Review article

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Teaching chemistry with LEGO® bricks

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Abstract: Teachers are developing unique teaching aids to attract students to the field of chemistry. Ideal teaching aids are tools that students can enjoy utilizing, reutilizing, and which can be constructed without employing special tools. LEGO®-based teaching aids satisfy all these requirements. Chemistry teachers have employed bricks to illustrate basic chemical concepts. Moreover, LEGO-based chemistry teaching aids have been vigorously reported by Campbell and coworkers since the late 1990s and are still being persistently reported by several groups. The focus of this review is the applications of LEGO bricks in teaching chemistry. This review describes LEGO-based teaching aids that are easily constructed and may be beneficial to readers, in terms of creating new teaching aids. Since LEGO bricks possess varieties of shapes and colors, they can be employed to design various teaching aids, including periodic tables, molecular models, polymer structure models, and frameworks for handmade measuring instruments. The polymeric structure models are generally difficult to build with typical ball-and-stick type molecular models; however, they can be easily built, employing LEGO bricks. The bricks are suitable for the construction of handmade measuring instruments because of their versatility and computer interface, as well as their non-requirement of special tools.

Keywords: hands-on-learning; LEGO brick; teaching aid.

Introduction

LEGO® bricks are an interlocking building plastic-block toys that originated in Denmark and are extensively desired globally. The Danish words “leg godt,” meaning “play well,” are the origin of its name (Lipkowitz, 2018). Additionally, the word “LEGO” means “I put together” in Latin (Lauwaert, 2008). LEGO bricks and LEGO-based models have been employed as teaching aids across a wide range of education fields, from early childhood education to computer programming (The LEGO® Education Community is Live!, n.d.). There are lots of reasons to consider applying the bricks for educational purposes. Moreover, since they possess varieties of shapes and colors, they can be employed to build various models. Each brick is sturdy and elaborate, rendering it safe to utilize. LEGO bricks are resistant to detergents and ethanol, so their surfaces can be disinfected. Depending on the type of parts, they are relatively inexpensive and can be distributed to all the students in a classroom. LEGO teaching aids can entertain students and revitalize classrooms. Many students may have already played with the bricks or other interlocking building bricks in their childhood and are, therefore, familiar with them.

In chemical education, LEGO bricks and models have been utilized as teaching aids to illustrate chemical structures and reactions, as well as to construct handmade instruments (Campbell, Miller, Bannon, & Obermaier, 2011). Since each brick can represent an atom, an ion, or a molecule, linking them together can represent molecular, crystal, and polymeric structures. Further, since the bricks can be easily connected and

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disconnected, brick-based molecular models can be used to represent chemical compositions and reactions. Repeated structures and chemical reactions are generally challenging to demonstrate with typical ball-and-stick molecular model kits because of their expensiveness and frangibility. Although durable molecular model kits are recently available, they are generally expensive. LEGO-based models can be employed as frameworks for handmade measuring instruments to illustrate their mechanisms. Allowing students to build their own measuring instruments affords them the opportunity to understand the fundamental physical principles underlying the measuring instruments. By employing LEGO bricks, the frameworks of measuring instruments can be built without utilizing tools, nails, or adhesives. Thus, assembling LEGO-based measuring instruments can be practiced in a typical classroom or chemistry laboratory. Another attractive feature of LEGO-based teaching aid is that they can be disconnected and reused subsequently, implying that their utilization is economical. When combined with LEGO Mindstorms®, LEGO models can be driven by computer programming, allowing the assembling of more complex measuring instruments.

This review describes the utilization of LEGO bricks, as teaching aids, in chemical education, in four sections, according to their applications. The first section describes the construction of a periodic table with the bricks, and illustrates basic chemical concepts, including a wide range of teaching aids for high school to university students, with the LEGO models. The second section presents the LEGO models of polymer structures, including polyethylene, polydimethylsiloxane, polysaccharides, and deoxyribonucleic acid (DNA). Because the typical ball-and-stick-type molecular models are better at illustrating detailed structures of molecules than the LEGO models, the author omitted the descriptions of the LEGO models to explain only the structure of discrete molecular models in this review. Further, the third section describes the illustrations of chemical reactions, including chemical equilibria, kinetics, and homogeneous catalytic reactions, with the bricks. The last section introduces the constructions of handmade instruments with LEGO bricks. Moreover, some visible-wavelength spectrophotometers and simple components have been constructed with LEGO bricks for education purposes. Students can easily work with these instruments and understand the important points in their designs.

