Facilitating Primary Student Teachers' Development of Critical Thinking Through a Nanotechnology Module

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***Abstract*—This study describes an attempt about facilitating primary student teachers to develop critical thinking through the implementation of a module regarding a modern scientific topic, namely Nanotechnology. Firstly, based on literature suggestions, we outline the specific skills and dispositions that are related to critical thinking. Secondly, we emphasize the salient features of the Nanotechnology content. Scrutinizing the Nanotechnology educational material that was implemented under the lens of critical thinking skills and dispositions, we seek to identify which tasks could have potential to promote critical thinking. On the one hand, findings indicate that skills such as analysis, explanation, interpretation and dispositions such as self-confidence and inquisitiveness could be promoted. On the other hand, we discuss that the need of enhancing or developing additional skills and dispositions may enlighten the design of future implementations.**

Keywords—critical thinking skills and dispositions, nanotechnology, primary student teachers

I. Introduction

The development of critical thinking (CT) is imperative, nowadays, since people are challenged to face complex situations, taking reasonable decisions and assessing alternative solutions critically [1] [2]. Consequently, students should promote their CT in order to be capable to dispute provided claims (e.g. by authorities), consider multiple perspectives and decide in responsible manner about the significance of modern scientific and technological progress to their life [3].

Furthermore, the rapid progress of science and technology in modern fields such as nanotechnology, raises concerns about the impact they may have on the environment, health and society. Adressing such challenges requires the development of students' CT [4]. In this regard, several research proposals describing inquiry–based learning environments have been published until now, aiming at involving students in topics associated with Responsible Research and Innovation (RRI) [5] [6].

The purpose of this study is to identify the CT skills and dispositions that can be promoted during the implementation of a nanotechnology module to primary student teachers (PTs).

II. Theoretical Background

A. *Inquiry learning environment for promoting critical thinking*

The various definitions of CT include aspects such as purposeful thinking, inductive or deductive reasoning, analyzing data or arguments, formulating inferences, justifying explanations, assessing the validity and the reliability of statements, making decisions or solving problems [7] [8] [3]. Furthermore, keeping in mind that "Human beings are more than thinking machines" [9], CT is associated with the attitudes or dispositions that someone has to demonstrate in order to be a good thinker [7]. Specifically, several dispositions have been identified: truth-seeking, self-confidence, willingness to plan, inquisitiveness, flexibility, cognitive maturity, open-mindedness, etc. [7] [9]. In brief, a critical thinker integrates both skills and dispositions into addressing successfully societal challenges.

In the context of Science, Technology, Engineering, Mathematics (STEM) education, specific aspects of inquiry teaching-learning environment are perceived as promoters of CT. Generally, inquiry-based learning is a form of active learning enabling posing questions and discussing problems or scenarios to students that have to identify research issues and questions in order to develop their own knowledge or provide their own solutions. The main learning outcome of this environment is students to be able to combine scientific skills (e.g. observing, classifying, analyzing data) with knowledge, reasoning and CT [10]. For example, the inquiry problem-solving strategy involves meaningful learning through real-world problems. It begins by presenting a problem and targets to a desired solution via a small-scale research [11] . Consequently, problem solving strategy is considered an appropriate approach for improving the CT skill self-regulation [12].

In addition, it is argued that a model-based inquiry environment promotes evaluation skills as it fosters students to think about the usefuleness and credibility of models [13]. An inquiry collaborative learning environment, supported by the use of cooperative learning techniques such as the constructive controversy and the jigsaw method facilitates the development of self-confidence as well as open-mindedness dispositions, since students interact with each other within small groups, gather data, exchange divergent or similar ideas, review solutions, justify their own judgments [14] [9] [15].

B. *Nanotechnology education as a platform for the promotion of critical thinking*

Nanotechnology means, literally, any technology conducted on the nanoscale regime having profound, practical applications in the real world [16]. Although no consensus has been reached so far, the nanoscale is placed within the range of 1-100nm approximately. Within these dimensions, emphasis is being placed on the manipulation of individual atoms or molecules to extended atomic or molecular structures with submicron dimensions, in order to design and create new materials, systems and devices with novel properties for practical applications in nearly all aspects of our lives [17] [16]. These new applications, coming from the explosion of new ideas and discoveries, have the potential to form "a greener, more efficient and healthier world" [6].

