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A Cost-Effective Physical Modeling Exercise To Develop Students' Understanding of Covalent Bonding

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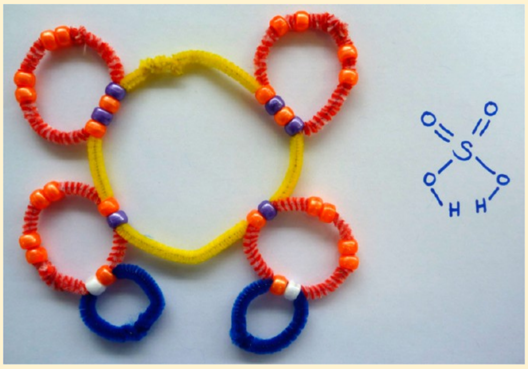
Supporting Information

ABSTRACT: Chemical bonding is one of the basic concepts in chemistry, and the topic of covalent bonding forms an important core of knowledge for the high school chemistry student. For many teachers it is a challenging concept to teach, not least because it relies mainly on traditional instruction and written work. Similarly, many students find the topic abstract and difficult to grasp and the traditional approach can be disengaging for some students. This modeling activity was used with 14–16 year old students to consolidate their understanding of the covalent bonding model extend their thinking beyond the "octet rule". This low cost, kinesthetic approach proved to be highly engaging for the students and a useful stimulus for discussion.



KEYWORDS: *High School/Introductory Chemistry, Collaborative/Cooperative Learning, Hands-On Learning/Manipulatives, Problem Solving, Covalent Bonding*

INTRODUCTION

> *In school science teaching, ideas need to be presented in ways that are both authentic representations of the scientific concepts and simple enough to be meaningfully understood by learners.*[1]

Understanding of the nature of chemical bonding is a fundamental in high school chemistry courses. Student activities in this topic concentrate on the analysis and reproduction of covalent bonding models on paper, a task that is undoubtedly driven by the demands of examination syllabuses. While this is a teaching approach that has stood the test of time and translates into examination success for many students, it can be disengaging and contribute to a lack of variety in the teaching sequence. There are relatively few experimental activities associated with this topic, which may further contribute to learner dissatisfaction. Examination syllabuses for the 14–16 age group concentrate on covalent molecules of atoms of period 1 and 2 elements. This exposes students to examples of substances which obey the "octet rule", and it has been suggested that an overemphasized "octet framework" may impede higher level learning.[2−4]

This activity was designed to increase the diversity of student activities in a program of study for the chemical bonding topic and provide a stimulus for discussion of ideas beyond the "octet rule" for more able students. In post-16 study students meet a greater diversity of molecules as they move toward the study of basic VSEPR, and this activity was extended into the post-16 curriculum to engage students with the limitations of the "octet rule" and the study of incomplete and expanded octets.

As a physical model, the activity proved to be highly engaging activity and provided welcome relief from paper based exercises for both students and teachers. The models have the further advantage of being closely aligned to the Lewis structures required by examination syllabuses, providing reinforcement of the basic principles of electron sharing through a different medium and learning style. The finished models can be taken home by the students, providing stimulus for school–home discussion or used as a wall display to further reinforce learning.

MODELING ACTIVITIES IN HIGH SCHOOL CHEMISTRY CURRICULA

Although the theory of the existence and value of learning styles has been widely discredited,[5,6] many teachers seek to include a variety of pupil activities in their lessons for both ideological and practical reasons. Since the mode of instruction in high school chemistry is often practical and experimental in its nature, it makes sense for teachers to seek out hands-on activities that can be used to enhance the teaching of more theoretical topics such as bonding.

