–315.

Cochran, S. W. (1983). The Delphi method: Formulating and refining group judgements. *Journal of the Human Sciences*, *2*, 111–117.

Custer, R. L., Scarcella, J. A., & Stewart, B. R. (1999). The modified Delphi technique: A rotational modification. *Journal of Vocational and Technical Education*, *15*, 1–10.

Dalkey, N. C. (1969). An experimental study of group opinion. *Futures*, *1*, 408–426.

Dalkey, N. C., & Helmer, O. (1963). An experimental application of the Delphi method to use of experts. *Management Science*, *9*, 458–467.

Delbecq, A. L., Van de Ven, A. H., & Gustafson, D. H. (1975). *Group techniques for program planning*. Glenview, IL: Scott Foreman.

Dori, Y. J., Dangur, V., Avargil, S., & Peskin, U. (2014). Assessing advanced high school and undergraduate students' thinking skills: The chemistry from the nanoscale to microelectronics module. *Journal of Chemical Education*, *91*(9), 1306–1317. doi:10.1021/ed500007s

Foley, E., & Hersam, M. (2006). Assessing the need for nanotechnology education reform in the United States. *Nanotechnology Law and Business*, *3*, 467–484.

Glaser, B., & Strauss, A. (1967). *The discovery of grounded theory: Strategies for qualitative research*. New York, NY: Aldine de Gruyter.

Hasson, F., Keeney, S., & McKenna, H. (2000). Research guidelines for the Delphi survey technique. *Journal of Advanced Nursing*, *32*, 1008–1015.

Hsu, C. C., & Sandford, A. (2007). The Delphi technique: Making sense of consensus. *Practical Assessment Research & Evaluation*, *12*(10), 1–8. Retrieved from http://pareonline.net/getvn.asp?v=12&n=10

Huang, C. Y., Hsu, L. R., & Chen, H. C. (2011). A study on the core concepts of nanotechnology for the elementary school. *Journal of National Taichung University: Mathematics, Science & Technology*, *25*, 1–22.

Jacobs, J. M. (1996). *Essential assessment criteria for physical education teacher education programs: A Delphi study* (Unpublished doctoral dissertation). West Virginia University, Morgantown.

Jones, M. G., Blonder, R., Gardner, G. E., Albe, V., Falvo, M., & Chevrier, J. (2013). Nanotechnology and nanoscale science: Educational challenges. *International Journal of Science Education*, *5*, 1490–1512. doi:10.1080/09500693.2013.771828

Jones, M. G., Gardner, G. E., Falvo, M., & Taylor, A. (2015). Precollege nanotechnology education: A different kind of thinking. *Nanotechnology Reviews*, *4*(1), 117–127. doi:10.1515/ntrev-2014-0014

Judd, R. C. (1972). Use of Delphi methods in higher education. *Technological Forecasting and Social Change*, *4*, 173–186.

Laherto, A. (2010). An analysis of the educational significance of nanoscience and nanotechnology in scientific and technological literacy. *Science Education International*, *21*, 160–175.

Lindeman, C. A. (1981). *Priorities within the health care system: A Delphi survey*. Kansas City, MO: American Nurses' Association.

Linstone, H. A., & Turoff, M. (1975). Introduction. In H. A. Linstone & M. Turoff (Eds.), *The Delphi method: Technique and applications* (pp. 3–12). Reading, MA: Addison-Wesley.

Ludwig, B. G. (1994). *Internationalizing extension: An exploration of the characteristics evident in a state university. Extension system that achieves internationalization* (Unpublished doctoral dissertation). The Ohio State University, Columbus.

Martino, J. P. (1983). *Technological forecasting for decision making*. New York, NY: North Holland.

Menaa, B. (2011). The importance of nanotechnology in biomedical sciences. *Journal of Biotechnology & Biomaterials*, *1*, article no. 105e. doi:10.4172/2155-952X.1000105e

Murray, J. W. J., & Hammons, J. O. (1995). Delphi: A versatile methodology for conducting qualitative research. *Review of Higher Education*, *18*, 423–436.

