Good practice report

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Design of a structure model set for inorganic compounds based on ping-pong balls linked with snap buttons

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Abstract: Structure model sets for inorganic compounds are generally expensive; their distribution to all students in a class is therefore usually impractical. We have therefore developed a structure model set to illustrate inorganic compounds. The set is constructed with inexpensive materials: ping-pong balls, and snap buttons. The structure model set can be used to illustrate isomerism in coordination compounds and periodic structures of ceramic perovskites. A hands-on activity using the structure model set was developed for high school students and was well-received by them. Despite the concepts being slightly advanced for them, the students' retention of the knowledge gained through the activity was tested a week after they completed the activity and was found to be relatively high, demonstrating the usefulness of the activity based on the structure model set.

Keywords: hands-on-learning; inorganic compounds; isomerism; teaching aid.

Introduction

Commercially available ball-and-stick molecular model sets are usually expensive and contain only a few balls with several holes for illustrating metal ions (Walker, 2017). Hence, distributing them to all students in an inorganic chemistry class is impractical. Three-dimensional (3D) printers are powerful tools for producing models for interpreting the structures of inorganic compounds (Chen, Lee, Flood, & Miljanić, 2014; Jones & Spencer, 2018; Lederle & Hübner, 2020); however, they are expensive and cannot be easily manipulated. We have therefore designed a structure model set that consists of inexpensive materials: ping-pong balls linked with snap buttons. This structure model set can be used to illustrate isomerism in coordination compounds and periodic structures of ceramic perovskites. Although these topics are outside the scope of high school chemistry, they are good subjects to stimulate high school students' interest in chemistry. Using the structure model set, we developed a hands-on activity for high school students to illustrate the two aforementioned topics. Although both topics were somewhat advanced for them, many of the students who participated in the activity showed a high degree of retention of the content of the activity.

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Preparation

The Supplementary material presents detailed instructions for constructing the structure model set. Although its assembly takes time, this structure model set is easy to construct. A small hole is drilled in a ping-pong ball, and a snap button is glued to the ball at the location of the hole. A weak point of the structure model set is that the snap buttons on the ping-pong balls can be peeled by wrenching of the balls. We therefore recommend that instructors bring spare parts to the activity. This model is easy to repair because of its simple design. After peeled snap buttons have been washed with a mixed solution of ethanol and water to remove dried adhesive, they can be easily re-glued to a ping-pong ball.

Activity

Instructor-directed constructions of inorganic compound structure models, including isomers of coordination compounds and periodic structures of ceramic perovskites, were performed in this hands-on activity. The activity PowerPoint slides are provided in the Supplementary material. The activity required ~50 min. The structure model set, depicted in Figure 1, was distributed to all the participants. The cost of the materials for the structural model set is around 6.8 USD. The content of the activity is described as follows. The students were required to continuously check the structure model set and the schematics of the inorganic compounds displayed on the PowerPoint slide. Details of the methods used to evaluate the instructiveness of this activity are described in the Supplementary material.

Isomerism in coordination compounds

Isomerism is defined as the phenomenon in which more than one compound possess the same chemical formula but different arrangements of atoms within their structures (Esteban, 2008). Although descriptions of isomerism of organic compounds is found in high school chemistry textbooks (Keller, 2013; Davis, Frey, Sarquis, & Sarquis, 2009), those of inorganic compounds are typically encountered by chemistry majors in their second year at university. Although isomerism of inorganic compounds is interesting (Constable & Housecroft, 2013), the concept may be advanced for high school students. At the beginning of the activity, the instructor should mention that hydrogen atoms on ammonia and ethylenediamine groups are omitted for clarity.

The square-planar platinum complex $\text{PtCl}_2(\text{NH}_3)_2$ is a representative example of *cis/trans* isomerism (Kauffman, 2013). In this context, the terms *cis* and *trans* means “on the same side” and “on opposite sides,” respectively. After introducing this terminology, the instructor constructed and demonstrated the *cis* isomer of $\text{PtCl}_2(\text{NH}_3)_2$ using the structure model set and then asked the students to model both its *cis* and *trans* isomers (Figure 2a). The *cis* isomer is known to be an effective anticancer drug.

Figure 1: Photograph of the structure model set distributed to all students. Yellow, pink, blue, and green ping-pong balls indicate platinum(II) ions, cobalt(III) ions, nitrogen atoms, and chloride ions, respectively. Blue ping-pong balls linked with a white plastic band represent an ethylenediamine (en) ligand.

