

ORIGINAL ARTICLE

Teaching Crystal Structures using a Transparent Box with Tennis Balls

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Teaching crystal structures using a transparent box with tennis balls

Abstract

In this essay we describe how we designed and implemented a class discussion session on the concepts of crystal structure where students are required to create a wide variety of crystal structures by stacking tennis balls into a transparent box. The box enabled them to view the crystal structure from different angles to better appreciate the appearance of different facets of the crystal. With this approach, the students gained an intuitive, hands-on appreciation of the crystal structures, their geometry and their conventional cubic unit cell. This hands-on practical pedagogical experiment was carried out and repeated over two academic years, during which we surveyed the students with the aim of determining the effectiveness of this approach and identifying areas for improvement. Survey results show that this method was well received by the students and valuable feedback on areas for improvement was also gathered. Possible future extension of this teaching approach is also discussed.

INTRODUCTION

For a long time, many science educators have favoured the use of hands-on experience for students in science classes (Shulman and Tamir 1973, Shaw & Frederick, 1999; Sivertsen, 1993; Vesilind & Jones, 1996). Hands-on learning can be a powerful experience, and we know that engaging students actively and thoughtfully in their studies leads to better learning (Rutherford, 1993, p.5). According to Shapley & Luttrell (1993), science must be experienced to be understood. These vivid experiences allow students to be actively engaged as they instinctively make use of observation and exploration to learn. Hands-on learning has been shown to increase learning and increase student achievement in science content (Bredderman, 1982; Brooks, 1988; Mattheis & Nakayama, 1988; Saunders & Shepardson, 1984). In a broader sense, hands-on science can be considered to enable learning science through investigation and inquiry (Flick, 1993). There is a strong belief that students must actively manipulate and handle materials and objects as part of their science explorations (Lumpe & Oliver, 1991). In hands-on science with manipulative models, students tend to remember the materials better as they get to manipulate and handle the items

they are studying. In addition, students enjoy the learning process as they are usually much more engaged in the process of constructing knowledge by *doing* and there is a high degree of teacher-student and student-student interactions.

The study of crystal structure deals with how atoms are arranged to create the physical world around us and constitutes the core of the courses on solid state physics and crystal chemistry. Specific crystal structures such as face-centred cubic (fcc), hexagonal close-packed (hcp), simple cubic and diamond structure play a leading role in these courses. They are important in teaching fundamental concepts such as crystal geometry, symmetry and packing fractions. However, it is challenging for most students to visualise how crystal symmetry results from stacking of atoms. Different views of the 3D arrangement of the atoms often make the same structure appear differently. They have a hard time gaining a good feel for the geometry and symmetry of different faces of the same crystal structure and differences between crystal structures. Hence, in order to help the students better appreciate the symmetry and nature of these structures, researchers have developed a wide variety of models as teaching aids when it comes to the discussion of crystal structure. For examples, Claudine Betrencourt et al. (1981) introduced a method of teaching physics out of a bag of marbles. Thomas Bindel (2002) discussed the idea of using a clear plastic box to show the relationship between unit cell and the crystal lattice. Jon Eggert (2000) made use of wooden-ball models to “aid the discussion of close-packed lattices, the identification of the conventional cell in the fcc structure, and the location of the various interstitial sites.” For this project, we designed and implemented a discussion session on the concept of crystal structure, where students were required to create crystal structures by stacking tennis balls into a transparent box. In doing so, the students gained an intuitive, hands-on appreciation for the structures, their geometry and their conventional cubic unit cells. In addition, with a transparent box, they could hold up the box and view the crystal structure from different angles to better appreciate the appearance of different facets of the crystal. The hands-on practical pedagogical experiment was carried out and repeated over two academic years, during which we surveyed the students to determine the effectiveness of this approach and to identify areas for improvement. The results of the survey and analysis of its implications are discussed in detail in this article. In addition, possible future extension of this teaching approach is also discussed.