Modeling is commonplace in chemistry. Richard Zare[7] describes chemists as "...highly visual people who want to 'see' chemistry and to picture molecules and how chemical transformations happen." Modeling in chemistry can be split into two distinct representations: those that are internal, mental

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Figure 1. Modeling materials.

representations and those that are external symbolic expressions. External symbolic references such as paper and pencil drawings, physical models, and computer simulations are commonly used in high school chemistry curricula to aid students in successfully developing the skills to "see" chemistry in their minds in terms of images of molecules and their transformations.[8]

The most common physical models used in chemistry teaching are commercial molecular model kits, used to visualize molecular geometry and bonding connections between atoms. In addition to this, many other "homemade" models are used in schools, including pipe-cleaners, Q-tips, cocktail sticks, and craft straws.[9−11] In the overwhelming majority of cases these improvised models are also used to visualize molecular geometry. One study found that "do-it-yourself" model kits using pipe cleaners appeared to be "more meaningful for the better students and to be more enjoyable for all".[12]

■ VISUAL REPRESENTATIONS OF BONDING IN HIGH SCHOOL CHEMISTRY CURRICULA

There are two distinct representations of covalent bonding that students are exposed to when learning about covalent bonding. Representations which show the (co)valence between 2 atoms as a line are usually referenced as Kekulé structures although there is evidence that this representation was developed simultaneously by both Kekulé[13] and Couper.[14] Lewis structures[15] show the "overlap" of outer shells of electrons, explicitly showing the electrons that are involved in the covalent bond(s) and the atom they originate from, allowing dative covalency to be shown. The order in which these are approached by the various curricula and by individual teachers does not appear to be fixed, and both representations can be used as a starting point for this modeling activity.

■ ACTIVITY

The modeling activity requires two low cost and readily available materials (Figure 1).

1. Pipe cleaners (sometimes also known as chenilles), to represent the valence electron shell of the atoms.
2. Plastic beads with a suitable sized lumen, to represent the electrons in the outer shell of the atoms.

These materials can be easily sourced from supermarkets and craft shops; suggested sources are included in the Supporting Information, information for instructors.

■ PRIOR KNOWLEDGE

Prior to introducing the modeling activity students will need to have a basic knowledge of atomic structure and electron configuration. They should be confident in writing electron configurations in terms of principal energy levels and predicting the number of valence electrons using the position of an element in the Periodic Table. There are two possible approaches to the modeling activity which have equal merit depending on the needs of the class.

The first approach requires only that students are familiar with molecules represented as Kekulé structures such as those shown in high school text books. The modeling lesson is used to further develop their understanding of this as a representation. This leads the students to the definition of a

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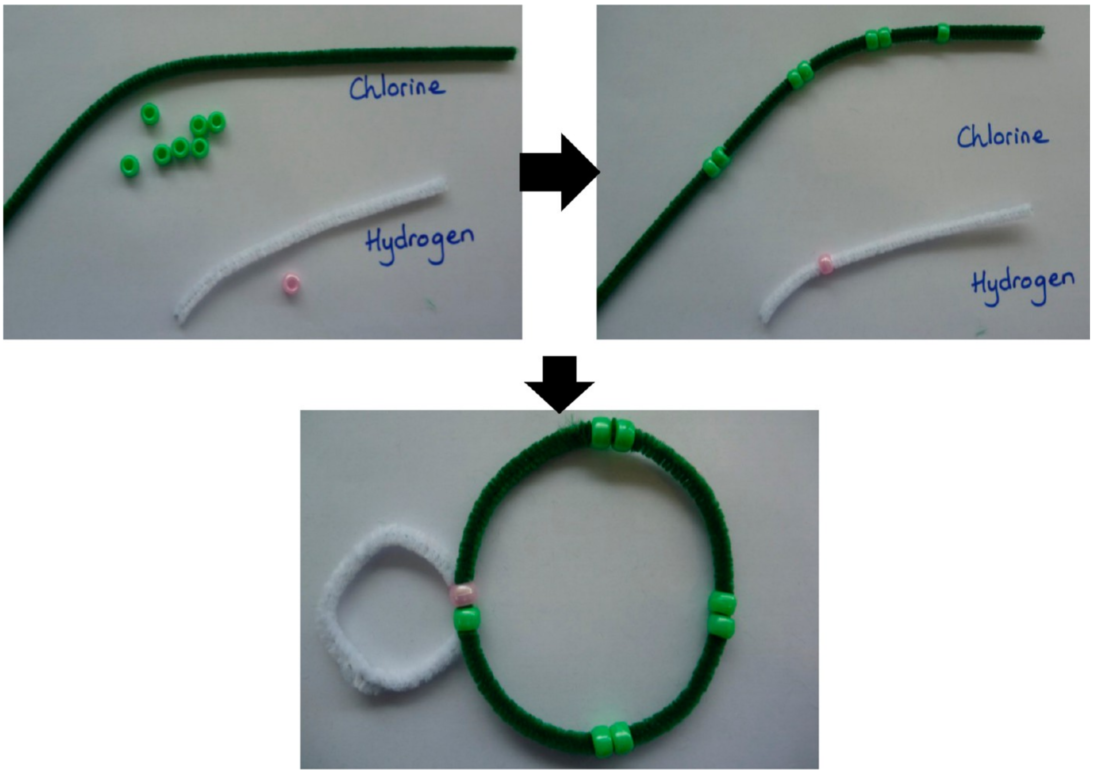

