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Creating and Using Interactive, 3D-Printed Models to Improve Student Comprehension of the Bohr Model of the Atom, Bond Polarity, and Hybridization

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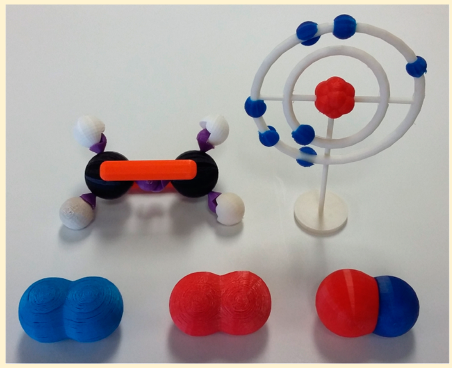
Supporting Information

ABSTRACT: Molecular model kits have been used in chemistry classrooms for decades but have seen very little recent innovation. Using 3D printing, three sets of physical models were created for a first semester, introductory chemistry course. Students manipulated these interactive models during class activities as a supplement to existing teaching tools for learning typically difficult concepts that currently lack physical models: the Bohr model of the atom, bond polarity, and hybridization. The results from student surveys show that these easy-to-produce models have a positive impact on students' perceptions of learning.



KEYWORDS: *First-Year Undergraduate/General, Hands-On Learning/Manipulatives, Misconceptions/Discrepant Events, Atomic Properties/Structure, Molecular Modeling, Covalent Bonding*

Physical models have a long history of use in chemistry education.[1] Many studies over the past several decades have validated their effectiveness,[2] but new designs for physical models are lacking.

The traditional rationale behind the lack of new physical models is the rise of computer-generated models. Comparing the figures in a modern chemistry textbook like Tro's *Chemistry: A Molecular Approach*[3] to one from 20 years ago, the changes are staggering. Many figures from older textbooks are hand drawn, while newer textbooks, like Tro's, have bright and colorful computer-generated models on almost every page. This integration of technology with chemistry education has mostly been positive for students, with many studies showing the usefulness of this approach.[4] However, no matter how advanced these computer generated models get, the figures in textbooks and on screens are still just two-dimensional representations of three-dimensional objects.

One area of educational technology that has received much attention recently is 3D printing.[5] In the most common consumer 3D printers, seen in many schools and colleges, a plastic filament is melted and deposited in layer-by-layer fashion to create three-dimensional structures. This technology has been around for decades, but is currently at a more affordable price point for smaller schools and colleges to afford. Many chemical educators are already seeing the benefit of this new technology, with groups making models for teaching about physical chemistry,[6] potential energy surfaces,[7] block copolymers,[8] and symmetry.[9] Many others are also discovering the usefulness of using existing structure databases to print models for classroom demonstrations.[5b,10] For laboratory use, two different colorimeters have been designed and manufactured with 3D printing,[11] showing the potential for low-cost laboratory equipment.

While these applications of 3D printing are creating new models for chemistry education, they are lacking interactivity. Traditional molecular models kits are still used in classrooms today because they allow students to make something on their own. In this study, 3D printing was used to create a series of interactive models for an introductory chemistry course.

■ DESIGN

The physical models were designed in OpenSCAD, a free computer-aided design (CAD) program commonly used to design models for 3D printers. This program makes parametric designs that fit a variety of projects. OpenSCAD does not have a graphical interface; instead each geometric object must be written. Afterward, the model was then exported as an STL file, a universal file format for 3D printing. Simplify3D was used to encode the file to the specific printer, in this case a FlashForge Creator Pro.

Unlike traditional paper printing, the consumer-level 3D printers used in this study take a long time to make an object (up to 3 h for some of the models in this project) and have a significant failure rate. Due to these restraints, most of the

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J. Chem. Educ. XXXX, XXX, XXX−XXX

models are printed in separate pieces and then placed together, which also allows increased interactivity.