TEACHING METHOD

We introduced this teaching method in the first semester of academic year (AY) 2010/2011 and used it again in the first semester of AY2011/2012 in the module

SP2173: “Atoms and Molecules”. We were the lecturers who taught this module with about 40 first year undergraduate students from the Special Program in Science (SPS) at the Faculty of Science, NUS. This is one of the modules in the Integrated Science Curriculum in SPS that focus on the basic properties of atoms and molecules. The module covers the concept of how atoms can join together in an orderly manner to form a crystal. We developed an exercise aimed to help the students develop insight into the crystal structure and raise their interest about the materials.

Both the faced-centred cubic structure (fcc) and the hexagonal closed packed structure (hcp) are based on periodic stacking of close-packed hexagonal layers of spheres. Figure 1 provides an illustration of the different sequences of stacking of the spheres forming a fcc [Figure 1 (a)] and a hcp [Figure 1 (b)] structure. In a 3D stack, each sphere is in contact with six spheres from the two adjacent layers, three above and three below. If we denote the first two layers as A and B, there are two translational choices for the third layer, i.e. sites A or C [Figure 1 (a)]. An ABCABC... stacking leads to a cubic-close-packed (ccp) structure while an ABABAB... stacking leads to a hexagonal closed packed (hcp) structure. The cubic closed packed structure is equivalent to the faced-centred cubic structure.

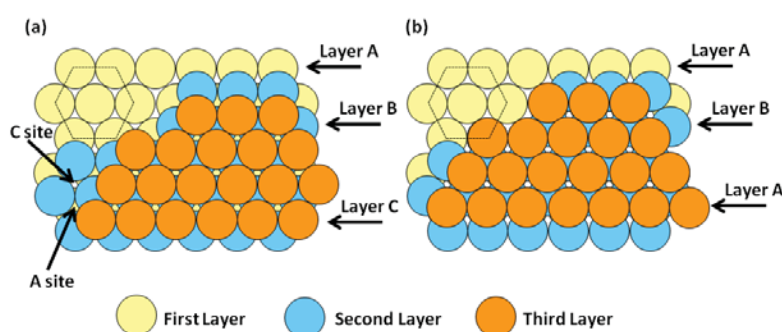


Figure 1: Schematics of the stacking of hexagonally closed packed hard spheres according to different sequences. (a) Stacking according to ABC sequence en route to a fcc structure. (b) Stacking according to ABAB sequence en route to a hcp structure.

For the class, we constructed about 12 transparent boxes out of hard perspex and provided each student with one transparent box and a normal box (made of cardboard) that contains about 80 tennis balls. During the class, the students were asked to stack tennis balls into the transparent box according to different configurations and different sequences. In this way, the students created a three dimensional (3D) ordered arrangement of the packed tennis balls forming different types of crystal structures similar to 3D arrangement of atoms in different crystal structures. Once the tennis balls were packed into the

transparent box, the students could easily hold the box up and view the crystal structure from different angles. This would reveal the symmetry of the crystal structures discussed. Figure 2 shows images of a transparent box with tennis balls stacked inside in an orderly manner forming a type of crystal structure. The structure formed is hcp in this case. The images show views of the same structure from different angles.

For the class, we repeated the exercise through 5 sessions of small group discussion: the class size for each session was typically about 10 to 12 students. The duration of each session was about 2 hours. This module was repeated for two academic years (AY2010/AY2011 and AY2011/AY2012) and we sampled feedback from 100 students over the two years. We began with a discussion of the importance of crystal structures in Physics and Chemistry. We discussed the fact that there are a wide variety of crystal structures and scientists classify them into different crystal systems. For this class, we primarily focused on the cubic crystal system where the unit cell is in the shape of a cube. This is one of the most common structures found in crystals. For the cubic system, there are three main varieties of the cubic structure. These structures are illustrated in Figure 3 below.

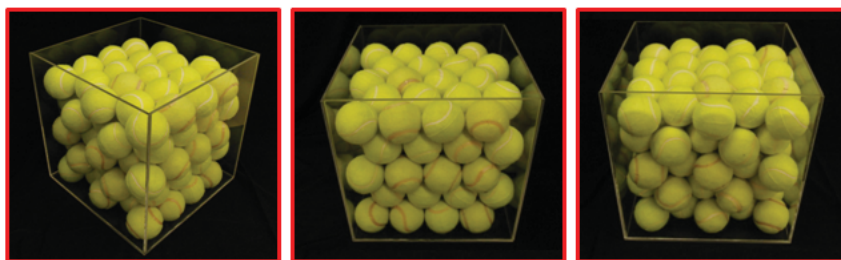


Figure 2 Image of a transparent box with tennis balls stacked inside in an orderly manner forming a type of crystal structure. The structure formed is hcp in this case.