Furthermore, this review describes LEGO-based teaching aids that can be readily assembled and utilized by readers to create new teaching aids. Some investigations by Campbell and coworkers, such as the illustrations of the crystal structure and physical properties of materials, with LEGO bricks were omitted because they have already been compiled on their excellent web page (Exploring the Nanoworld with LEGO® Bricks, 2008). LEGO bricks consist of many kinds of components that can be purchased worldwide. Resultantly, teachers and students can build the LEGO models described in references. The author has reproduced and validated several brick models, which have been reported by several groups. For detailed instructions on the building of the brick models, please refer to the original papers and their supporting information.

Illustrations of basic chemical concepts with LEGO models

For 21st-century students who can search and watch anything on Wikipedia and YouTube, respectively, chemistry classes should be offered as much as possible with unique teaching aids. Chemistry teachers regularly develop teaching aids to attract students' interest. It is fun work, although it is challenging. LEGO bricks and the previous reports presented here may help teachers to develop new teaching aids.

Periodic table of elements

The essence of chemistry is packed in the periodic table. Employing the LEGO bricks to build a fun periodic table will spur the students' interest in chemistry significantly. Kuntzleman and coworkers reported a very enjoyable outreach activity in which students built a periodic table of the 114 elements using over 6000 pieces

of LEGO bricks (Kuntzleman et al., 2013). The symbol of each element was lined on a 16 stud $\times$ 16 stud LEGO square plate, which were color-coded (red for the alkali metals and green for the halogens). Since the bricks were angular, it was challenging to draw round element symbols, like “Be,” with them. However, they solved that challenge by creating the 16 stud $\times$ 16 stud square plate. The LEGO-designed periodic table served as a basis for many topics regarding elements. According to their report, the author constructed plates for the symbols of three elements, corresponding to the initials of the abbreviation of my university, Osaka Sangyo University (OSU) (Figure 1). Each plate was significant, hence the periodic table of 114 of them must have been overwhelming.

Figure 1: Plates for the symbols of three elements, O, S, and U.

Three states of matter

A wide range of chemical topics, for upper secondary (age group 14–18 years) to freshman/sophomore (age group 18–20) have been explained by the LEGO brick models. The three states of matter could be illustrated by a simple combination of LEGO bricks (Geyer, 2017), namely several 1 $\times$ 1 round plates and a 6 $\times$ 10 plate. Figures 2a–c shows the solid, liquid, and gaseous states of matter, respectively. The round plates represent the particles while also considering the ease of removing them from the large plate. The LEGO model is simple and readily comprehensible, rendering it is an excellent teaching aid.

Figure 2: Brick models illustrating the three states of matter: (a) solid, (b) liquid, and (c) gaseous states.

Density

Density, a topic closely related to chemistry, is also introduced to students, utilizing the LEGO bricks (Kuntzleman, 2015). The model includes 17% brine, 2-propanol, a LEGO minifig, four 1 $\times$ 2 yellow brick pieces, and four LEGO models, which were constructed with 1 $\times$ 2 blue bricks and a 1 $\times$ 2 blue plate, are placed in a clear bottle, shaken well, and allowed to stand. Thereafter, the minifig and four 1 $\times$ 2 yellow brick pieces floated in brine while the four blue LEGO models floated in 2-propanol (Figure 3). The LEGO pieces, which were manufactured from acrylonitrile butadiene styrene (ABS), floated in 17% brine and sank in 2-propanol. The difference between the LEGO pieces that floated in brine and the LEGO models that floated in 2-propanol is caused by the entrapment of air by the LEGO models. A typical 500 mL plastic bottle possesses a small

opening (inside diameter *ca.* 22 mm) and cannot hold the LEGO minifigs with a large headgear. Weight was attached to the legs of the minifig so that its head faced upward in the water. However, teachers should handle carefully because 2-propanol is a toxic, flammable compound with odor.