Figure 2. Construction of a model of HCl.

covalent bond as a shared pair of electrons leading to the use of the Lewis model.

The second approach is used with students who already have some confidence in drawing Lewis "dot and cross" diagrams within the requirements of their examination syllabus and is useful as a revision lesson.

■ LESSON PLAN: APPROACHING THE ACTIVITY FROM KEKULÉ STRUCTURES

The modeling activity can be approached with students who have little prior knowledge of covalent bonding using Kekulé structures as the initial stimulus. Kekulé structures are used extensively in materials for high school chemistry such as text books and, therefore, have a degree of familiarity, even before students are taught what they mean in terms of electron pairs.

A suitable starter for the lesson would be a visual stimulus of a number of Kekulé structures of simple molecules, leading to a discussion about what the line represents and the definition of a covalent bond, and linking this to the number of valence electrons for the atoms. The teacher is then able to lead the class in how a model can be built of the covalent bonding using pipe cleaners and beads, illustrating this with a simple molecule such as HCl as shown in Figure 2.

The students are then set the task to construct models of simple molecules from suitable Kekulé structures. The level of difficulty can easily be differentiated to suit the abilities of the students in a class and provide suitable support or challenge. A suitable framework for differentiating the activity in this way can be found in the Supporting Information for this manuscript, in the file notes for instructors. Figure 2 shows the construction of a model of HCl. First the appropriate quantities of materials are selected. In this model the green pipe cleaner will represent the outer shell of the chlorine atom and the white pipe cleaner that of the hydrogen atom. They are different sizes as the student has attempted to make some reference to their different atomic radii. The green beads will represent the valence electrons of the chlorine atom and the pink bead the valence electron of the hydrogen atom. The first step in the construction is to thread the appropriate number of beads onto each pipe cleaner, 7 green beads for the valence electrons of chlorine on the green pipe cleaner and one pink bead for valence electron of hydrogen on the white pipe cleaner. The covalent bond is now constructed by threading both pipe cleaners through the two beads representing the shared pair of electrons. The pipe cleaners can then be bent into circular shapes and the ends twisted together to secure them.

This example shows the construction of a simple diatomic molecule. When models are constructed of molecules with a greater number of covalent bonds, there needs to be some planning for the placement of the beads initially. When students become confident in the construction of the models, they tend to construct them bond by bond rather than beginning with the requisite number of beads threaded onto the pipe cleaners.

When students have constructed their models, the teacher can then use them as a way of introducing students to the pen and paper Lewis model as required by their examination syllabus. Students can be directed to try to represent their model on paper thus leading to the Lewis model. They can then practice this using examples from the visual stimulus at the start of the lesson or from examination papers. Approaching the modeling activity from Kekulé structures provides a genuine opportunity to discuss the octet rule and its limitations with more able or motivated students.

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Figure 3. Model of BF_3.