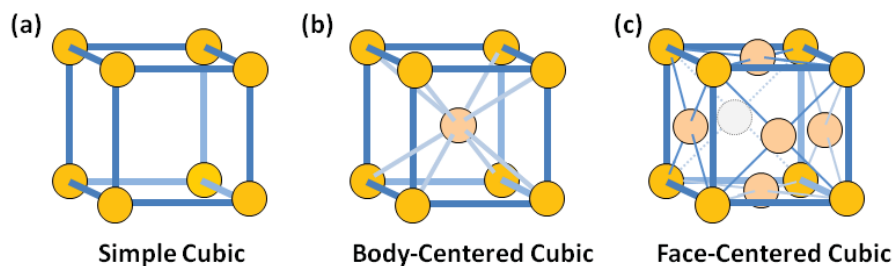


Figure 3 Illustrations of the three basic cubic structures: (a) Simple cubic structure, (b) Body-centred cubic structure and (c) Face-centred cubic structure.

After the discussion of the cubic structures, we discussed how a wide variety of complex crystal structures could be created just by stacking spheres in an orderly manner. As a first exercise, the students were asked to stack the tennis balls in the transparent box in an orderly manner but without any specific instructions. Without the benefit of specific instructions, a wide variety of structures were created. Figures 4(a)-(h) illustrate some of the structures created. Note that (a) and (e), (b) and (f), (c) and (g), (d) and (h) correspond to the same structure imaged from different angles. The students were then asked to walk around the class and examine the crystal structures created by the others. During the walk-around, the students were challenged to identify structures that were identical and structures that were different. This was a challenging task for the students as they were not yet familiar with the various structures. For structures which were identical in appearance, it was straightforward for the students to match them. On the other hand, when it was pointed out that two seemingly different structures were actually from the same crystal family, many students found it hard to believe and expressed surprise. For example, Figures 4(c) and 4(d) show two seemingly different structures but they are from the same crystal system! After the first exercise, the students began to develop some appreciation of the complexity of the crystal structures; i.e. there are many different crystal families depending on how the spheres are stacked together. Some structures belonged to the same crystal family but appeared to be different because the structure is viewed from different orientations.

After the first exercise, we went through a discussion on how different structures could be stacked together in a hexagonally close-packed manner in the different sequences as depicted in Figure 1. In the second exercise, the students were

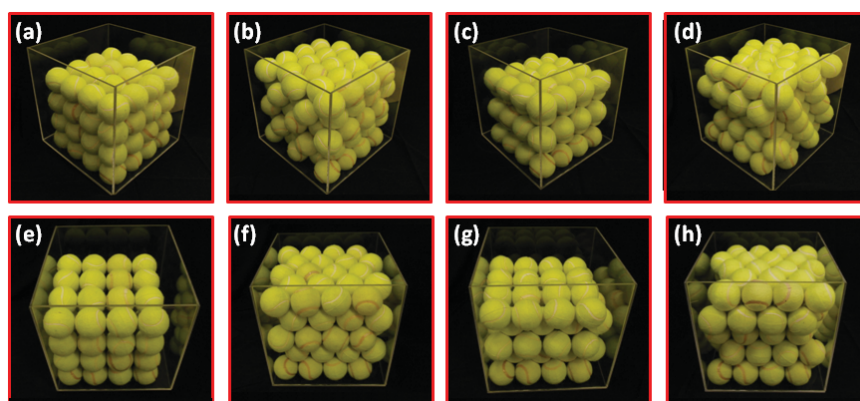


Figure 4 Images of various crystal structures created. Note that (a) and (e), (b) and (f), (c) and (g), (d) and (h) correspond to the same box of spheres but imaged from different angle.