The magnetic, mechanical, optical, electrical properties of the materials at the nanoscale gain major attention and speed up the progress of this field [4]. Most phenomena taking place at the nanoscale involve entities that are studied by chemistry (e.g. macromolecules) or biology (e.g. biological nanomachines such as viruses or individual cells), whose interactions are governed by physical laws. As a consequence, interdisciplinary teams of scientists and engineers are required in order advances to occur [18].

The coming era of nanotechnology has raised societal, ethical and health/safety issues. It is remarkable, that the emergence of new fields of research, creating debates concerning the risks and benefits of the new advances, is not so rare [19] [20]. In the case of nanotechnology, it is a matter in question what happens to the human body when it is infused with nanomaterials or to the environment when nanomaterials end up to natural resources such as to rivers or to lakes [16]. "Nanotechnology [..] demands not only public support but public skepticism and critical thinking as well" [20].

In the next paragraphs we pursue arguments concerning how the inclusion of nanotechnology to school curricula has the potential to promote students' CT skills. We stress how the abstractness of the nanoscale, the interdisciplinary nature of nanotechnology, the risks and benefits, emerging from this new field and the myriads of practical applications may justify the promotion of CT.

To begin with, due to the progress that has been made in the field of microscopy within the last decades, scientists and engineers has been offered the opportunity of entering the abstract nanoworld. Advanced microscopes such as Scanning Probe Microscopes (SPMs) and Electron Microscopes provide visualization to targets (viruses, molecules such as DNA, nanotubes) otherwise inaccessible [21] [22] [6] [23]. Nanoscale images created by advanced microscopes can provide some knowledge about how nanoscale entities look like. However, that kind of images can be misleading. SPM images often have artificial colors whereas some shades are added in order the object to be depicted as three dimensional as much as possible. This intrinsic imperfection of nanoimages raises some serious considerations. For example, "how do we know what is real when we see a picture of a nanoscale object?" [24]. We consider that this kind of questions can promote CT since learners need to assess the credibility of various nanoscale representations (electron microscope photographs, nanoimages, 3D models and computer stimulations) in order to form accurate mental models about the abstract world of the nanoscale. In addition, the misleading factor of nanoimages can serve as an appropriate context for someone to promote the dispositions of truth-seeking and open-mindedness, which have been acknowledged as kinds of the CT dispositions [9]. Truth-seekers should evaluate new information and evidence and an open-minded learner should be able to consider that different nanoimages could trigger divergent explanations about the same nanoscale entity.

The next kind of argument derives from the inherent interdisciplinary nature of nanotechnology. "Interdisciplinary innovation is primarily about team-work, where members of the team bring different skills and perspectives which together bring added benefit" [5]. On the one hand, nanotechnology represents a modern subject where the demarcations of the traditional fields are blurred, resulting in the collaboration of scientists. On the other hand, it has already been discussed that students can hardly become successful in their real life by learning content knowledge from isolated disciplines [25]. In this direction, it is pointed out that "Students need to develop skills in critically evaluating and integrating knowledge across a variety of fields in order to solve unique problems that arise in the ever-changing economic and global environment in which they will be pursuing their careers" [26]. Following the above consideration open-mindedness can be promoted within the interdisciplinary nature of nanotechnology, in view of multiple perspectives from a variety of fields.

Moreover, the third argument comes from the need of promoting RRI [5]. In brief, RRI takes into consideration effects and potential impacts of new technologies on the environment and society. The advent of nanotechnology raises dilemmas concerning the benefits and risks for the environment and citizens' health and safety that emerge due to the integration of nanomaterials to everyday products [6]. It is argued that the exploration of socio-scientific dilemmas fosters students to develop CT [27]. Therefore, students are challenged to overcome, open-mindedly, their personal biases, to gather, analyze and interpret data from multiple perspectives in order to make a decision whether an innovation is meaningful or becomes a menace for their life. Furthermore, we stress that RRI will offer opportunities for promoting cognitive maturity CT disposition, if concrete context-based approaches are developed, taking into consideration different opinions, ethical norms that involve multiple stakeholders and entities [9].