Figure 2: Photographs of the structure model set showing (a) the *cis/trans* isomers of $\text{PtCl}_2(\text{NH}_3)_2$, (b) the *cis/trans* isomers of $[\text{CoCl}_2(\text{en})_2]^+$, (c) the *lambda/delta* isomers of $[\text{CoCl}_2(\text{en})_2]^+$, and (d) the *facial/meridional* isomers of $\text{CoCl}_3(\text{NH}_3)_3$.

The octahedral cobalt complex $[\text{CoCl}_2(\text{en})_2]^+\text{Cl}^-$ (en = ethylenediamine) also has *cis/trans* isomers (Kauffman, 2013), in which the Cl^- acts as a counter anion and therefore does not coordinate to the metal center. As with the platinum complex, the instructor illustrated the *cis* isomer and required the students to construct both the *cis* and *trans* isomers (Figure 2b). An actual sample of the *cis* isomer is purple, whereas that of the *trans* isomer is green. The instructor asked the students to compare their own *cis*- $[\text{CoCl}_2(\text{en})_2]^+$ models with those of neighboring students and to find the mirror image of them.

The *cis*- $[\text{CoCl}_2(\text{en})_2]^+$ isomer possesses two enantiomeric forms, *lambda* and *delta*, as depicted in Figure 2c (ChemTube 3D, *cis*- $\text{CoCl}_2(\text{en})_2$ Enantiomers, n.d.). The *lambda* and *delta* indicate left-hand and right-hand propeller twist, respectively, and they are mirror images each other (Herrero & Usón, 1995). The instructor confirmed the relation of their mirror image by using a mirror.

The octahedral cobalt complex $\text{CoCl}_3(\text{NH}_3)_3$ possesses *facial/meridional* isomers. In the *facial* configuration, three identical ligands form a face around the metal center; in the *meridional* configuration, three identical ligands and the metal center form a plane (Mohamadou & Haudrechy, 2008). After introducing this terminology, the instructor asked the students to construct both isomers and then explained the difference between them in detail (Figure 2d).

Periodic structures of ceramic perovskites and their mixed-anion derivatives

The instructor used a pre-constructed perovskite model (Figure 3a) to explain the perovskite structure (Tilley, 2016). A perovskite structure is defined as any compound that possesses the general form ABX_3 and the same crystallographic structure as calcium titanate (CaTiO_3). Each A-site ion, usually a mono- or divalent

cation, locates at six corners of the lattice and coordinates to 12 X anions. Each B -site ion, usually a transition metal, locates at the center of the lattice and coordinates to six X anions. Although the X anion is usually a divalent oxygen anion, monovalent halogen or other anions are also allowed.

Compounds with the perovskite structure are interesting from a materials science perspective because of their broad range of applications (Tilley, 2016), which include superconductors (She & Liu, 2008), electrochromic devices (Small, Wolf, & Spoerke, 2014), solar cells (Corpus-Mendoza, Moreno-Romero, & Hu, 2019), and catalysts (Nishihata et al., 2002). Recently, solar cells based on perovskites have been actively studied (Manser, Christians, & Kamat, 2016). Perovskites containing organic ammonium cations at the A site, Pb^{2+} at the B site, and halide ions at the X site exhibit high performance in solar cells (Jena, Kulkarni, & Miyasaka, 2019).

Using a pre-constructed $BaTiO_3$ structure model (Figure 3b), the instructor explained the chemical composition and structure of $BaTiO_3$ (ChemTube 3D, Barium Titanate $BaTiO_3$, n.d.). The cost of the materials for the $BaTiO_3$ model is around 36 USD. Of course, this model could be used from the outset without constructing the $CaTiO_3$ model. $BaTiO_3$ exhibits an extremely high dielectric constant and has been used as a main component of capacitors (Tilley, 2016). Likewise, the instructor showed a pre-constructed structure model of $YBa_2Cu_3O_7$ (Figure 3c). The cost of the materials for the $YBa_2Cu_3O_7$ model is around 37 USD. $YBa_2Cu_3O_7$ and related compounds exhibit superconductivity at temperatures greater than the boiling point of liquid nitrogen (Tilley, 2016). In this compound, yttrium and barium ions correspond to A -site cations, whereas copper ions correspond to the B -site cation in the ABX_3 perovskite structure (ChemTube 3D, Yttrium Barium Copper Oxide $YBa_2Cu_3O_7$, n.d.). Interestingly, the amount of oxygen anions is substantially less than expected on the basis of the general formula ABX_3 . This discharge is referred to as oxygen deficiency and is closely related to the superconducting properties of the compound (Tilley, 2016). The instructor also explained another cutting-edge topic using the $BaTiO_3$ model. $BaTiO_3$ can be transformed into the mixed-anion perovskite compound $BaTiO_{3-y}N_{2y/3}$ (Figure 3d) via topochemical reactions (Kobayashi et al., 2017). Mixed-anion compounds are solid-state materials with more than one anionic species in a single phase (Kageyama et al., 2018, 2019). The term “topochemical reaction” is defined as a solid-state reaction in which the structure of the resulting product is governed by that of the starting material (Kageyama et al., 2018, 2019). The mixed-anion compound $BaTiO_{3-y}N_{2y/3}$ catalyzes the synthesis of ammonia from nitrogen and hydrogen gases at high temperature and pressure. That is, chemists can tune the properties of perovskite compounds as desired by tailoring their compositions (Kageyama et al., 2018, 2019).