asked to construct a structure following the ABCABC... sequence leading to a cubic closed-packed (ccp) structure as illustrated in Figure 1(a). The cubic closed-packed structure is equivalent to the faced-centred cubic structure. After this, we discussed the idea of a single unit structure of the faced-centred cubic (fcc) structure (see Figure 3(c)), which when duplicated and stacked together, could create the entire crystal. The structure which they have just created, i.e. the ccp structure, is equivalent to the fcc family. The students were then challenged to identify such a single unit structure within the crystal they have created. Identifying the unit cell was akin to a 3D puzzle and led to a lot of fun and excitement. It was not easy for the students to identify the single unit structure for a crystal such as for that in Fig 5 (a). We allowed the students to struggle with this exercise for a while before hinting to them that it is easier if one removes some tennis balls from the structure (Figures 5(b) and 5(c)). Once some tennis balls were removed, the single unit structure could be much more readily identified as shown in Fig 5(b) and 5(c). In Fig 5(c), one of the six square faces of the fcc unit was highlighted with a red square. Comparing this structure with Figure 3(c) shows that the fcc structure is tilted in the case of Figure 5(c). Successful identification of such a unit in their crystal structure was one of the “eureka” moments for the students. To wrap up this segment of the discussion, we discussed the idea of packing fraction and the students created the hcp structure following the sequence as depicted in Fig 1(b).

The beauty of a crystal structure is that different facets of a crystal can exhibit very differently ordered patterns. After we had focused our discussion by starting with a hexagonally closed-packed arrangement, in the next segment, we considered another sequence of the crystal structure, where the initial configuration of the spheres adopted a square arrangement instead of a hexagonal one. Figure 6 provides an illustration of the stacking sequence. It is important to note that, unlike the sequence shown in Figure 1, the third layer lines up with the first layer and hence the most natural way to stack the spheres up is

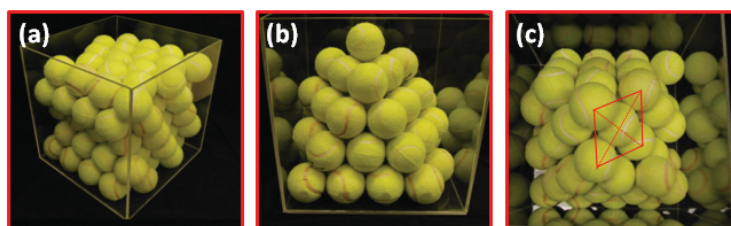


Figure 5 Images of a (a) ccp structure and (b) the same structure as (a) but with some tennis balls removed to better reveal the unit structure of the fcc system. (c) a red box was added to highlight one of the six square faces of a unit of the fcc structure.

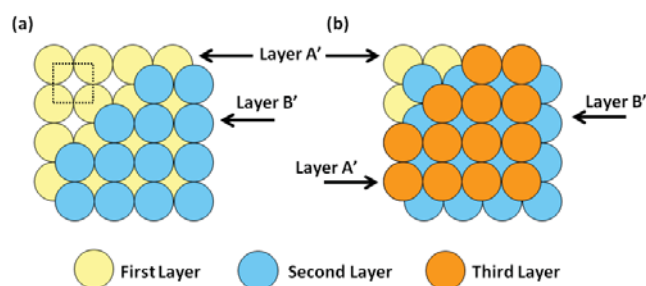


Figure 6 Schematics of the stacking of packed hard spheres in square arrangement according to A'B'A'B'

by following the A'B'A'B' sequence. In Figure 1, the third layer has a choice between the A site and the C site.