The last kind of argument regards research suggestions concerning factors that increase students' engagement in science. On the one hand, the introduction of a modern breakthrough conforms to this statement. On the other hand, a disguishable feature of nanotechnology is that there are myriads of applications available on the market which increase with an unprecedented rate. In particular, while in 2005, 54 nano-related products were available on the commercial market, this number was increased to 1.628 products by 2013 [6] [28]. How do the above data correlate to CT? To answer this question, we should take into account the dispositions that have been defined and are considered vital for fundamental CT [9]. We advocate that inquisitiveness is a kind of a CT disposition that can be promoted when students are introduced to modern advances as students' intellectual curiosity and desire for learning can be boosted. In this direction, a study has revealed some issues regarding why nanotechnology topics may provoke secondary students' curiosity for exploration. The novelty of this subject in combination with the plethora of applications had been defined by students themselves, being the factors that can motivate them and provoke further their inquisitiveness in order to explore the new field of Nanotechnology [29].

Until now we can hardly find any study aiming at measuring CT skills in the context of an intervention regarding a particular nanotechnology topic. However, studying published research papers relating to CT and being based on the above argumentation, we can identify relevant aspects. One study describes the implementation of a nanotechnology module about the modern application of Light-Emitting Diode (LED) by using constructivistic pedagogy [30]. Although not explicitly alluded to by authors, some evidence regarding CT can be found in this study. For example, some of the students at the beginning of the course showed reluctance to take control of their own learning and they stressed their deficiency to conduct and explain the data produced from an experiment or to pose relevant questions. On the contrary, when the implementation was completed, students emphasized that the student–centered pedagogy in combination with the modern topic of LED increased their eagerness to seek knowledge about other advances of science [30]. In addition, we should note that the vast majority of the research efforts regarding the introduction of nanotechnology to students of all grades include instructional practices that take place in an inquiry–based learning environment. Arguments are associated with the statement that inquiry–based instruction that emphasizes the role of evidence and scientific explanation can promote CT skills, being necessary for scientific inquiry [4] [31].

According to the above-mentioned discussion, we ascertain that research on how nanotechnology can be a vehicle for promoting CT to students is in its infancy. Based on this statement, in this paper we present a module that was designed and implemented for introducing concepts and phenomena of nanoscale. Within the educational materials of the nanotechnology module we seek to identify CT aspects (skills or dispositions). Specifically, we aim at answering the following question: "Which CT skills and dispositions are expected to be developed by engaging PTs in specific educational tasks concerning nanotechnology content?"

III. Research Methodology

A. The context of the research

The nanotechnology module was designed in order to educate PTs during an one-semester course. It consisted of six units with two-hour duration each including interdisciplinary concepts and phenomena that provided opportunities for identyfing relations among Science, Technology and Engineering. Specifically, PTs were introduced to the interdisciplinary concepts of: (a) size, (b) size-dependent properties, (c) tools, (d) Science-Technology-Society and (e) models [22]. Concerning the concept of size, PTs classified biological and technological objects (e.g. cells and nanopores) into macroworld, microworld and nanoworld, from largest to smallest. Moreover, they used observation tools such as optical microscopes and discussed how they contribute to the study of these three worlds. Regarding size-dependent properties, the concept of superhydrophobicity was introduced. PTs examined how the nano-sized structures of natural and technological materials (e.g. acacia leaves and nano-wood respectively) affect their wettability and their self-cleaning. Concerning Science-Technology-Society participants investigated how nature inspires scientists and engineers to create applications that solve everyday problems (biomimicry) e.g. superhydrophobic textiles. Furthermore, they explored how nanotechnology can positively contribute to the potable water shortage problem in Africa via nanofilters. Upon models PTs were introduced to the nature and role of models and to modeling practices as well. For instance, they created models of the nano-structure of the acacia leaf, they presented their own models and discussed how they concluded to the particular representations.