HAZARDS

The extruder in fused deposition 3D printers gets extremely hot, and students should be instructed to avoid touching it when the instrument is running. Additionally, improperly cured models from resin based 3D printers have been shown to be toxic to some aquatic organisms.[12] Additional information can be found in the Assembly Instructions in the Supporting Information.

MODELS

The Bohr model of the atom, bond polarity, and hybridization are topics commonly seen in the first semester of introductory chemistry courses and were selected for this study. These three sets of models were chosen because they cover topics traditionally difficult for introductory chemistry students to understand. All three of these topics also focus on three-dimensional atoms and molecules that cannot be fully depicted with two-dimensional images or molecular model kits.

Bohr Model of the Atom

On the first day of the semester, a series of Bohr models were set up in the front of the classroom with nameplates with different element names in front. Only one had the correct name; the rest were wrong. Students were then asked to make all of the models show the correct atom. Since this was the first day of class, the instructor left the room on the pretext of forgetting something from his office, giving the students 5 min alone to accomplish this. Without any extra guidance or instructions on how to use the models, all of them were correct when the instructor came back into the room.

The Bohr models are composed of a red nucleus on a stand with white circles to represent orbitals and blue electrons (Figure 1). The electrons clip onto the orbitals, and the orbitals themselves can be added or removed. The electrons move freely around the orbitals, and the orbitals rotate around the nucleus, simulating orbital motion. This customization allows students to see the Bohr model in motion and to make a variety of atoms, from hydrogen to neon.

In addition to the activity at the start of the semester, students were also tasked with creating models of their own during a later recitation session. In pairs of two, students would take turns creating atoms and having their partner identify them. This relatively quick activity allowed students another opportunity to visualize the Bohr model of several atoms. This model also allows for mistakes. More than two electrons can fit on the first orbital of this model, and this error happened several times. Identifying problems like this allows the instructor to clear up these common misconceptions instead of seeing it on a test.

Bond Polarity

Another concept that can be difficult for introductory chemistry students to understand is the idea of bond polarity and its effect on electron density. Figures in textbooks commonly show differing radii due to electronegativity differences, but this can still be difficult to grasp for some students.

To illustrate this effect, three different molecular models were made: two showing nonpolar bonds and one a polar bond. Oxygen and nitrogen were chosen for the nonpolar bonds due to their similar size. When printed, both appear almost identical in size (Figure 2A,C). Students are presented with both and asked what the difference is. Invariably the answer comes back that they are different colors and that is it. The instructor then asks one student to hold one model in each hand. The oxygen is printed with a higher infill (an aspect of 3D printing changing the object's density) than the nitrogen, making it heavier. When holding the models, the student can easily identify this and is then asked why. The final step is to ask what would happen if one nitrogen atom bonded to one oxygen. This final model shows that the oxygen would appear bigger due to its higher electronegativity. By exaggerating this difference slightly, it is possible for students actually see and feel what this would look like (Figure 2C).

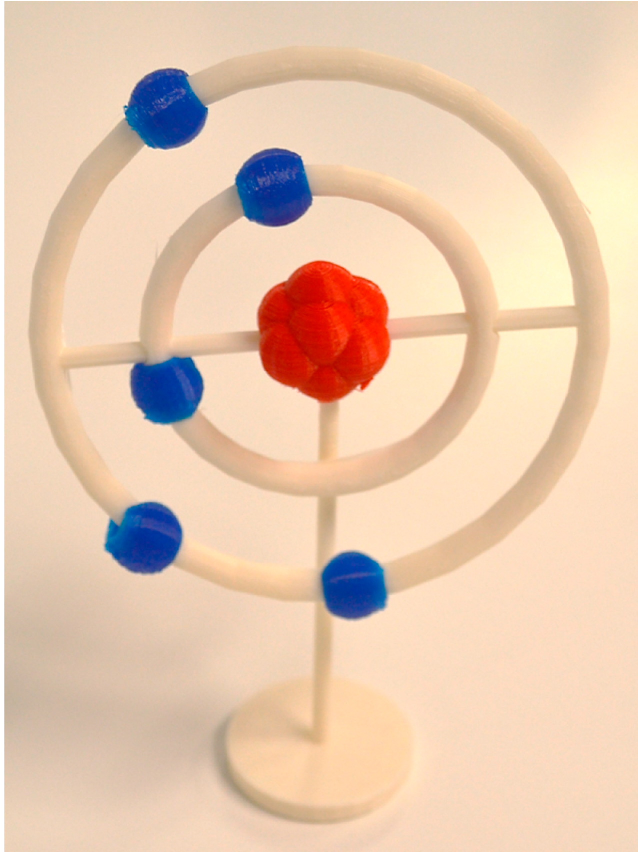

Figure 1. Bohr model of a boron atom.

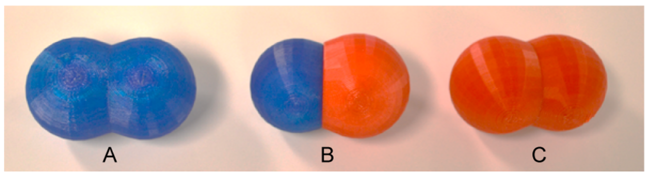

Figure 2. Model of a nitrogen molecule (A), nitrogen monoxide (B), and an oxygen molecule (C).

Hybridization

Perhaps the most difficult concept from first semester introductory chemistry is hybridization. Up until this point, every bond has been the same and each electron is neatly divided into s, p, d, or f subshells. Making the transition to a more complete view of hybrid orbitals is critical for understanding future concepts like bond geometry but cannot be adequately described by 2D pictures in textbooks or traditional molecular model kits.

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To correct some of the issues with molecular model kits, several new kits were developed that clearly distinguish between sigma and pi bonds, something not possible with traditional molecular model kits. In Figure 3, a model of propene is depicted with purple sigma bonds and an orange π bond. The atoms and bonds can be rearranged, added, and removed in similar fashion to other molecular model kits.

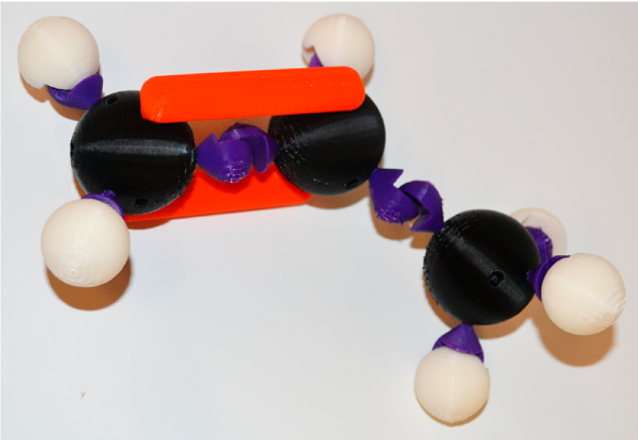

Figure 3. Model of propene made with a hybridization model kit. Sigma bonds are purple, pi bonds orange, carbon atoms black, and hydrogen atoms white.

During class, students were asked to first identify the bonds and type of hybridization present in several molecules on paper and then make the structure using traditional molecular model kits and the new ones showing hybridization. The new hybrid kits fit together in a similar fashion to traditional molecular model kits, making them relatively intuitive for the students. Having the distinct and different models for sigma and pi bonds allows students to easily visualize the structure of the molecule and adjust their original assumptions accordingly.

■ STUDENT RESPONSE

After covering the concepts involving the new models, the students involved were given a short Likert survey to gauge their perceptions (Figure 4). Each survey had four statements: "I understood (topic) before the class lecture", "I understand (topic) now after the class lecture", "The figures in the book and/or lecture helped me understand (topic)", and "The 3D-printed models helped me understand (topic)". The available responses were strongly disagree, disagree, agree, and strongly agree.

As expected, the number of students claiming to understand the topics covered prior to class decreased as the semester progressed with only a few claiming to understand hybridization, which is one of the last topics covered in this course, before the lecture. Most encouraging was that most of the students claimed to understand all three topics after being covered in the course.

While most students claimed that the figures in the book helped them understand the topics, a slightly higher number said the new models helped. The relative similarity in these results is encouraging because the models are designed to work with the figures in the textbook, not by themselves. The class size for this trial was small as well (26 students), allowing for more personalized instruction. Since students need to be instructed on the use of most of these models and their work needs to be confirmed, this smaller class size and recitation were ideal.

Somewhat interesting are the one or two students that strongly disagreed that the new models ever helped them. From the comments on the surveys and talking with the students informally after class, it seems that some students simply do not like to do hands-on activities during class. These students said they prefer to just listen to a lecture and take notes. While this was not the norm for this class, it is important to recognize this mentality in some students.

Besides the few students mentioned above, the comments for the new models were generally positive. Most students liked having physical models to interact with: "Physical representation of Bohr models are great for people like me who like visual things." "I think it helps to see how atoms are built and you can build different atoms too." "I'm still a little iffy on the understanding, but the models do help." Some students were critical of the design: "I love the models! I just dislike how hard it is to move the electrons." Others acknowledged that sometimes chemistry is simply difficult to understand: "Hybridization is just hard."

■ CONCLUSION

All three sets of interactive models were well-received by students and proved to be a useful tool in teaching some of the

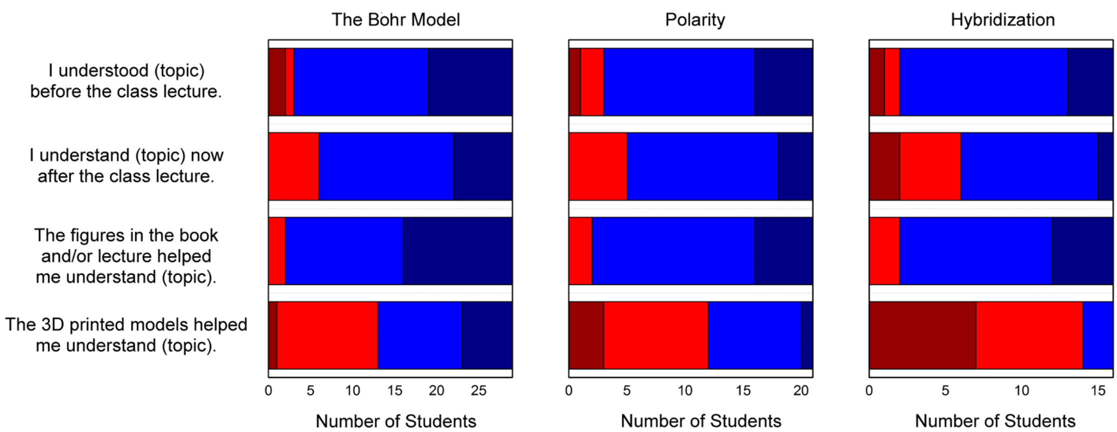

Figure 4. Results of a Likert survey given to students after covering the three topics listed above each graph. Dark red represents strongly disagree, red represents disagree, blue represents agree, and dark blue represents strongly agree.

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J. Chem. Educ. XXXX, XXX, XXX−XXX

most difficult concepts from introductory chemistry. The growing affordability and access to 3D printing means that this new technology can play an increasingly important role in chemistry education.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.6b00297.

Detailed assembly instructions (PDF, DOCX)
Design (.scad) and 3D printing files (.stl) (ZIP)

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Notes

The authors declare no competing financial interest.

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J. Chem. Educ. XXXX, XXX, XXX−XXX