After a brief discussion of the new way of stacking the spheres, the students were asked to create this structure by following the sequence shown in Figure 6, i.e. stacking with a square base layer (A') and following the A'B'A'B' sequence. Images of the completed structures are shown in Figure 7 (a) and (b). Upon completion, the students were asked to identify the resulting crystal. We asked whether this is a (i) simple cubic structure, (ii) body-centred cubic structure or (iii) face-centred cubic structure. “Body-centred cubic structure” was the answer chosen by many students. This, in fact, turned out to be the wrong answer. Many students did not realize that they had just constructed a fcc structure and appeared surprised even after the answer was revealed. The main reason is that by grouping a single sphere with its nearest interlayer neighbors (4 spheres in the layer above and 4 spheres in the layer below), the structure does appear to be a body-centred unit, but the height of the structure is longer than the width of the structure. Hence it does not satisfy the requirement of a cubic structure. Then, we went on to identify the fcc unit structure in this crystal. As shown in Figures 7 (c) and 7 (d), we removed some of the tennis balls to better reveal the embedded fcc unit. Red boxes were added in Figure 7 (c) and (d) to highlight one of the six square faces of a unit of the fcc structure. Again, comparing Figure 7 (c) and Figure 3 (c) shows that this is indeed a fcc structure. With this, the students were convinced that they had the same fcc crystal structure! It is just that this one is oriented at a different angle. During the class, we also prepared a model of the fcc unit structure formed by tennis balls which were glued together. This unit structure was used to help the students visualise what a fcc unit structure of tennis balls look like.

The next segment of the discussion involved the construction of an even more complicated structure. Figures 8 (a)-(d) provide an illustration of the stacking

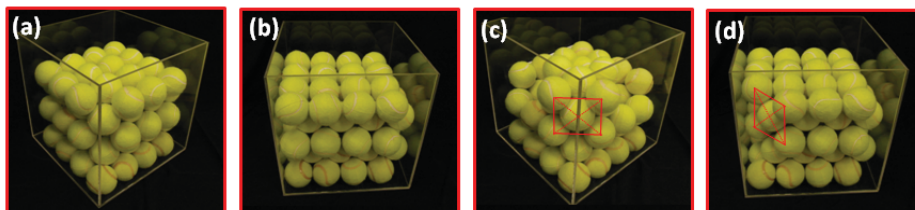


Figure 7 Images of crystal structure created according to the A'B'A'B' sequence. The red boxes added were meant to highlight one of the six square faces of a unit of the fcc structure.

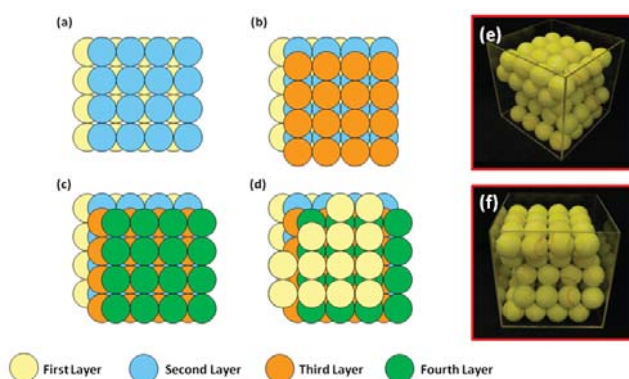


Figure 8 (a)-(d) Schematics of the stacking of packed hard spheres in square arrangement according to a variation to the A'B'A'B' sequence. (e)-(f) Images of crystal structure created according to this sequence.

sequence of this structure. It resembles the one shown in Figure 6. Here, the students followed a similar A'B'A'B'... stacking but this time with each layer intentionally shifted by a small step compared with the layer below. If the first step (i.e. during the stacking of second layer on top of the first layer) was towards the right, then the next step (i.e. during the stacking of the third layer on top of the second) must be in a downward direction and so on. This is the most complex structure to be created in this class and students found that they required additional support in the form of thin books as spacer during the construction to prevent the structure from collapsing. Images of the crystal structure created are shown in Figures 8(e) and (f). After the construction of the crystal structure, we again challenged the students to identify or guess the crystal structure they had created. Again, being unfamiliar with this structure, it was not easy for the students to guess. We went on to hint to the students that this structure was in fact similar to a structure that they are very familiar with, namely the diamond structure! This came as a surprise to the students.

In order to help the students appreciate the properties of this complex structure, we brought out commercially available ball-and-stick diamond models as shown in Figure 9. Students are familiar with these models of the diamond structure from their past experience. We made use of these models and showed the students that they could indeed identify the same sequence of ball arrangement as depicted in Figure 8 in the ball-and-stick diamond model. By orienting the diamond structure in the way as shown in Figure 9(c), we went on to identify the sequence of arrangement as depicted in Figure 8. We provided each student with one such ball-and-stick diamond model (a smaller version as shown in Figure 9(b)) so that every student could take their time to examine the diamond structure carefully. This was again another exciting moment when the students managed to see the pattern within the 3D structure. The exercise allowed students to make the connection that the tennis ball structure they had created was indeed similar to the diamond structure.

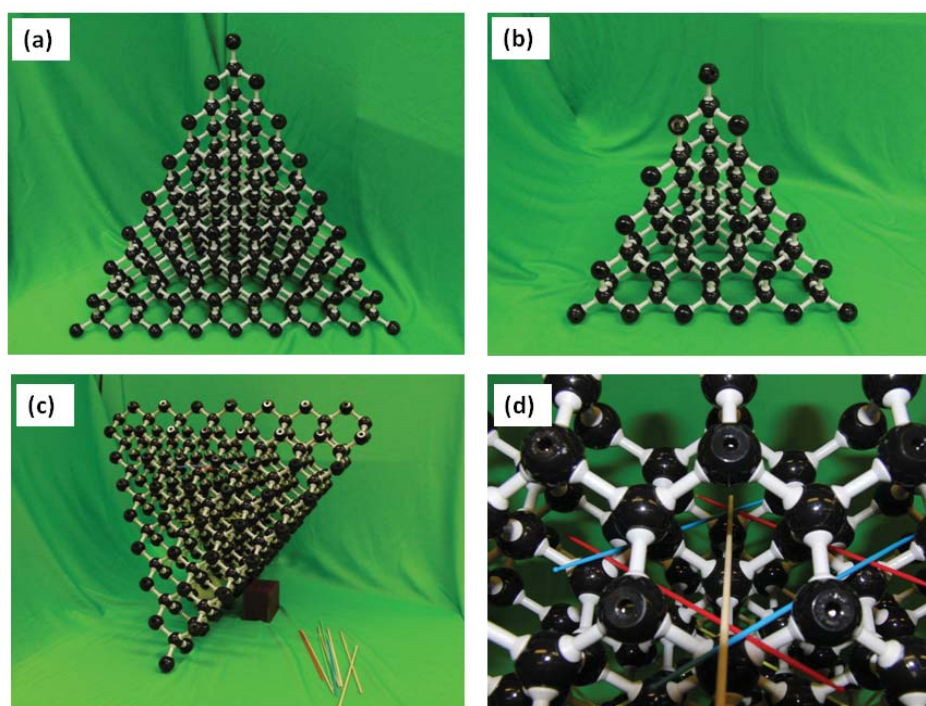


Figure 9 Ball-and-stick models depicting the diamond structure. Fig 9 (a) shows a ball and stick model of the diamond structure. Fig 9 (b) shows a smaller version of Fig 9 (a) provided to each student for examination of the structure. Fig 9 (c) shows a tilted diamond structure for identification of the students' tennis ball model as stacked in Fig 8. Fig 9 (d) shows colored sticks marking out a face of the fcc model.

One of the amazing properties of the diamond structure is that it is comprised of two interpenetrating fcc structures. In the final segment of the class, we invited the students to identify the fcc unit structure from the ball-and-stick diamond model. To identify such a structure from a complex diamond structure, we made use of colored sticks to mark one of the six faces of the fcc unit. An image of the diamond structure with the colored sticks marking one of the six faces of the fcc unit is shown in Figure 9. This was a challenging task and it took a while for the students to find their way in the complex 3D model. Once the students were successful in identifying the fcc structure, there was a happy sense of achievement.

After each class, we administered survey questions to find out how the students felt about this teaching approach. A total of 51 and 49 survey forms were completed by the students in AY2010/2011 and AY2011/2012 respectively. The response rate was >99%. Participation in the survey is voluntary and no incentive was given to the participants. The participants answered 5 structured questions, which are listed below:

1. Using a tennis ball model is an easy and effective method to help me understand the properties of crystal structures.
2. It makes the experience of learning the lattice structure vivid and accessible for everyone.
3. Constructing a 3D model is very helpful to understanding lattice structure, more so than 2D diagrams.
4. This hands-on approach is better as it requires me to become an active participant instead of a passive learner.
5. This approach stimulates my thinking and satisfies my curiosity as I can test and discover by hands-on interaction with the material.

Each question was given a 1-to-5-response scale: (1) strongly disagree, (2) disagree, (3) neither agree nor disagree, (4) agree and (5) strongly agree.

In addition, two open-ended questions were also included to allow students to share their opinions in details. They were:

- a) Should we continue with this teaching method of using tennis balls to teach crystal structures and why?
- b) What are the areas of improvement that you hope to see for this teaching method?

RESULTS AND ANALYSES OF SURVEY

Structural questions

Figure 10 shows an overview of the survey results. The values on the five sets of bar chart represent the average ratings of the five structured questions. The values labeled by the red bars and green bars are for AY10/11 and AY11/12, respectively. The numerical values are presented in Table 1 that follows. The high mean values for questions 1-5 reflect the students' overall satisfaction with the teaching method. The low variance indicates the level of consensus among the students. Comparing the two cohorts, the students' responses were similar.

Question 3 garnered the highest mean rating of 4.84 among all the questions. The students felt that being able to construct a 3D model is indeed very helpful in understanding the lattice structures. This is in contrast to the 2D diagram that they were used to in the past. Students are also in favor of the vivid learning experience where active participation is an essential component of the process.

In comparison, Question 5 received an average rating of 4.64. Though this is still a high score, it is slightly lower than for the other questions. We felt that one of the possible contributing factors is that the current format of the lesson plan is still more structured and hence the element of "discovery" may be somewhat reduced. One possible area for improvement in the future is to invite the students to invent and construct structures not covered in the class.

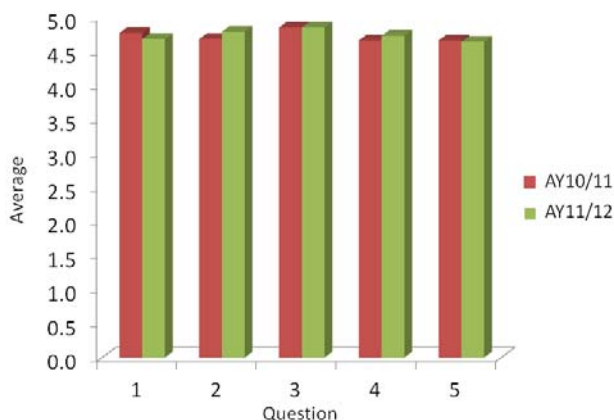


Figure 10 Bar chart representing the average ratings in response to the five structural questions collected during the survey. The values labeled by the red bars and green bars are for AY10/11 and AY11/12, respectively.

Table 1: Summary of the Survey Results. Note that a total number of 51 and 49 surveys were collected for AY10/11 and AY11/12 respectively

Survey questions	Cohort	Summary of statistics			
		Ave.	Var.	Min.	Max.
1. Using a tennis ball model is an easy and effective method to help me understand the properties of crystal structures	AY10/11	4.76	0.18	4	5
	AY11/12	4.67	0.27	3	5
2. It makes the experience of learning the lattice structure vivid and accessible for everyone.	AY10/11	4.67	0.23	4	5
	AY11/12	4.78	0.26	3	5
3. Constructing a 3D model is very helpful to understanding lattice structure, more so than 2D diagrams.	AY10/11	4.84	0.17	3	5
	AY11/12	4.84	0.18	3	5
4. This hands-on approach is better as it requires me to become an active participant instead of a passive learner.	AY10/11	4.65	0.31	3	5
	AY11/12	4.71	0.21	4	5
5. This approach stimulates my thinking and satisfies my curiosity as I can test and discover by hands-on interaction with the material.	AY10/11	4.65	0.23	4	5
	AY11/12	4.63	0.28	3	5