Murray, W. F., & Jarman, B. O. (1987). Predicting future trends in adult fitness using the Delphi approach. *Research Quarterly for Exercise and Sport*, *58*(2), 124–131.

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. A. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching*, *40*(7), 692–720. doi:10.1002/tea.10105

Panyala, N., Pena-Mendez, E., & Havel, J. (2009). Gold and nano-gold in medicine: Overview, toxicology and perspectives. *Journal of Applied Biomedicine*, *7*, 75–91.

Parchmann, I., & Komorek, M. (2008). The model of educational reconstruction—a research model for the investigation of students' and teachers' conceptual ideas. In B. Ralle & I. Eilks (Eds.), *Promoting successful science education—the worth of science education research* (pp. 169–181). Aachen: Shaker.

Petros, R., & DiSimone, J. (2010). Strategies in the design of nanoparticles for therapeutic applications. *Nature Reviews Drug Discovery*, *9*, 615–627.

Roco, M. C. (2001). From vision to the implementation of the U.S. national nanotechnology initiative. *Journal of Nanoparticle Research*, *3*, 5–11.

Samet, C. (2009). A capstone course in nanotechnology for chemistry majors. *Journal of Nano Education*, *1*, 15–21.

Skulmoski, J. G., Hartman, T. F., & Krahn, J. (2007). The Delphi method for graduate research. *Journal of Information Technology Education*, *6*, 1–21.

Stevens, S., Sutherland, L. M., & Krajcik, J. S. (2009). *The big ideas of nanoscale science and engineering: A guidebook for secondary teachers*. Arlington, VA: NSTA Press.

Taylor, R. E., & Judd, L. L. (1989). Delphi method applied to tourism. In S. Witt & L. Moutinho (Eds.), *Tourism marketing and management handbook* (pp. 180–186). New York, NY: Prentice Hall.

Toth, E. E., & Jackson, J. K. (2012). Pedagogical challenges for nanotechnology education: Getting science and engineering students to examine societal and ethical issues. *International Journal of Engineering Education*, *28*, 1056–1067.

Turoff, M., & Hiltz, S. R. (1995). Computer based Delphi processes. In M. Adler & E. Ziglio (Eds.), *Gazing into the Oracle: The Delphi method and its application to social policy and public health* (pp. 56–88). London: Jessica Kingsley.

Wagner, H. D. (2007). Nanocomposites: Paving the way to stronger materials. *Nature Nanotechnology*, *2*(12), 742–744.

Walters, K. A., & Bullen, H. A. (2008). Development of a nanomaterials one-week intersession course. *Journal of Chemical Education*, *85*, 1406–1409.

Wanson, S., Mason, T. O., Hershman, M. C., Drane, D., Light, G., Cormia, R. … Bodner, G. (2009). A rubric for post-secondary degree programs in nanoscience and nanotechnology. *International Journal of Engineering Education*, *25*, 615–627.

Young, S. J., & Jamieson, L. M. (2001). Delivery methodology of the Delphi: A comparison of two approaches. *Journal of Park and Recreation Administration*, *19*, 42–58.

Appendix 1. Delphi Round 1 Questionnaire

Dear (Name of scientists/teachers)

The word "nano" is becoming increasingly present in our daily life, with its ability to create materials, devices, and systems with fundamentally new properties and functions by working at the atomic, molecular, and supramolecular levels. Preparing high-school students to be nanoliterate future citizens is therefore important.

Teaching nanoscale science and technology at the high-school level is a new challenge for high-school science educators. But how can this be done? I explore this challenge in my Ph.D. thesis with my advisor Dr. Ron Blonder. We would like to find answers to the following questions:

What are the essential concepts in nanoscale science and technology that should be taught in school science and what are the best ways to teach these concepts?

I would like to base the answer to these questions on your professional knowledge, experience and opinion.

Please answer the following questions, considering high-school level science education. Please write as many details as you can, to clarify your answers. For your convenience, please fill in the following tables.
Your answers will be treated confidentially and only applied to our research.

Thank you for your cooperation,

The authors

Please give us brief information about:

Your formal background:_______________________________________

Your research: _____________

Teaching experience: ____________________________________

Possible / actual industrial applications of your research:

Suggest concepts in nanoscale science and technology that are important to be taught in high school (please use the table to provide the needed information regarding each concept).