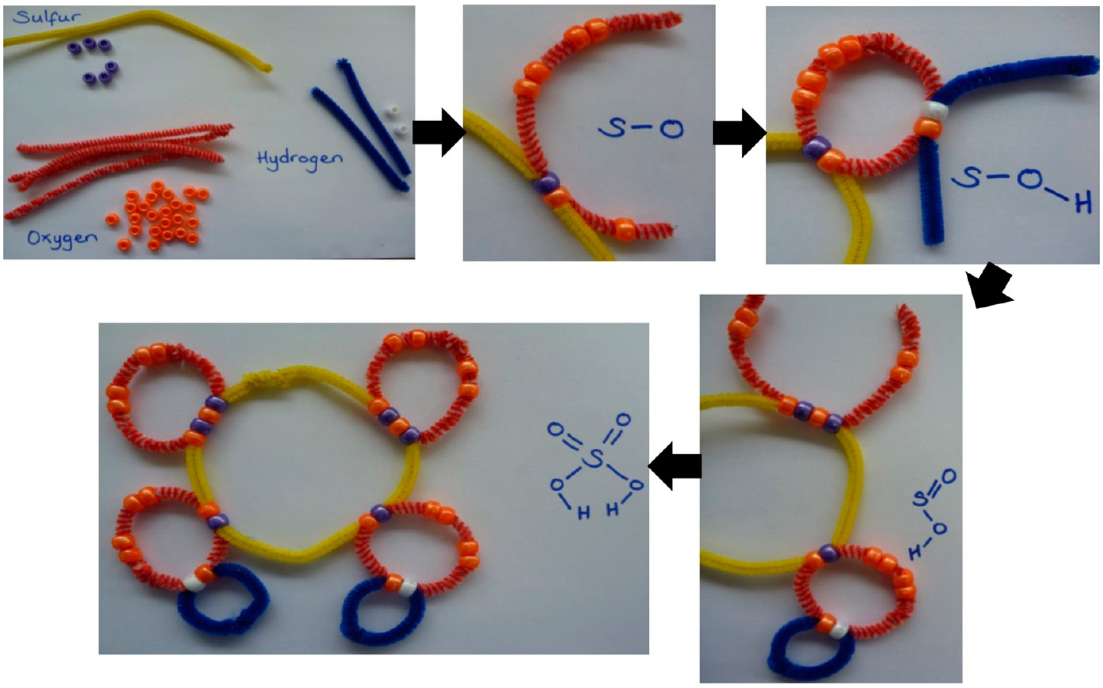

Figure 4. "Bond by bond" construction of a model of sulfuric acid.

DECONSTRUCTING THE "OCTET RULE"

Because it is simple for the learners to visualize and use, the octet "rule" is "often presented as an obligatory condition for "proper" bonding; this causes some students to have difficulties accepting anything that is not clearly explicable in "octet" terms".[1]

For students in the 14–16 age range the octet "rule" is a useful one: it provides a suitable set of criteria to work from that will lead to examination success since the molecules they will be tested on are limited to those involving covalent bonding of atoms of period 1 and 2 elements. If students are to study chemistry no further than this level, then there may be no problem with them not exploring the limits of the rule. However, students' attachment to the octet rule has been widely criticized as leading toward a number of misconceptions and hindering further development of more advanced ideas on chemical bonding.[3] For many students there is a great deal of benefit in introducing them to the idea that "rules" they may have been presented with may be simplifications and, as such, have limitations.