Figure 3: Density experiment: (a) immediately after shaking, (b) after allowing to stand for 10 min, and (c) after allowing it to stand for 20 min.

Coulomb force

The Coulomb force, one of the essential knowledge in learning chemistry, was visualized by an instrument, which was assembled with the LEGO bricks (Hendrix & Prilliman, 2018). The frame for fixing the magnets and measuring instrument was constructed with the bricks. The bricks could be utilized to build robust frames that could resist magnetic repulsions. Additionally, the bricks were nonmagnetic and were, therefore, an optimum frame for measuring the force between magnets.

Molecular mass

Hudson, Katz, and their coworkers reported activity for teaching green chemistry in which the molecular mass of the H_2SO_4 molecule was illustrated by assembling LEGO plates (Hudson et al., 2016). The hydrogen, oxygen, and sulfur atoms were represented by two 1×1 white plates, four 4×4 red plates, and one 4×8 yellow plate, respectively. The number of studs in each plate corresponded to the atomic weight, i.e., $\text{H} = 1$, $\text{O} = 16$, and $\text{S} = 32$. The two 1×1 white plates were staked on two of the four 4×4 red plates, and the four 4×4 red plates were stacked on the 4×8 yellow plate to represent the molecular mass of the H_2SO_4 molecule (Figure 4). In the original paper, 1×1 bricks rather than 1×1 plates were employed to illustrate the hydrogen atoms because students may easily sustain injuries when a small plate, attached to another, is removed. Teachers are required to design LEGO, based on the teaching needs while also considering safety.

Figure 4: Brick model to illustrate the molecular mass of H_2SO_4 .

Bond order and the octet rule

Several simple molecular models can be constructed, employing a 1×2 white brick, as a hydrogen atom. Similarly, 2×4 grey, blue, and red bricks can be employed as carbon, nitrogen, and oxygen atoms, respectively (Figure 5a) (Lin et al., 2018). However, when teachers try to represent large molecules, the corresponding LEGO models tend to be long (Figure 5b). Therefore, it is important for teachers to inform the students that LEGO molecular models could possess shapes that very different from their actual molecular structures. Therefore, it is preferable to employ the LEGO molecular model in combination with ChemDraw[®] illustrations and typical molecular models. Additionally, these LEGO models could be employed to teach the bond order and octet rule. In the molecular model of water (Figure 5a, left), there were eight studs in the red brick to represent oxygen, and four of them were occupied by two bricks, which represented the hydrogen atoms. This model indicated that the oxygen atom of the water molecule is bonded to two hydrogen atoms via two single bonds and possesses two noncovalent electron pairs. In the carbon dioxide molecular model (Figure 5a, middle), the red and grey bricks were stacked via four studs, indicating that oxygen and carbon form a double bond in carbon dioxide. Several molecular models have been built similarly and reported by other groups (Profbonomi, 2017).

Figure 5: Brick molecular structure models of (a) water, carbon dioxide, and ammonia (from left to right) and (b) a large molecular L-carnitine [(3R)-3-hydroxy-4-(trimethylazaniumyl)butanoate].

Valences of ions and the compositions of salts

A LEGO-based activity to teach the valences of representative ions and the compositions of simple salts was reported by Ruddick and Parrill (Ruddick & Parrill, 2012). In the activity, the LEGO bricks representing the cations and anions were distinguished by color. The number of studs in each LEGO brick corresponded to the valences of the ions. Hence, Ca^{2+} , O^{2-} , Al^{3+} , and P^{3-} were represented by 1×2 yellow, 1×2 blue, 1×3 yellow, and 1×3 blue bricks, respectively (Figure 6a). The activity was intuitively comprehensible and expectedly highly effective. The author also attempted to build brick models to represent Al_2O_3 , Ca_3P_2 , AlP , and CaO (Figure 6b). For clarity, the bricks were labeled with the symbols of elements, employing a label printer. When applying stickers to the bricks, those that readily peel-off should be considered. One of the good points of LEGO bricks is the ease of removing them from a model and reutilizing them in other models. Accordingly, it is preferable to not label, color, cut, or drill LEGO bricks.