Nano concepts that are important to be taught in school science	Explain the concept (its features, basic principles, etc.)	Why is it important to teach the concept (benefits, advantages, scientific contributions).	Suggest how to teach the proposed concept
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

Thank you for your cooperation!!!
The authors

Appendix 2. Round 2 Questionnaire

Essential nanoscale science and technology concepts that should be taught in high school science

I would like to thank you for participating in my PhD research concerning:

What "**essential nanoscale science and technology concepts**" should be taught in school science and what are the best ways to teach these ideas.

With the help of more than 40 participants, we succeeded in completing the first round of the Delphi study and assembled a list of essential concepts that should be taught in school science. In the next stage we will try to categorize them according to their importance.

Would you please rank the importance of each concept on a 5-point Likert-type scale, with a score of 5 representing the highest degree of importance.

You can also justify your rating and write your comments regarding the accuracy of the title and the definition of the theme to reflect your understanding of a specific theme.

Your answers will be treated confidentially and they will only be used in our research.

Thank you for your cooperation.

The authors

Name: __________________

Did you teach a course in nanotechnology?

Yes ____ No _____

Please write the course title and where did you give it:_______________________________

1. **Characterization methods**

Tools for observing, imaging, studying and manipulating the nanomaterial size, techniques that are available for the characterization of nanomaterials

Not important	1	2	3	4	5	Very important

a. SPM: Scanning Probe microscopy, STM- Scanning tunneling microscopy, AFM-Atomic force microscopy

Not important	1	2	3	4	5	Very important

b. EM- Electron microscopy, TEM- Transmission electron microscopy, SEM – Scanning electron microscopy

Not important	1	2	3	4	5	Very important

c. DLS: Dynamic light scattering

Not important	1	2	3	4	5	Very important

d. Nano scale resolution: Resolution as a term in science is defined as a measuring value to resolve things. It is conjugated to different area such as pictures resolution, pixels resolution, audio, etc. At the Nanoworld, resolution measures size of objects or distance of objects. In fact, it is a tool for defining whether the object is considered nano-scale or not.

Not important	1	2	3	4	5	Very important

Comments

____

1. Classification of nanomaterials

Not important	1	2	3	4	5	Very important

a. Classification of nanomaterials according to their chemical composition (carbon nanocompounds, inorganic NP, organic nanocompounds)

Not important	1	2	3	4	5	Very important

b. (semiconductors, conductors, insulators)

Not important	1	2	3	4	5	Very important

Comments

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2. Dimensionality

The number of dimensions in which a nano-structure expands beyond the 100 nm.

Not important	1	2	3	4	5	Very important

Comments

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3. Functionality

A property that is provided to a material, or for a specific area in it. This property provides the material a specific activity or bonding ability. Functionality turns nanoscience into nanotechnology.

Not important	1	2	3	4	5	Very important

Comments

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4. Size & Scale

Size is defined as the extent or amount of something. Scale is the size that is characteristic of observing, measuring of something.

Not important	1	2	3	4	5	Very important

Comments:

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5. Fabrication approaches of nanomaterials

A wide variety of options that can be used for fabrication of nanomaterials

Not important	1	2	3	4	5	Very important

a. Top down vs. Bottom up Fabrication approaches of nanomaterials

Not important	1	2	3	4	5	Very important

b. Self-assembly fabrication approach of nanomaterials *Is the leading example of bottom-up approach: The ability of molecules to arrange into ordered structures "on their own" to satisfy thermodynamics.

Not important	1	2	3	4	5	Very important

Comments

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6. Innovation & application of nanotechnology

The potential applications and innovations of nanotechnology

Not important	1	2	3	4	5	Very important

a. Current & Future applications: Innovative implementing of nanoscience and nanomaterials into current and future technologies and products for everyday use

Not important	1	2	3	4	5	Very important

b. Nature's mimics: Mimicking nature (that has devised motors, machines and surface nano-structuring based on single molecules or collections of them) for many tasks such as energy harvesting and transfer, motion, cleaning surfaces and replication.