Open-ended Questions

On the first question: “Should we continue with this teaching method of using tennis balls to teach crystal structures and why?” we received overwhelmingly positive replies that we should continue with this teaching approach. This is attributable to the positive experience students enjoyed in this discussion session. For example, many students opined that “it is cost effective and this system caters to each individual and promotes creativity and questioning” and “it allows us to look at the structure from different angle, which is not easy to be done in 2D picture.” Consistent with the survey results from structured questions, visualisation is one of the main advantages of this teaching method. This is evident from feedback such as “this method is more interactive and visually friendly”, “as the understanding of crystal structures needs 3D understanding, using tennis ball is a very good way to see and identify the crystal structure”, “we can manipulate the balls to try out different ways and observe for fun” and “physical structures are more conducive to developing geometric intuition”. Interestingly, some of the statements on the benefits of hands-on learning appeared in the students’ feedback. One student wrote “yes experiential learning

is highly beneficial as it stimulates all our senses, which translates to a longer memory storage.” Other similar feedback statements include “yes because such active methods of learning are better at getting the confusing patterns properly integrated into memory”, “it is also more hands-on and interactive, promoting participation and probably results in better understanding” and “it engages us on a whole new level”. Other important feedback from the students read “some people learn better by hands-on exercise. It makes learning fun”, “yes because I find it impossible to fall asleep during this class”, “hands-on approach gives us the opportunity to make mistakes in the structures and thus gain a better appreciation of the structures” and “by using tennis ball, one can appreciate the knowledge as in how simple things could be used to show the beauty of nature.”

On the second question: “What are the areas of improvement that you hope to see for this teaching method?” we received a great deal of useful and valuable feedback from students on how to further improve this teaching method. We feel that implementation of these suggestions will be very helpful in future sessions of the same module. We shall organise the feedback into the following categories.

- (a) **Use balls with different sizes.** Many students repeated feedback similar to the following: *“A mixture of different balls with different sizes. This is realistic as it allows the students to develop an appreciation of the structures of compounds made up of atoms/ions with different size”, “different sizes of balls to elucidate structures with different atoms” “inclusion of ping pong balls, which can mimic the structure of different molecules”.*
- (b) **Use tennis balls with different colours.** Many students repeated feedback similar to the following: *“Use different colored tennis balls to show the unique cubic structure”, “have different colored tennis balls to mark out the edges of the cube”, “color the balls in 1/8, 1/2 or full colored to highlight the unit cell.”*
- (c) **Use coloured ball in ball-and-stick model.** Many students repeated feedback similar to the following: *“Two different colors can be used to color the atoms in the 3D diamond model to show the interpenetrating FCC structures instead of using sticks to delineate the lines”, “colored balls to act as markers to make the fcc structure in the diamond structure more obvious”.*
- (d) **Improve stability of the structures created.** *“use magnetic balls or balls with Velcro surfaces so that structure can be formed more easily”, “hope the balls could be easier to stabilize and manipulate” and “custom-made containers or containers with variable sides to hold balls in various*

configurations without the use of books to support the structure”.

- (e) **Classroom Management.** *“Can be done better with smaller groups”, “maybe have worksheets to allow us to draw out the different structure, to reinforce what we have learnt”, “maybe team discussion and building models”, “bigger crystal model (diamond) for everyone?”, “more freedom to try out different atomic structures”.*
- (f) **Addition of computer simulation.** *“use computer simulation to rotate the crystal structure freely. Sometimes it will be easier than to rotate the physical lattice”, “incorporate more 3D computer simulated graphic structure when explaining crystal structures”.*
- (g) **More structures!** *“would be great if we could see/construct orthorhombic, trigonal and triclinic structures as well”, “generalization to crystal structures other than the cubic system”.*

CONCLUSION

In summary, the implementation of this hands-on teaching method was a fruitful experience. The experience in constructing the crystal structures with the tennis balls helps to engage the hands and minds of the students. It certainly helps to link theory with the real world, increase the students’ interest in the subject and stimulate their thinking. We were pleased to observe that students were active during the class, with lots of movement, discussion and laughter throughout the 2-hour sessions. The students’ feedback was overwhelmingly positive, with the key attribute being the ability to visualise the 3D structures via this method. In addition, students’ feedback provided valuable suggestions on future improvement and extension of this teaching approach. With the addition of these improvements, additional sessions are perhaps required to cover all these topics.

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