Periodic properties of elements and molecular orbital theory

Dabke and coworkers reported several LEGO-based teaching aids to illustrate the periodic properties and electronic configurations of elements and the molecular orbital theory (Melaku, Schreck, Griffin,

Figure 6: Brick models of (a) cations and anions and (b) salts.

& Dabke, 2016). The bricks were developed as teaching aids for blind and visually impaired students. However, they were beneficial to all high school and undergraduate students. Based on their report, the author constructed a LEGO model to illustrate the electronegativities of the second- and third-row elements (Figure 7). From this model, students could easily observe that the electronegativity values of the second- and third-row elements differ greatly. The electronegativity values, according to Pauling are 2.55 for C, 3.04 for N, 3.44 for O, and 3.98 for F (Electronegativity, Wikipedia, n.d.). This model represents a 3D periodic table. The author also built a LEGO model to illustrate the formation of molecular orbitals by combining the atomic orbitals of O₂ (Figure 8). The LEGO model contained rubber bands to ease the comprehension of the energy diagram. Since the LEGO model was small, teachers would have to demonstrate the movements of the bricks on a projector and distribute the same models to all the students.

Figure 7: Brick model, illustrating the electronegativity values of the second- and third-row elements.

Figure 8: Brick models of the (a) atomic and (b) molecular orbitals of O_2 .

Coordination bonds and the chelate effect

Campbell and coworkers introduced the coordination bonds and chelate effects between metal ions and organic ligands employing a unique model, which combined LEGO bricks with magnets (Campbell, Freidinger, & Querns, 2001). The LEGO models representing metal ions and organic ligands were built with different colored LEGO bricks and attached to different orientations of magnets. Figure 9 shows a LEGO model, illustrating the square planar, linear, and T-shaped coordination geometries, constructed according to Campbell's report. In the square planar model, the metal center (red bricks) was surrounded by two monodentate ligands (yellow bricks) and a chelate ligand (orange bricks). The LEGO model required two parts that were not produced in that work: a cylindrical magnet [73092] and a 2×2 magnet holder tile [2609] (the numbers in the brackets are the official LEGO brick catalog numbers, as applicable to those below). The interaction between the magnets was not strong enough to hold the blocks together. Of course, there are many techniques to load a magnet onto a LEGO brick; therefore, teachers do not have to utilize those particular parts. This model could be employed to represent linear and T-shaped coordination geometries, although they cannot represent tetrahedral and octahedral geometries. It is very challenging to construct a tetrahedron with rectangular LEGO bricks.

Figure 9: Brick models of (a) square planar, (b) linear, and (c) T-shaped coordination geometries. The black parts are the cylindrical magnet and the 2×2 magnet holder tile. The red, yellow, and orange bricks indicate the metal ion and the monodentate and chelate ligands, respectively.

Self-assembly

Self-assembly in supramolecular and coordination chemistries can be illustrated with a teaching aid that demonstrates the spontaneous assembly of several LEGO bricks, floating upside down in the water (Exploring the Nanoworld with LEGO® Bricks, 2008). This interesting idea also accrued from Campbell and coworkers (Figure 10). Teachers should float the LEGO bricks gradually, to prevent them from sinking. Because LEGO bricks can assemble rapidly, it is best to allow the students to perform the floatation.

Figure 10: Bricks illustrating self-assemblies: (a) four and (b) seven brick assemblies.

Photolithography

Photolithography, one of the most recent technologies, was illustrated with a simple LEGO brick assembly (Garvey et al., 2008). The photolithographic technique consists of five processes (Figure 11): (a) the deposition of a photoresist (yellow brick) on the substance (red), (b) the masking of the photoresist with a photomask (blue) and its exposure with light, (c) the utilization of a developer to remove the photoresist, (d) the etching or deposition on the exposed areas of the substrate, and (e) the washing off of the residual photoresist. When teachers intend to diagrammatically explain complex chemical reactions or processes to students, it is better to employ computer software, such as Illustrator or PowerPoint, to illustrate them. However, it is generally challenging to draw a solid figure, and it is sometimes easier to draw and explain with LEGO bricks than with software applications.

Figure 11: Brick models to illustrate the photolithographic technique. The letters correspond to those in the text to represent the various processes.

Atomic force microscopy (AFM)

Two activities, which were employed to introduce the mechanism of AFM, utilizing LEGO bricks, were reported. One of them applied to upper-secondary students while the other applied more to freshmen, sophomores, and upper-level students. In the former, the surface of the material, which was scanned by AFM, was expressed by LEGO models (Goss, Brandt, & Lieberman, 2013). Conversely, in the latter, the operation of AFM was reproduced with a LEGO model, which was operated and controlled by a computer (Olson et al., 1999). One of the features that makes LEGO bricks appealing is that they can be utilized in a number of ways, depending on the class of student (grade- and ability-wise). Interestingly, even for the purpose of illustrating the mechanism of the same instrument, this teaching aid could be greatly varied.

Illustrations of chemical structures with LEGO models

Although LEGO bricks are not suitable for illustrating the structures of discrete molecules, as described above, they are suitable for representing periodic structures, such as the crystal and polymeric structures. Conversely,

typical ball-and-stick-type molecular models are good for describing the shapes of discrete molecules, although they are not good at describing periodic structures. Put differently, LEGO and ball-and-stick models are complementary. The utilization of abstract LEGO models can ease the comprehension of students on the correlations between the structures and properties of materials. Moreover, combining them in a lecture would deepen the students' comprehension.

Polyethylene

An outreach activity, employing LEGO bricks, to introduce the synthesis and recycling of plastics was reported in which a 2×4 brick was utilized as an ethylene monomer, and some of the bricks were connected to illustrate polyethylene (Figure 12) (Enthaler, 2017). The polyethylene model could be readily reverted back to ethylene monomers. In this report, the energy recovery was explained through a unique approach involving the combustion of the bricks by a gas burner. Moreover, the burning of the bricks must have impressed the students. However, teachers should be careful because a harmful gas is generated from the burning of LEGO bricks.

Figure 12: Brick model of polyethylene and the corresponding structural formula.

Polydimethylsiloxane

Polydimethylsiloxane is employed as a pharmaceutical and food additive. Campbell and coworkers built a polydimethylsiloxane model by combining simple LEGO bricks (Campbell, Miller, Bannon, & Obermaier, 2011). An attempt to construct the polydimethylsiloxane model with a typical ball-and-stick molecular model would require several kits, and the model would be fragile. One way to engage the students is to utilize the impactful LEGO model built by them. However, this model makes it challenging to understand the relationship between LEGO bricks and their corresponding atoms. The students would wander between the LEGO model and the corresponding ChemDraw illustration to understand their relationship.

Polysaccharides

When teaching students the relationship between the structure and properties of polymers, it is effective to treat polysaccharides, including amylopectin, amylose, and cellulose, as an example (Horikoshi, 2017). The differences and similarities among amylopectin, amylose, and cellulose were illustrated with the LEGO-based models. Amylopectin and amylose form helical structures (Figure 13) while cellulose adopts a zigzag structure (Figure 14). The differences are attributable to the different structures of their monomers, α -D-glucose and β -D-glucose, respectively. In α -D-glucose, which is the monomer that makes up amylopectin and amylose, the OH group on **C1** is attached downward to the six-membered ring (Figure 15a) while in β -D-glucose, i.e., the monomer of cellulose, the OH group on **C1** is bonded upward to the six-membered ring (Figure 15b). This model utilizes a rare 1×2 plate with a handle at the end [60478] and another 1×2 plate with a clip at the end [63868].

Therefore, it is expensive to increase the length of the polymer chain. When utilizing such a big LEGO model, teachers should explain the distinction between the essential and reinforcement brick parts of the model to the students. Additionally, when employing this model, caution must be observed to avoid breaking it.

Figure 13: Brick model of amylose and the corresponding structural formula: (a) top and (b) side views.

Figure 14: Brick model of cellulose and the corresponding structural formula: (a) the assembled structure and (b) the individual chain.

Figure 15: Brick models and the corresponding structural formulas of (a) α -D-glucose and (b) β -D-glucose.

Deoxyribonucleic acid (DNA)

There are abundant examples in which the double-helix structure of DNA was illustrated by LEGO bricks (for example, The accurate DNA structure from Japan, n.d.). A Google image search for “LEGO, DNA, and model” will return several spiral models. As a typical example, a LEGO DNA helix model, built by Eric Harshbarger is known (Eric Harshbarger’s LEGO® Website, n.d.). Further, LEGO bricks are employed as a tool to explain the outline of DNA sequencing in which the four bases, A, G, C, and T, that make up DNA, are represented by colored 1×1 bricks (Macori, Romano, Decastelli, & Cotter, 2017).

Illustrations of chemical reactions with LEGO models

Actually, there are few hands-on teaching aids that can effectively explain chemical reactions (Fieberg, 2012). To teach chemical reactions to students, chemistry teachers are required to write reaction schemes on whiteboards or project reaction schemes, drawn by ChemDraw, in slides. However, lots of reaction schemes on the whiteboard could discourage students from chemistry. Therefore, chemistry teachers should consider employing unique teaching aids periodically. Moreover, a few lectures explaining chemical reactions with LEGO-based teaching aids have been reported.

Balancing chemical equation and conservation of mass

LEGO bricks can also be used to teach the techniques involved in balancing chemical equations and calculation of the conservation of masses. Students can learn these two topics while watching YouTube videos (Kerr, 2020; Scarborough, 2016; The 8 Orange Community *formerly 8 Gold*, 2017). Unlike general molecular models, LEGO brick molecular models can easily remove atoms from a molecule. The lecturers in the YouTube videos use this advantage to teach these two topics in an easy-to-understand manner.

Chemical equilibria and kinetics

An activity employing a discovery-based method with LEGO bricks to enhance students’ understanding of chemical equilibrium was reported by Hutchison and coworkers (Cloonan, Nichol, & Hutchinson, 2011). This activity utilized 50 2×2 yellow bricks and 50 2×2 green bricks in a box. The yellow bricks represented atoms A while the green ones represented atoms B. The connection between A and B represented the formation of molecule AB. The students participated in this activity in groups of four. Of the four in each group, one assembled two bricks, A and B, to build AB, another disassembled AB into A and B, yet another mixed the bricks, and the last one measured time. After a period, the LEGO brick reaction system attained equilibrium. From this work, the students observed and understood the equilibrium state. A similar activity was reported by another group (Xian & King, 2020).

Chemical equilibria and kinetics were described, utilizing a teaching aid based on LEGO bricks, transparent CD cases, and beads. This teaching aid was designed to demonstrate the topics by observing the beads that crossed a barrier that was made of LEGO bricks. This teaching aid was very simple and was an excellent tool in explaining the two chemical concepts (Campbell, Brewer, Martinez, & Fitzjarrald, 2017).

Homogeneous catalytic reactions

Unexpectedly, both upper-level undergraduate and graduate students enjoyed learning the catalytic cycles, utilizing the LEGO-based teaching aids. Professor Negishi explained the versatility of palladium-catalyzed

cross-coupling reactions, utilizing the expression, “LEGO game approach,” in his Nobel Prize in Chemistry Lecture (Ei-ichi Negishi Nobel Lecture, 2010). The author and co-workers employed LEGO models to explain four homogeneous catalytic reactions, including the palladium-catalyzed cross-coupling reaction (Figure 16) (Horikoshi, 2015a), ruthenium–carbene-complex-catalyzed olefin metathesis reaction (Figure 17) (Horikoshi, Kobayashi, & Kageyama, 2014), BINAP–ruthenium-complex-catalyzed asymmetric hydrogenation (Figure 18) (Horikoshi, 2015b), and metallocene-catalyzed propylene polymerization (Figure 19) (Horikoshi, Kobayashi, & Kageyama, 2013). All the models indicated that the active species (catalyst) did not change, before or after the catalytic reactions. Further, utilizing LEGO bricks to determine the shape of the catalyst eased the comprehension of its molecular design. Some LEGO bricks in these models contained magnets, which attracted the other LEGO bricks containing magnets. This magnetic coupling between the LEGO bricks was easy to attach and detach, and was employed to represent removable bonds, namely coordination bonds, oxidative addition, and reductive elimination. The mechanisms and steric hindrance effects of homogenous catalysis are challenging to illustrate with chemical drawing tools and cannot be easily represented by ball-and-stick type molecular models. A typical ball-and-stick molecular model is not suitable for representing chemical reactions, such as reductive elimination, because it is challenging to remove the constituent atom balls. Actually, since it is challenging to teach the details of the reaction mechanism with only LEGO models, chemistry drawing and typical molecular models were combined effectively. These models utilized fewer common bricks, e.g., a 2×2 turntable [3680c02] and 2×2 plate with a groove and 1 stud in the center [87580]. Therefore, the distribution of these brick models to all the students will be relatively expensive.

Figure 16: Brick model and the corresponding structural formula illustrating the catalytic cycle of the palladium-catalyzed cross-coupling reaction.

Figure 17: Brick model and the corresponding structural formula illustrating the ruthenium–carbene-complex-catalyzed ring-opening olefin metathesis polymerization (ROMP) reaction.

Figure 18: Brick model and the corresponding structural formula illustrating the correlation between the BINAP–ruthenium complex and the subsequently generated β-hydroxy ester.

Figure 19: Brick model and the corresponding structural formula illustrating the correlations between the structure of a metallocene catalyst and the stereoregularity of polypropylene.

Constructions of handmade instruments with LEGO bricks

When students construct handmade measuring instruments themselves, they tend to understand the mechanics of the instrument in-depth and analyze the results extensively (Albert, Tobt, & Davis, 2012). LEGO bricks are suitable, as materials, for handmade instruments because there are a variety of parts and special tools that are not necessary for the construction of assembled frameworks.

LEGO bricks are made of ABS, and they can be damaged by some organic solvents, such as acetone. When utilizing LEGO bricks in the laboratory, care must be taken to avoid exposure to organic solvents. If the surface of the brick becomes dirty, it should be wiped with a cloth, soaked in water or ethanol.

Spectrophotometer, colorimeter, fluorimeter, and polarimeter

Several groups have developed hands-on activities with handmade instruments, utilizing LEGO bricks to aid students in understanding the fundamental concepts of various analytical instruments (Albert, Tobt, & Davis, 2012; Bouza, Nastou, Panigyraki, & Makedonas, 2019). Kvittingen and coworkers reported the designs of the following analytical instruments from a combination of LEGO bricks and LEDs for chemical education: a visible photometer (Kvittingen, Kvittingen, Sjursnes, & Verley, 2016), colorimeter (Asheim, Kvittingen, Kvittingen, & Verley, 2014), and a phosphorescent analyzer (Kvittingen, Kvittingen, Melø, Sjursnes, & Verley, 2017). Referring to Kvittingen's reports, the author built three LEGO-based instruments (Figure 20). Each instrument possessed the same basic structure in which a large LEGO plate was fitted with 2 × 2 bricks, 2/3 off the top, for fixing quartz cells and perforated 1 × 2 bricks [3700] for fixing LEDs. Noteworthy, it is not recommended to cut or color LEGO bricks when they are utilized for play. Of the three LEGO analytical instruments, the visible photometer possessed the simplest structure. LED for emitting visible light, and LED for detecting the light, were arranged and fixed to face the perforated bricks across the quartz cell. The simple photometer could be employed to illustrate the workings of ultraviolet–visible (UV–Vis) spectrophotometers, which are largely employed in chemical experiments. The LEGO-based colorimeter could hold two quartz cells, side-by-side, on a large LEGO plate. This instrument could be employed to teach the Beer–Lambert law. The LEGO phosphorescent analyzer was equipped with LED for the detection of long-wavelength light in a direction, perpendicular to the path of short-

wavelength light. After building one instrument, the teacher could rip its components apart and build the other two. This is convenient because LEDs were firmly fixed to the perforated LEGO bricks. A teaching aid, developed based on a similar concept, was reported by another group. The LEGO models are easy to recreate; hence, students can build their own models through trial and error. Recently, Kvittingen and Sjursnes reported the design of a polarimeter, employing LEGO bricks, as the framework, for student experiments (Kvittingen & Sjursnes, 2020). They employed the instrument to measure the optical rotations of honey, syrups, and essential oils. Like the aforementioned instruments, this polarimeter employed perforated 1×2 bricks [3700] to secure LEDs. It also employed the perforated 1×2 bricks and a peg part [3673] to fix a protractor and a plastic dial.

Figure 20: Central portions of the LEGO-based (a) spectrophotometer, (b) colorimeter, and (c) fluorimeter.

Full-fledged visible spectrophotometer and fluorescence microscope

In some activities in which the students built a full-fledged visible spectrophotometer (Bougot-Robin, Paget, Atkins, & Edel, 2016; Knagge & Raftery, 2002; Wilson & Wilson, 2017) and a fluorescence microscope (Varra et al., 2020), LEGO bricks were employed as the frame of the instruments or as holders to secure the components, such as the slit, mirror, prism, and quartz cell. In some reports, a hole was drilled in the LEGO brick to create the moving part of the spectrometer. Noteworthy, it is not recommended to drill holes when utilizing LEGO bricks outside of education. However, several hinge components are available and should be considered for utilization, although they are quite expensive. There are also reports on LEGO-based instruments that utilize LEGO Mindstorms (Hosker, 2018) and smartphone sensors (Kocanda, Wilke, & Ballantine, 2010) as photodetectors. The performance of the handmade instruments was compared to those of commercial instruments. Evidently, the handmade instruments exhibited lower measurement accuracy than the commercial ones, although they exhibited enough accuracy for educational purposes. Additionally, the handmade instruments were, by far, the best for educational illustrations.

Research instruments

Christus and coworkers reported a teaching aid that extensively utilized the functions of LEGO Mindstorms (Anunson, Winkler, Winkler, Parkinson, & Christus, 2013). The teaching aid, which was named “SHArK,” an acronym for Solar Hydrogen Activity Research Kit, was designed to explore the combinations of semiconductors that could be photocatalysts for the degradation of water. With this elaborate construction, the SHArK model evolved from a teaching aid to a research instrument.

LEGO handmade instruments are employed in the fields of chemical education and cutting-edge research. They, combined with the Mindstorms, are employable, as automatic fraction collectors in high-performance liquid chromatographic (HPLC) systems (Caputo, Lyles, Salazar, & Quave, 2020), interfacing system between thin layer chromatography (TLC) and ambient mass spectrometer (AMS) (Cheng et al., 2012), and peristaltic pumping systems in a microfluidic platform (Conde et al., 2014). The benefit of the handmade instrument built by combining LEGO models with 3D printed materials was also reported (Owens & Hart, 2018). In the future, these instruments may be employed in chemical education.

Conclusions

In this review, the benefit of LEGO-based chemistry teaching aids was introduced by illustrating some actual LEGO brick models. Their utilization could increase students' enthusiasm in participating in lectures, thereby easing the lecturing burden of teachers. LEGO-based teaching aids could be tailored to students' class levels. A software, LEGO Digital Designer, eases the design of new LEGO-based teaching aids and explains their assembling. Although there are many reports on the fabrication of teaching aids with wood and metal materials, it is sometimes challenging for other teachers to reproduce them. However, many LEGO-based teaching aids can be largely reproduced if the necessary bricks are prepared. The ball-and-stick-type molecular models have been improved to be less-breakable. Further, 3D printers have been commercialized and molecular models, built from them, are being reported (Fourches & Feducia, 2019; Savchenkov 2020). Applications that display molecular models on smartphones have also become popular (Fatemah, Rasool, & Habib, 2020; Sanii, 2020). However, they are still expensive and require advanced skills for handling. Therefore, it will require a prolonged time to achieve their usage in the classroom. Therefore, the author believes that the development and utilization of LEGO bricks, as described in this review, will persist for some time.

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