Not important	1	2	3	4	5	Very important

c. Benefits & Risks of nanotechnology: Is nano dangerous? Understand that the benefit of being small can be also harmful for human health, environment. Socio scientific issues concerning nanotechnology

Not important	1	2	3	4	5	Very important

d. Tailoring nano-materials to the application *Constructing complicated systems (for example, due to the scale-dependent properties of the nanomaterials) to meet the need of a certain application.

Not important	1	2	3	4	5	Very important

Comments

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7. Size-dependent properties

The changes and the effects of material properties as a function of its size

Not important	1	2	3	4	5	Very important

a. Surface area to volume ratio (SA/V). When you go down to the nanoscale, the surface area to volume ratio increases dramatically, there are more atoms on the surface. This turns to be a very effective factor on a variety of materials' properties (e.g., color, catalysis, intermolecular forces effects, roughness, etc.).

Not important	1	2	3	4	5	Very important

b. Quantum properties: Unique properties based on the wave nature of the electron. These properties appear at the nanoscale.

Not important	1	2	3	4	5	Very important

c. Optical properties: Near-field is a relatively recent optics theory which explains optical properties at the nano scale. In near-field a small light source (e.g., 50nm size) is brought to a very close distance from the inspected object (few nanometers). This distance is much less than the diffraction limits and thus called Near-field.

Not important	1	2	3	4	5	Very important

d. Defects: Nanomaterial structures have a small number of atoms. So the chance to find defects in these structures is very small. That is why nanomaterials have very high mechanical properties compared to macro materials that do have defects.

Not important	1	2	3	4	5	Very important

Comments

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8. The making of nanotechnology

How is nanoscience done?

Not important	1	2	3	4	5	Very important

a. Multidisciplinary science and technology: Combining the knowledge that comes from different backgrounds and different disciplines of science and technology.

Not important	1	2	3	4	5	Very important

b. Team work: Collaboration between chemists, physics, biologists, electrical engineers and

materials engineers

Not important	1	2	3	4	5	Very important

c. Development of nanotechnology: The chronological development of nanotechnology research and applications

Not important	1	2	3	4	5	Very important

Comments

Appendix 3: Round 3 Questionnaire

Essential nanoscale science and technology concepts that should be taught in high-school science

I am appending the third and **final** round of the Delphi study regarding the question **What are the essential concepts in nanoscale science and technology that should be taught in school science?**
The questionnaire deals with the essential concepts of nanoscale science and technology. For each concept we present representative anonymous statements from the previous round that support or reject the importance of each concept. We also give the percentage of participants that found each concept to be important.

Please mark the importance of each concept on a 5-point Likert-type scale, with a score of 5 representing high degree of importance.

You can also write your comments regarding the concept and suggest any predicted difficulties while teaching each of the concepts.

Your answers will be treated confidentially and they will be used only in our research.

Thank you for your cooperation.

The authors

1. Innovation and application of nanotechnology:

The potential applications and innovations of nanotechnology

This concept includes current and future applications, how nature mimics, risks & benefits of nanotechnology, tailoring nano-materials to the application.

95% of the participants reached a consensus regarding the importance of this concept.

Representative anonymous statements:

Support the importance of the concept: "I think the applications that the students see and can relate to will be of most interest to them". "Generally, applications are important and should be discussed with relation to materials".

Reject the importance of the concept: "It is not critical to understand how the nanotechnology applications work – this should not be considered as a basic concept".

Mark the importance of the concept on a 5-point Likert-type scale, with a score of 5 representing the highest degree of importance.

	1	2	3	4	5	
Not important	○	○	○	○	○	Very important

Comments:

____

Suggest difficulties expected while teaching this concept

____

2. Size-dependent properties:

In the nanoworld, material properties change as a function of material size. This effect does not exist in the macroscopic world.

This concept includes: surface area to volume ratio (SA/V), quantum properties, optical properties, and defects.

88% of the participants reached a consensus regarding the importance of this concept.

Representative anonymous statements:

Support the importance *of the concept:* "if you want to teach nano - this is what should be taught."