Figure 3: Photographs of the structure model set showing (a) a representative perovskite, $CaTiO_3$, (b) a high dielectric constant capacitor material, $BaTiO_3$, (c) an ammonia synthesis catalyst, $BaTiO_{3-y}N_{2y/3}$, and (d) a high-temperature superconductor, $YBa_2Cu_3O_7$. Large blue (or clear), light-blue, and pink balls indicate calcium, barium, and yttrium ions, respectively. Green, orange, yellow, and blue ping-pong balls indicate titanium ions, oxygen anions, copper ions, and nitrogen anions, respectively.

Crystal structure models specializing in inorganic compounds are commercially available (ICE Online Store, n.d.); however, these are not suitable for illustrating the topochemical reactions because the constituent elements are difficult to remove. In addition, these commercially available structural models are somewhat expensive for teachers to use. For example, the SOLID-STATE MODEL KIT and POLYHEDRAL MODEL KIT are very good structural models (ICE Online Store, n.d.); however, at 148 and 128 USD, respectively, they are very expensive. These models can represent several crystal structures. Moreover, our structural model contains ping-pong balls and snap buttons, whose fabrication is time consuming. Hence, these models cannot be simply compared. However, the commercial models are several times more expensive than our model.

A cost-effective crystal structure model comprising ping-pong balls and Dual Lock™ adhesive tape has been reported (Elsworth, Li, & Ten, 2017). This model specializes in illustrating the unit cell of the crystal structures; however, unlike in our model, it is difficult to illustrate the periodic structures. Specialized 3D printed ball-and-stick models for large molecules (Paukstelis, 2018) and laser-cut models have been reported for representing molecular geometry (Dean, Ewan, Braden, & McIndoe, 2019). Both are excellent teaching aids that can be made of inexpensive materials. In the future, if 3D printers and laser cutters become commonplace in schools many useful teaching materials will be reported.

Instructiveness of the activity

Activities using handmade teaching aids are popular among high school students (Lenzer, Smarsly, & Graulich, 2019; Ma, Yang, Wang, Wang, & Tian, 2020). This hands-on activity using a structure model based on ping-pong balls with snap buttons was conducted as an extracurricular lecture in four high schools. The participants were 51 second-year students, and they favorably received this activity (Table S2 in Supplementary material). From the results of the worksheet completed by students during the activity and the comprehension test one week after the activity, we evaluated the activity's instructiveness. The participants generally showed a high level of understanding. One week after the activity, the students' retention of their learning was higher for the isomer content than for the perovskite content. We speculatively attributed this difference to the students learning about the isomers by building structure models themselves but learning about the perovskites by observing structure models the instructor had built in advance. We concluded that the hands-on activity contributed to memory consolidation.

This activity was modified for non-chemistry-major undergraduates without any major changes. The participants viewed the activity favorably and well understood its content. Preliminary data are presented in the Supplementary material.

Hazards

None of the materials used in the activity are hazardous.

Summary

Slightly advanced topics or descriptions of cutting-edge research are popular themes in high school extracurricular lectures but are rarely addressed by high school teachers in their regular lectures (Horikoshi, 2021; Horikoshi, Takeiri, Mikita, Kobayashi, & Kageyama, 2017). The structure model set described herein provided students with an opportunity to understand somewhat advanced topics: isomerism in transition metal complexes and periodic structures of ceramic perovskites. Handmade teaching aids are still highly instructive and will continue to be developed.

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