B. Data sources

The sources for this data analysis were six lesson plans, eight students' worksheets and a poster. The lesson plans describe in detail the teaching and learning activities e.g. teacher's questions and participants' tasks. Worksheets include motivating questions for inquiries, tasks for supporting observation, data collection and a model creation as well. The poster is about the nature and role of models and was used as a reflection tool in the modeling process and the related discussion.

C. Data Analysis

This research follows a top-down qualitative content analysis [32]. Specifically, the description of the educational tasks were analyzed and were matched to the "list of mental skills and habits of mind" that promotes CT [9].This proposal is the result of a two-year collaboration of 46 experts from different scientific fields (humanities, science, social sciences and education) who implemented the Delphi Method, under the authority of Peter Facione. More specifically, this framework-proposal was chosen as the most appropriate one because it compiles in a complete and integrated manner, both skills and dispositions, their descriptions as well as related fire-up questions that are expected to promote CT. As a result, we were able to identify the specific CT skill or disposition that was promoted by each task.

Six core CT skills and seven dispositions are suggested along with corresponding fire-up questions that ignite CT. The core CT skills comprise: interpretation, analysis, inference, evaluation, explanation and self-regulation. The dispositions include: truth-seeking, open-mindedness, analyticity, systematicity, self-confidence, inquisitiveness, cognitive maturity [9].

In order to identify the particular CT skill that is promoted within the educational material we have matched the fire up questions of CT skills listed in [9] with the description of each educational task of the nanotechnology module. In the following, we present two illustrative questions that trigger each CT skill.

- “What is the best way to characterize/categorize/classify this?” or “How can we make sense out of this (experience, feeling, statement)?” (Interpretation skill).
- “Why do you think that?” or “What is your basis to saying that?” (Analysis skill).
- “What does this evidence imply?” or “What are the consequences of doing things that way?” (Inference skill).
- “How credible is that claim?” or “How confident can we be in our conclusion, given what we now know?” (Evaluation skill).
- “How did you come in that interpretation?” or “How could you explain why this particular decision was made?” (Explanation skill).
- “Before we commit, what are we missing?” or “How good is our evidence?” (Self-Regulation skill).

We have acted in the same manner in order to identify which CT disposition is promoted through the nanotechnology module. Specifically, taking into account the detailed description of each disposition that is outlined in [33], we carefully examined the self-rating form consisted of 20 questions in order to identify correspodences between the seven CT dispositions [9] and these questions. Two illustrative questions for each CT disposition are presented below.

- “Was I courageous enough to ask tough questions about some of my longest held and most cherished beliefs?”, or “Did I back away from questions that might undercut some of my longest held and most cherished beliefs?” (Truth-seeking).
- “Have I showed tolerance toward the beliefs, ideas, or opinions of someone whom I disagreed?, or “Have I tried to find information to build up my side of an argument but not the other side?” (Open – mindedness).
- “Have I tried to think ahead and anticipate the consequences of various options?”, or, “Have I made a serious effort to be analytical about the foreseeable outcomes of my decisions?” (Analyticity).
- “Have I manipulated information to suit my own purposes?”, or “Have I organized for myself a thoughtfully systematic approach to a question or issue (Systematicity).
- “Have I approached a challenging problem with confidence that I could think it through?”, or “Instead of working through a question for myself, did I take the easy way and asked someone else for the answer?” (Self-confidence).
- “Have I read a report, newspaper or book chapter or watched the world news or a documentary just to learn something new?”, or “Did I put zero effort into learning something new until I saw the immediate utility in doing so?” (Inquisitiveness).
- “Have I showed how strong I was by being willing to honestly reconsider a decision?”, or “Have I attended to variation in circumstances, contexts, and situations in coming to a decision?” (Cognitive maturity).

D. Results

In Table I, we present the CT skills, the sub-skills and the related fire-up questions deriving from the data sources.

Several tasks were implemented in order PTs to construct two criteria for clarifying the meaning (interpretation skill) of the three worlds (macroworld, microworld and nanoworld). Our aim was PTs to classify the three worlds according to: (a) the tools used for their observation, namely unaided eye, optical microscope, electron microscope and (b) the landmark objects of each world (e.g. ant, red blood cell, DNA). We focused on the following question “What is the best way to characterize the three worlds, macroworld, microworld, nanoworld?”.

In addition, they examined data (analysis skill) from multiple sources in order to identify relations among concepts, descriptions and phenomena.

TABLE I. QUESTIONS TO FIRE-UP CRITICAL THINKING SKILLS IN THE NANOTECHNOLOGY MODULE

Critical Thinking		**Fire-up Questions**
Skills	***Sub-skills***	
Interpreta-tion	Clarify meaning Categorize	What is the best way to classify the three worlds, macroworld, microworld, nanoworld? What is the best way to characterize the three worlds, macroworld, microworld, nanoworld?
Analysis	Examine Data	Why do you think some surfaces show the super-hydrophobic property?
Inference	Draw logically justified conclusions	Purifying dirty water with nanofilter, what are the consequences to human health and economy in Africa? What does this experiment about testing different size pores imply?
Evaluation	Assess credibility	Why do you think we can accept this model as an appropriate representation of these nanoscale objects?
Explanation	State the results Justify cogent arguments	How would you explain your reasoning about your classification of macroworld, microworld, nanoworld? You have concluded that the most effective water filter should consist of nanopores. How do you explain this conclusion?
Self-regulation	Self-correction Self-monitor	Before we create our model, what are we missing? How good is my evidence in order to teach my homegroup classmates about the super-hydrophobicity of plants and materials?

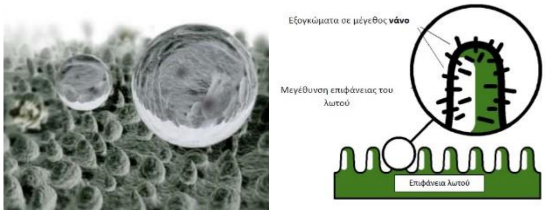

Fig. 1. Different representations of nanobumps[a].

For example, they identified the existing relation among the concept of superhydrophobicity, the nanoscale structures (nanobumps) and the self-cleaning phenomenon. Additionally, they conducted experiments observing on which materials the water forms spherical droplets and roll (cabbage leaf, nanotextile, etc.), as well as they watched videos and studied different representations of nanobumps (Fig. 1).

Furthermore PTs were assigned to query the evidence concerning how nanotechnology research and innovation have the potential to solve global social problems such as the potable water shortage (inference skill). They were motivated by watching a video, presenting this social problem in Africa, to consider health and economic impacts on Africa citizens. In this context, they experimented on alternative technical solutions about the water purification sector. For example, they tested different sized pores filters concluding that the nanofilter is the most effective.

Throughout the module, PTs were assigned to present their constructed models of objects and phenomena before the whole class. They were encouraged to participate in interactive dialogues for assessing the credibility of the constructed models. For example, they created models in order to represent nanoscale landmark objects e.g. virus and DNA. Using the fire-up question "why do you think we can accept this model as an appropriate representation of these nanoscale objects?", PTs evaluated the credibility of the models having been constructed by other groups (evaluation skill).

PTs were asked to present a poster in order to explain the criteria that they created for classifying the three worlds, macro-micro-nano. During their presentation they were triggered to explain their reasoning about the classification once more (explanation skill). Additionally, we asked them to state the results of three different experimental tasks and furthermore to justify in a persuasive manner their own conclusion (explanation skill). The intended learning was PTs to be able to explain how the nanoworld affects the macroworld. Specifically, they were engaged in inquiry learning activities in order to study the viral infection, the lotus effect and the water nano-purification. For each case, they created a model (e.g. a model of virus infection) in order to explain how the objects and the phenomena of the nanoscale affect the macroworld of scale (Fig. 2).

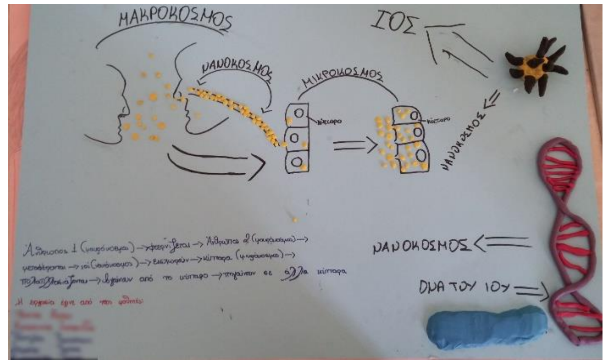

Fig. 2. A PT's model for representing how the nanoworld affects the macroworld: the viral infection case.

Concerning the self-regulation skill, we underline one of the most common learners' self-questions during the modeling practices: "before we create our model, what are we missing?".

In addition, we implemented the jigsaw inquiry collaborative method. Four expert groups as well as heterogeneous homegroups were formed [34]. Each expert group experimented with different super-hydrophobic plants and materials, sought for information and prepared their evidence in order to teach their own classmates back to homework about their expertise. During this process PTs were encouraged to think how good their evidence is.

In Table II we display the CT dispositions and the related fire-up questions in the nanotechnology module. In particular we focused on a special characteristic of the nature of nanotechnology content, namely the misleading factor of nanoimages. More specifically, having already discussed that a model represents only specific aspects of the target (e.g. size, color, property), we sought to challenge them to explore the underlying truth perspective in several modes of nanoscale depictions (truth-seeking disposition). For example, three modes of visualizations were presented for the depiction of virus and of DNA helix: computer simulation, drawing representation and a video model (Fig. 3). Raising the question "how do we know what is real when we see a picture of a virus?", PTs become encouranged to seek the "best" knowledge in the given representations. In parallel during this kind of activity we opted to evoke them to be openminded that is, to acknowledge "It is important to us to understand that divergent representations could describe the same aspect of the virus".

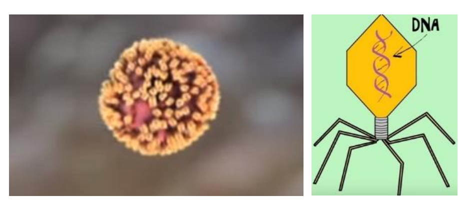

Fig.3. Visualizations of a virus and DNA[b].

[a] Retrieved from http://www.nisenet.org/catalog/lotus-leaf-effect

[b] Left visualization. retrieved from https://www.youtube.com/watch?v=Rpj0emEGShQ, Right visualization retrieved from https://www.youtube.com/watch?v=PHp6iYDi9ko

TABLE II. QUESTIONS TO FIRE- UP CRITICAL THINKING DISPOSITIONS IN THE NANOTECHNOLOGY MODULE

Dispositions	**Fire-up Questions**
Truth-seeking	Was I courageous enough to ask questions what is real when we see a picture of a virus?
Open-Mindedness	Have I showed tolerance towards the divergent representations of the virus that describe the same aspect of it?
Inquisitiveness	Have I read a newspaper article about how could athletic shoes be superhydrophobic? Have I read online sources whether there are water flasks including nanofilter that we may use in our everyday life?

We should underline that during the lotus effect and nanofilter purification tasks, PTs were engaged in real world contexts e.g. superhydrophobic t-shirts in sports. As a consequence, they became curious for nanotechnology-related applications. For example, we started a discussion about "how could athletic shoes be superhydrophobic?" or "are there water flasks including nanofilter that we may use in our everyday life?". Moreover, we presented several nanotechnology products demonstrating videos and slides. We estimate that these teaching-learning tasks could really facilitate the development of the disposition of inquisitiveness concerning nanotechnology advances.

IV. CONCLUSIONS AND FUTURE WORK

In this paper, we outlined some remarks about the subject of nanotechnology: a) the abstractness of the nanoscale, b) the interdisciplinary nature of this field c) the need to promote RRI and d) the myriads of applications. For each of the above-mentioned directions, we sought to identify which particular CT skills and dispositions could be developed through a nanotechnology module, having been implemented to PTs.

A. Direction 1: the abstractness of the nanoscale

One of the primary challenges that nanotechnology educators face when they train learners about this modern field regards the ability of inventing techniques in order to overcome the abstractness of the nanoscale. "The problem is conceptual and practical; objects and concepts at the nanoscale are hard to visualize, difficult to describe, abstract, and their relationships to the observable world can be counterintuitive" [35]. Studying the module with adherence to CT, several skills and dispositions were revealed. For example, the establishement of the two criteria (the corresponding landmark objects and the appropriate observation tools) in order PTs to develop awareness about the three worlds, led us to identify two subskills, the categorization and the clarification of the meaning of each world, that belong into the interpretation CT skill [9].

Having approached the nanoworld, we introduced one example of a counterintuitive phenomenon coming from the presence of nanoscale structures on the surface, i.e. the superhydrophobic effect. The drive-in question "Why do you think some surfaces show the superhydrophobic property?" dominated learners' inquiry, during which several hands-on experiments were conducted. Since PTs searched for relations between concepts and phenomena, we identified the analysis CT skill that could have been developed addressing this effect.

Furthermore, following research recommendations [36], another technique we implemented in order to help PTs to conceptualize the nanoworld was the use of multiple modes of representations. Drawings, computers simulations, video animations, 3D concrete models were used throughout the module. We paid attention to the identification of CT skills and dispositions, based on the crucial consideration concerning what we can learn when we study a picture of an abstract nanoscale object [24]. We discussed that a succesfull response to the above consideration promotes certain CT dispositions such as truth-seeking and open-mindedness.

B. Direction 2: the interdisciplinary nature of nanotechnology

Nanotechnology is considered a highly interdisciplinary field. Its significance is indicated by statements such as "[interdisciplinarity] is a non–negotiable ingredient of nano-education" [37].We can trace some features to our module that correspond to the interdisciplinary feature of nanotechnology. For example, landmark objects studied by biology were introduced (virus, DNA helix), concepts that derive from physics were defined (superhydrophobicity) and innovations from the field of technology were demonstrated (e.g. water filters, superhydrophobic wooden surfaces).

However, the interdisciplinary character of nanotechnology was not emphasized during the intstruction. Our main goal was to help PTs realize that the nanoworld, though its small size, may have serious effects within the macroworld we experience every day. Thus, it remains an open question how we can build on the inherent interdisciplinarity of nanotechnology to facilitate learners' CT. We plan to develop educational materials within our future implementations that will explicitly include the interdisciplinary feature of nanotechnology and seek to provide insights regarding the aforementioned consideration.

First priority in this direction could be the negotiation of the interdisciplinary content of the lotus effect that would clarify the interaction among Physics, Mathematics, Biology, Engineering and Technology. For instance, based on Physics, the phenomenon is explained through the hierarchical micro and nano-structure of the leaf's surface. Mathematics are needed in order the dimension of the invisible structures and the contact angle between droplet and the leaf's surface to be measured. Biology explains how the superhydrophobicity supports the leaf transpiration. Engineering and Technology addresses the idea of biomimicry for designing and producing applications that solve daily problems e.g. non-wetting and self-cleaning textiles[16]. Consequently, taking into account that the interdisciplinarity of nanotechnology can help students to estimate how different stakeholders (e.g. scientists and engineers) think about the same phenomenon, [9] we think that the disposition of open-mindedness could be developed.

C. Direction 3: Responsible Research and Innovation (RRI)

RRI has been established recently and is associated with the balance of risks and benefits that emerge from any new idea or discovery [5]. Having PTs participated in such RRI debates in classroom could foster their CT skills and dispositions about new fields of research.

We have not designed any task that would present to PTs the risks and at the same time the benefits of nanotechnology innovations to their health or to the environment. As a concequence, we have not researched for relevant skills and dispositions. In a similar manner towards interdisciplinarity, we raise the question "How can the perceptions of RRI, increased through the advent of nanotechnology, contribute to the promotion of the learners' CT?"

In order to answer this question, we plan to implement the Six Thinking Hats method [38]. According to this method, the color of each hat represents a different style of thinking about a particular subject. For example, the yellow hat corresponds to the benefits of the subject under inspection, whereas the black hat has to do with the difficulties, dangers and potential problems. This method has the potential to promote decision making, the understanding that more than one plausible explanations, options, risks or benefits are acceptable in some situations. Through this case, we plan to promote the PTs' cognitive maturity disposition. A particular nanotechnology topic, through which this method can be implemented could be the water nano-filters application.

D. *Direction 4: the myriads of applications*

Nanotechnology is a field whose innovations are increasing exponentially in multiple sectors, such as health, energy, electronics, transportation etc. We demonstrated those applications that are associated with learners' everyday life. We also encouraged PTs to experiment with some superhydrophobic surfaces (stone, wood, glass, fabrics) and water filters. These specific applications provided some real-world contexts. We expect that our option has the potential to develop the inference CT skill of learners, as we encouraged them constantly to elaborate on the consequences to human health and economy of the above applications (water filter). Furthermore, taking into account that the advances of science have the potential to excite PTs and capture their imagination [30], we argue that their disposition of inquisitiveness was supported.

Apart from the above four directions that relate to nanotechnology content, we should also note two features of the learning environment that can promote learners' CT. The first one relates to the model-based inquiry environment we set up for approaching the unfamiliar nanoscale objects and phenomena. Throughout the units, PTs had not only to use models as tools for obtaining information about the nanoscale phenomena and construct concrete models, but also to use them as communication tools in order to demonstrate the results of their exploration to other groups of PTs. Throughout this process, several CT skills were identified. For example, in the model construction stage, we identified the self–regulation CT skill when we encouraged learners to think about the "missing part" (Table I) before they concentrate on the specific aspect of the target which they decided to represent.

The second feature associates with the collaborative learning environment which, as having been already discussed, can foster certain CT skills and dispositions. The jigsaw method is a representative example of forming an environment in which PTs have to develop a high team spirit in order to accomplish the established learning outcomes. Supporters of this method, emphasize that the implementation of jigsaw can help learners build up their self-confidence. The latter is defined as a CT disposition [9].

All things considered, we identified all the CT skills proposed by Facione [9], while we did not trace any evidence regarding three certain kinds of dispositions: analyticity, systematicity and congnitive maturity. Analyticity is about using evidence to resolve problems. Systematicity is a kind of disposition that relates to an individual that can be organized in an inquiry, while the cognitive maturity associates with the identification that some situations have more than one plausible option [9]. It is expected that additional educational material in future implementations could promote these three dispositions. For example, in the water filter unit, we could add an alternative solution concering the water purification, namely the integration of carbon nanotubes to the filter matrix [39]. We may demonstrate that the drawbacks of the nanopores water filter (e.g. reusability) lead scientists and engineers to consider alternative solutions, such as the carbon nanotube filter. We argue that this kind of activities could help PTs to develop or enhance their cognitive maturity, as described above.

We consider that the impact of the present study on science education community is twofold: firstly, it describes a methodology about how to determine specific CT skills and dispositions within educational materials such as lesson plans, learners' worksheets and posters through an intervention. In particular, we emphasize the significance of drive-in questions that provide crucial insights concerning this direction. Moreover, the impact of this study associates with the contextualization of the particular research in a modern scientific field which already has serious effects on our everyday life, namely nanotechnology. The promotion of CT skills and dispositions in combination with the salient features of the modern content is something that can hardly be traced in other similar efforts published until now.

Our future research aims at studying whether PTs' CT skills and dispositions were really fostered through this nanotechnology module. We are going to create an instrument that will assess the extent of CT skills' and dispositions' promotion. We plan to implement some already designed instruments, such as the California Critical Thinking Disposition Inventory (CCTDI) [40], the California Critical Thinking Skills Test [41] or self-rating forms [9]. These particular instruments contain several Likert style items for estimating whether certain CT skills and dispositions were promoted. We are thinking of using some of these items with some alterations, conformed with the features of the Nanotechnology module (abstractness of the nanoscale, myriads of applications, etc.).

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