Reject the importance of the concept: "low ranking was given not because these issues are not important, but in the context of high school education I think this concept is secondary in priority."

	1	2	3	4	5	
Not important	○	○	○	○	○	Very important

Comments:

Difficulties in teaching the concept:

3. Characterization methods:

Tools for observing, imaging, studying and manipulating the nanomaterial size, techniques that are available for the characterization of nanomaterials

This concept includes: Scanning probe microscopy, electron microscopy, and the aspect of resolution.

86% of the participants reached a consensus regarding the importance of this concept.

Representative anonymous statements:

Support the importance of the concept: "*At the high school level visualization is very important to drive in concepts. For this reason, I place these categories very high*".

Reject the importance of the concept: "*Apart from showing nice pictures, there is not much that can be gained from relating to these tools*".

	1	2	3	4	5	
Not important	○	○	○	○	○	Very important

Comments:

____

Difficulties in teaching the concept:

____

4. Functionality

A property that is provided to a material, or for a specific area in it. This property provides the material a specific activity or bonding ability. Functionality turns nanoscience into nanotechnology.

81% of the participants reached a consensus regarding the importance of this concept.

Representative anonymous statements:

Support the importance *of the concept:* "That's the main point - how nano is different from bulk!"

Reject the importance of the concept: "*This concept is too complicated for high school students*"

	1	2	3	4	5	
Not important	○	○	○	○	○	Very important

Comments:

____

Difficulties in teaching the concept:

____

5. Classification of nanomaterials

Suggesting different categories of nanomaterials according to (1) their chemical composition (carbon nanocompounds, inorganic NP, organic nanocompounds), (2) their electrical conductivity (semiconductors, conductors, insulators).

86% of the participants reached a consensus regarding the importance of this concept.

Representative anonymous statements:

Support the importance of the concept: "I think that the main importance is in the expressed properties of the nanoparticles"

Reject the importance of the concept: "Classification is a bit difficult since there will always be overlap between different categories."

	1	2	3	4	5	
Not important	○	○	○	○	○	Very important

Comments:

____

Difficulties in teaching the concept:

____

6. Size and Scale

Size is defined as the extent or amount of an object. Scale is the size that is characteristic of observing, measuring or manipulating of that object.

81% of the participants reached a consensus regarding the importance of this concept.

Representative anonymous statements:

Support the importance of the concept: "It is important to differentiate between macro, micro and nano scales."

Reject the importance of the concept: "This concept is very difficult for high school students."

	1	2	3	4	5	
Not important	○	○	○	○	○	Very important

Comments:

Difficulties in teaching the concept:

7. Fabrication approaches of nanomaterials :

A wide variety of options that can be used for fabrication of nanomaterials

This concept includes: Top down vs. bottom up fabrication approaches of nanomaterials, self-assembly fabrication approach of nanomaterials.

62% of the participants reached a consensus regarding the importance of this concept.

Representative anonymous statements:

Support the importance of the concept: "All (Top down, bottom up & self-assembly) are very important and above all - life is self-assembly, and they are fundamental concepts that can be described in ways that are understandable at very elementary level."

Reject the importance of the concept: "it is not necessary to deepen in teaching these concepts, because of the students' lack of scientific knowledge concerning the fabrication approaches of nanomaterials."

	1	2	3	4	5	
Not important	○	○	○	○	○	Very important

Comments:

Difficulties in teaching the concept:

8. The making of nanotechnology:

The making of nanotechnology (behind the scenes of the nanotechnology field), how is nanoscience done?

52% of the participants reached a consensus regarding the importance of this concept.

This concept includes: Multidisciplinary science and technology, team work, and the brief history of nanotechnology.

Representative anonymous statements that:

Support the importance of the concept*:* “It is important to stress to the students that doing research in nanotechnology requires knowledge in a wide range of fields, from physics and chemistry to biology. No shortcuts!”

Reject the importance of the concept: “I may be wrong, but my feeling is that some degree of scientific experience and maturity is needed to understand these things, and I am not sure it is so different than other branches of science.”

	1	2	3	4	5	
Not important	○	○	○	○	○	Very important

Comments:

Difficulties in teaching the concept: