Good practice report

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Exploring fullerenes and nanotubes in the classroom

<https://doi.org/10.1515/cti-2020-0003>

Received January 29, 2020; accepted July 7, 2020

Abstract: Informing citizens about scientific issues in our highly technological world is of major importance. Toward this end, a teaching/learning sequence (TLS) focused on the nanostructures of carbon was developed and implemented in a class of secondary school students. This topic was chosen because, on the one hand, fullerenes and nanotubes are already used in a wide range of applications, and there are impressive promises for their future uses. On the other hand, from an educational point of view, students could be introduced to the important idea that some of the interesting properties at the nanoscale level are related to the structure of matter. During the development of the TLS, the fact that students would be studying extremely small-sized particles invisible to the naked eye was taken into consideration. Because of this, models and analogies were chosen as the main teaching tools to be used. In the present work, the TLS and some findings from the first implementation in the classroom are presented and discussed.

Keywords: analogies; fullerenes; high school; nanotechnology; nanotubes.

Introduction

Nanotechnology is at the cutting edge of scientific research, and while many of its applications are already a part of our daily life, its future usefulness is also promising (Pham et al., 2017). Products of nanotechnology are used in many areas, such as medicine, electronics, information systems and in the production of highly compact and self-cleaning materials (Schulenburg, 2004). While there are different interpretations of the term “nanotechnology”, the main definition on which everyone agrees is that it refers to all technologies which manipulate matter at the nanoscale level in order to design and produce new systems with new properties and functions (Roco, 1999; Ramsden, 2009). Accordingly, the term nanoscience is attributed to the scientific field which studies phenomena and materials ranging in size (at least in one dimension) from 1 to about 100 nm (Stevens et al., 2009).

Informing citizens about scientific issues in a highly technological world is of major importance. According to researchers in the field of science education who support the need to integrate aspects of nanotechnology into the educational process, the teaching of nanoscience concepts not only has a social dimension, but also has educational value since it requires an interdisciplinary approach (Laherto, 2012; Hingant & Albe, 2010). Chemistry education has to meet today’s requirements for teaching up-to-date topics like nanoscience and nanotechnology since they apply the unique properties of matter at the nanoscale to create new products and technologies (Pham et al., 2017). Researchers have proposed specific links of NST to the existing chemistry curriculum topics, such as structure and bonding, chemistry of food and atomic

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structure (Blonder & Sakhnini, 2017). Furthermore, in the chemistry education literature there are a considerable amount of papers with suggestions about educational material and teaching approaches related to the field of nanoscience and nanotechnology (Cox & Cooper, 2006; Gottfried, 2011; Haverkamp, 2009; Muniz & Oliver-Hoyo, 2014; Simpson et al., 2013; Sohlberg, 2006; Stavrou, 2018).

The above-mentioned teaching proposals are either teaching/learning sequences (TLS) that require a significant number of teaching hours, or are fragmentary and refer to a specific chemistry lesson. In addition, proposals relating to atomic structure are recommended for college or upper secondary school students. However, due to the time constraints of the school curriculum, our goal was to incorporate these topics into a chemistry course for 9th grade students, in a 4–5 h teaching, aimed at bringing today's students and tomorrow's citizens closer to some of the fundamental concepts and ideas in the field of nanotechnology. Towards this end, a TLS which focused on the nanostructures of carbon was developed and implemented in a class of secondary school students. This topic was chosen for two reasons: (a) Fullerenes and nanotubes have already been constructed and used in a wide range of applications, and scientists working in nanotechnology make impressive promises about their future uses (Basu-Dutt et al., 2012), and (b) By focusing on carbon nanostructures, students could be introduced to one of the “great ideas” of nanoscience, namely the idea that some of the interesting properties at the nanoscale level are related to the structure of matter (Stevens et al., 2009). In the present work, the TLS and some findings from its first implementation in the classroom were presented and discussed.

During the development of the TLS, the fact that students would be studying extremely small-sized particles invisible to the naked eye was taken into consideration. Because of this, models and analogies were chosen as the main teaching tools to be used. In fact, models and analogies are key features not only of science, but also of science education (Coll et al., 2005), and they are especially useful in cases where students have to study either very small or very large objects of the physical world (e.g. molecules or solar systems) (Gilbert, 2004). Furthermore, since one of our aims is to introduce students to a recent and complex scientific and technological field, we chose to use video presentations. The video had been created in the context of projects aiming to inform students about nanotechnology (Film: “Nanotechnology” – E.U. DVD in multiple languages <https://audiovisual.ec.europa.eu/en/video/I-045354>). Experts from the field of education agree “that video is best shown in short segments so as to maximize learners’ concentration” (Shephard, 2003). Thus, for purposes of the present work, parts of the video were selected and used.

The scientific content

Atoms form molecules and, in the next level of organization, they form nanoscale structures. The same atoms can be organized into various forms which interact differently with one another, resulting in materials with different properties (Stevens et al., 2009). In the present work, the geometry of the structure of the most well-known buckminsterfullerene or buckyball C₆₀ and of the single-walled carbon nanotubes are studied. The diameter of the molecule C₆₀ is 0.71 nm, and it includes 60 C atoms that are situated at the vertices of a truncated icosahedron. The C₆₀ resembles a soccer ball (Figure 1)

The structure of C₆₀ is comprised of 12 pentagonal rings and 20 hexagonal rings, and every pentagon of C₆₀ is surrounded by five hexagons. Each Carbon atom has three “neighbors”, linked by two “long” (or “single”) bonds 0.145 nm in length, and a “short” (or “double”) bond of 0.140 nm in length. There are 60 long bonds and 30 short bonds (Copley et al., 1993). The proposed teaching does not take into consideration the differentiation of the two types of bonds (i.e. “single”/“double”). Students are asked to calculate the ratio (x) of the diameter of the circumscribed sphere (D) to the edge (a) of the pentagon-hexagon of a truncated icosahedron by measuring the D and a of a soccer ball. The value of x is $4.956 \approx 5$ (<http://mathworld.wolfram.com/TruncatedIcosahedron.html>). Then, students measure the diameter $D_{C_{60}}$ of a buckyball by using an electron microscope photograph, and for purposes of their calculations, will assume that the distance a_{C-C} between two adjacent carbon atoms is $a_{C-C} = D_{C_{60}}/x$.

Figure 1: Icosahedron resembles a soccer ball.

Figure 2: The three types of nanotubes.

Nanotubes are depicted by creating cylinders from graphene sheets. Depending on the way a graphene sheet is “rolled up”, three different types of single-walled carbon nanotubes are created. These three types are called armchair, zigzag and chiral (Figure 2) (Daenen et al., 2003).

The teaching sequence

As previously mentioned, in the present work students explore the geometrical structures of both the buckyball C₆₀ fullerene and single-walled carbon nanotubes in order to realize that some of the interesting properties at the nanoscale level are related to the structure of matter. The steps of the proposed TLS follow.

Table 1: Details for the use of video.

Step	Start	End	Question/activity
Introduction	0.00.08	0.00.50	After watching the video, students were asked if they knew the term “nanotechnology”, where they had heard it, and if they would be interested in learning about it. They were also asked to express their view about the size of nanoparticles relative to a nucleus, a cell and a grain of sand.
	0.00.50	0.12.20	After watching the video, students were asked what had impressed them, and also to again express their view about the size of nanoparticles relative to a nucleus, a cell and a grain of sand, and also if they were still interested to learn about “nanotechnology”.
Step 1	0.12.20 & 0.14.05	0.13.46 & 0.14.14	After watching the video, students had to match the name of the graphite, diamond, fullerene and nanotube one by one with the corresponding model in the picture. Then, they were asked why the graphite and diamond have such different properties while both are made up of carbon atoms.
Step 2	0.12.31	0.13.51	After watching the video, a soccer ball was given to the students, and they were asked to count the number of pentagons, hexagons and carbon atoms (vertexes), and to express their view about why the fullerene is called C60.(Note: The section 0.12.31–0.13.46 of Step 1 was watched again).
Step 6	0.13.51	0.14.05	After watching the video, the students check their answers.
	0.14.05	0.14.24	After watching the video, the teacher explained that the three different ways the graphene sheets can be wrapped produce three different types of nanotubes with different electrical properties. Then, a figure (Figure 2), in which the three types of nanotubes were represented, was given to students. Finally, models of the grid of graphene sheet printed in paper were given to students and they were invited to explore the possible ways they can be “rolled up” and to match their constructions with the three types of nanotubes.
Step7	0.14.24	0.18.12	After watching the video, students discussed their impressions and possible queries.

Introduction

Aim: To introduce students to the nanotechnology framework.

Process: By watching a video, students are informed about what nanotechnology is, how scientists in the field of nanoscience work, and some products and applications of nanotechnology in everyday life. Students watch the video in parts, and a teacher-guided discussion follows each part (Table 1).

Step 1: The different forms of carbon

Aim: To inform students about the different forms (“allotropes”) of Carbon and to discuss the fact that when the same atoms are constructed into different forms, materials with different properties are created.

Process: Students watch video. Discussion follows and they have to answer questions (Table 1).

Step 2: The structure of the fullerene

Aim: To introduce students to the structure of the buckyball C60 fullerene.

Process: After watching the video (Table 1), a soccer ball (Figure 3) is given to the students, and they are asked to count the number of pentagons, hexagons and carbon atoms (vertexes).

Figure 3: The Soccer ball.

Figure 4: The four Soccer balls.

Step 3: Measurements by using models

Aim: To draw the conclusion that the ratio of the diameter to the edge of the pentagon–hexagon of different sized models (soccer balls) is the same.

Process: Students measure the diameter (D) and the edge of pentagon–hexagon (a) of four soccer balls of different size (Figure 4), and then they calculate the ratio D/a .

Figure 5: Buckyballs C60.

Figure 6: The smallest ball on a notebook.

Step 4: The length of a bond C–C

Aim: To calculate the diameter (about 0.7 nm) and the edge of a buckyball C60 (length of a carbon–carbon bond distance of about 0.14 nm).

Process: A picture that represents buckyballs C60 taken by an electron microscope is given to students (Figure 5). In the picture, a 1 nm segment is shown, making it possible for students to find the diameter D of the C60 by using a ruler and, since the ratio D/a is already known from Step 3, students can calculate the length of the edge a .

Step 5: The size of nanoparticles

Aim: To foster students' understanding of the relative size of nanoparticles in relation to observable objects of the real world.

Process: Students compare the diameter of a buckyball 60 ($D_1 = 0.7$ nm) with the diameter of a small ball ($D_2 = 4$ cm) (Figure 6). Then they have to calculate the diameter D_3 of an imaginary bigger ball, the proportionate size of which is as bigger than the small ball as the size of the small ball is bigger to a buckyball. In order to visualize the size of the imaginary big ball, students use the Google Earth application – with the city of Athens serving as the starting point – to determine a distance equal to D_3 .

Step 6: The types of carbon nanotubes

Aim: To present the characteristics of single-walled carbon nanotubes structures (i.e., armchair, zigzag and chiral) to students.

Process: After watching the video (Table 1), models of the grid of graphene sheet printed in paper are given to students (Figure 7) and they are invited to explore the possible ways they can be “rolled up”.

Step 7: Technological applications

Aim: To familiarize students with the technological applications of the fullerenes and nanotubes.

Figure 7: The grid of graphene sheet.

Process: Students watch a video to learn about the technological applications of fullerenes and nanotubes and their possible future uses (Table 1). Then, students discuss their impressions and possible queries.

In Table 1, the start and end times of the part of the video in each phase, together with the questions/activities for students are presented.

The implementation – findings

The TLS were implemented by a teacher in a class of 16 15-year-old students (9th grade), who worked in groups of four. Four hours were required for the lesson. The findings from this first implementation are presented below:

Introduction

The introductory discussion at the start of the class revealed that the term nanotechnology was known to a significant percentage (10/16) of students: They had heard about it from their family, their social environment, and the media, and they were curious to learn more. They defined nanotechnology as technology related to small objects; for example, six students stated that scientists working in this use a microscope. Some characteristic examples of the students' answers are:

“Nanotechnology relates to the microcosm, I have heard it from my uncle, who is a physicist.”

“It's about something very small, I think atoms or electrons.”

“It will be very interesting to learn about nanotechnology because scientists are working only with microscopes.”

Also, in the Introduction, the teacher elicited the students' views on the size of nanoparticles. Students stated that a nanoparticle is larger than a nucleus and smaller than a grain of sand, but they had difficulty in comparing nanoparticles with other microcosmic entities. For example, most of them (11/16) believed that a cell is smaller than a nanoparticle, and almost all of them said that nanoparticles are visible in an optical microscope. The video increased students' understanding of both the size of nanoparticles, and that they are only visible in electron microscopes. Some examples of student responses after watching the video are:

“I was impressed by the comparison that the size of a nanoparticle in relation to a grain of dust is the same as a man compared to the Himalayas.”

“The scientist tells us that he is working with an electron microscope, so nanoparticles are much smaller than a cell ... I remember seeing a cell with the school’s microscope.”

The role of the teacher in the Introduction was mainly that of moderator of the discussion, and to ask the appropriate questions at the appropriate time. In some cases, such as in the case of comparing particle sizes, he also clarified that students should write the answer to a question before the discussion started, in order to have a more accurate picture of students’ views at the end of the lesson.

Step 1: The different forms of carbon

Students were acquainted with the different forms, or allotropes, of carbon. In fact, after watching the video, all groups correctly matched the names of the forms with the corresponding models of graphite, a diamond, a fullerene and a nanotube. Also, students recognize that different properties of carbon materials are due to different structures comprised of the same atoms. Two characteristic answers to the question “Why do graphite and diamonds have different properties although both are constructed by carbon atoms?” were:

“The atoms are tied together in different way.”

“As the scientist showed students, in the diamond, atoms are bonded not only left and right, but also up and down.”

In this step, the role of the teacher was mainly to show students the selected parts of the video, and to ask the appropriate questions.

Step 2: The structure of the fullerene

The ball model has decisively helped all students understand the fullerene form, and they have all been able to find why it is called the C₆₀. In fact, by watching the video, students were informed that the fullerene structure can be represented by a soccer ball, so using the ball given to them did not make it difficult to measure the number of pentagons, hexagons and vertexes, and to logically conclude why the symbol of the fullerene is C₆₀. For example, one group of students wrote in the worksheet:

“We can count that the ball has 60 vertexes; so, the fullerene has 60 carbon atoms, thus the symbol is C₆₀”.

The teacher’s role was mainly to give instructions to students relating to the procedure.

Step 3: Measurements by using models

Using a ruler, students were able to measure the diameter (D) and the edge (a) of the four different soccer balls without difficulty. Indicatively, the measurements of one group are presented here:

1st ball: $D = 13.5$ cm, $a = 2.7$ cm [$(D/a) = 5.074 \approx 5.1$]

2nd ball: $D = 9.2$ cm, $a = 1.9$ cm [$(D/a) = 4.84 \approx 4.8$]

3rd ball: $D = 4.1$ cm, $a = 0.8$ cm [$(D/a) = 5.125 \approx 5.1$]

4th ball: $D = 3.0$ cm, $a = 0.6$ cm [$(D/a) = 5 \approx 5.0$]

During this step, a difficulty faced by the students – due to their lack of lab practice – emerged. Some students, who found small differences in the ratio (diameter of ball/edge of pentagons-hexagons) of each ball, claimed that the result was not constant, even though it was within the margin of error. It was found that the students assisted by the teacher managed to reach the desired conclusion. Therefore, in this step, the role of the teacher was to provide the materials to the students, to give instructions, and to help them to overcome the aforementioned barrier.

Step 4: The length of a bond C–C

Students used a ruler to measure the fullerene diameter, obtaining a good approximation of about 0.7 nm, and in combination with step 3, they managed to calculate with sufficient precision the length of the bonds between the atoms of C. This result seemed to impress them because they were able to “compute something that they do not see, even with an optical microscope”. It is worth noting that in the photograph given to the students, “the fullerenes have unclear boundaries”, which is why the students asked for the teacher’s help. The teacher suggested that for purposes of the experiment, the students could choose five fullerenes, measure their diameter, and calculate the mean. Thus, in this step, the teacher provided the materials, the instructions, and the necessary clarifications to the students.

Step 5: The size of nanoparticles

The students were informed by the video about some proportions in order to realize how small the objects of the nanocosm are compared to those of the macrocosm. However, in order to inquire into this relationship themselves, the activity described in step 5 was chosen. Students have to do the calculations:

$$(D_2/D_1) = (D_3/D_2) \text{ that is } (4 \times 10^{-2} \text{ m} / 7 \times 10^{-10} \text{ m}) = (D_3 / 4 \times 10^{-2} \text{ m})$$

Thus $D_3 \approx 2.3 \times 10^6 \text{ m} \approx 2300 \text{ km}$

The diameter of the ball that students had to imagine is about 2300 km. In order to visualize the size of the big ball, students used the Google Earth application. They had to determine a distance equal to D_3 , with Athens as starting point. They found that the distance D_3 is equal to the distance from Athens to Moscow. Students were surprised by the result and the analogy used helped them to “visualize” the size of the fullerene (e.g. “Wow! How small the fullerene is!!”). Specifically, students appeared to be impressed when, using the Google Earth application and the proposed analogy, they found that if the fullerenes were as large as the small ball (diameter about 4 cm), then the diameter of the small ball would be equivalent to the spatial distance between Athens to Moscow. However, the performance of mathematical operations was an obstacle for students. The teacher had to mediate, especially in cases where the result of a division was a power of ten. In this step, in addition to giving directions, the teacher helped the students to overcome the aforementioned difficulty in mathematics.

Step 6: The types of carbon nanotubes

All groups responded positively to step 6. Students found the three ways of rolling the grids, and then matched them with the three types of nanotubes. Only students in one group did not manage to find the “chiral”.

In this step, the teacher’s role was to provide the materials, instructions, explanations, and information to the students, as mentioned in Table 1.

Step 7: Technological applications

With the help of the video, the students learned about the applications of nanotubes and fullerenes. They were impressed by the prospects for future use in medicine, as well as the properties of materials made from nanotubes.

In this last step, the teacher’s role was mainly that of moderator of the discussion, and to ask the appropriate questions at the appropriate time.

Discussion

In this work, a TLS for the teaching of nanoscience and nanotechnology concepts and the findings of the implementation in a class of secondary school students are presented. The TLS does not require any special technological equipment or difficult calculations. Students are familiarized with the concepts of fullerenes and nanotubes through multimedia resources (e.g. video clips and specific images) and web applications (i.e., Google Earth). The information is presented to the students through an appropriate video, and they work “as researchers”, using simple materials. For the activities used, ideas were drawn from the referenced literature on section introduction and some activities, such as the process of measuring the distance between carbon atoms in fullerenes or the activity with the Google Earth application, designed entirely by us. As already explained in the Introduction section, what differentiates the present work is that it is designed to be incorporated in a small number of teaching hours into a chemistry course aimed to acquaint 15-year-old students with some core ideas of nanoscience, and to inform them about the achievements and prospects of nanotechnology.

The findings show that the use of analogies and models helped students to perceive the structure of the “imperceptible” nanoparticles, make calculations, and use their imagination to understand the size of these particles by making appropriate comparisons using the “perceptible” models. From the educational perspective, it is worth pointing out that with the help of the teacher and the use of the photograph from the electron microscope together with the ball model, 15-year-old students were able to calculate the length of the bond between atoms through simple measurements and analogies. In conclusion, we could argue that the lab work of students using models and analogies seems to play an important role when teachers have to teach structures of the nanocosmos. However, the use of analogies, when (even simple) mathematical calculations are required, should be accompanied by corresponding preparation of the students. From the findings relating to students’ difficulties, we could recommend that when students have to use models and make measurements and calculations, they should be informed and exercised in advance on the types of calculations they will use, as well as on simple rules of experimental measurements.

A well-prepared video presentation used together with simultaneous discussion and questioning seems to be an effective process. In fact, as reported in the findings, the way the video was used in teaching seemed helpful and helped students to approach the idea that some of the interesting properties at the nanoscale are related to the structure of matter.

There is a delay in incorporating modern scientific and technological achievements into formal education. Thus, students become aware of these achievements, usually incorrectly, from their environment or from informal learning sources. This situation was confirmed during the “introductory discussion” section of the TLS used in this study, and the findings support the view that the science curricula should incorporate concepts related to recent scientific and technological research because it is a contribution to the scientific literacy of citizens.

Conclusion

Curricula should be characterized by flexibility and by taking more aggressive and timely action to integrate new scientific and technological discoveries. For this purpose, TLSs which can be completed within a few teaching hours could be designed so that it is possible to integrate them into existing curricula. The role of Information and Communication Technologies (ICT) in such didactic efforts should be important, and help not just the students in the process of understanding and extending their scientific knowledge, but also the teacher, who finds in technology an important ally in the process of the transfer of knowledge. With the help of ICT, teachers can easily access both online educational materials and ideas in general about ways to use both simple materials and software in order to structure the corresponding TLS, as demonstrated in the present study.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: None declared.

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

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