A suitable exercise for able students is to produce a model of a molecule which does not adhere to the octet rule. Molecules

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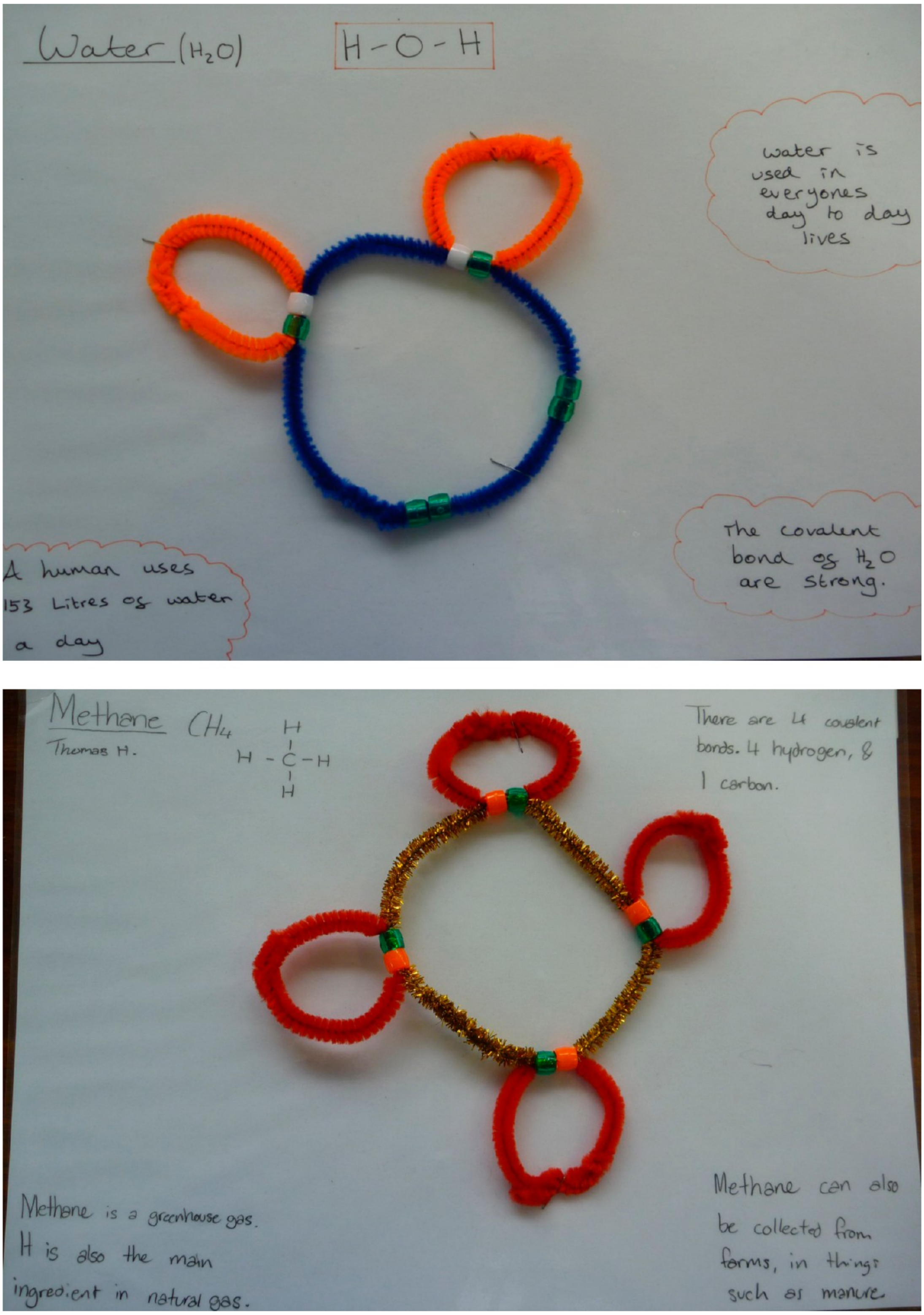

Figure 5. Examples of student produced backing cards for display.

with incomplete octets such as BF_3 (Figure 3) and hypervalent molecules such as sulfuric acid (Figure 4e) are useful examples to use.

The best prompt to begin such a construction is a Kekulé representation of the molecule; able students can build quite complex molecules using this modeling technique from such representations. When students are familiar in the method of constructing the models, they are able to build the models bond by bond, dealing with each electron pair in turn. Figure 4 shows the construction of a model of sulfuric acid using this method; the sulfur has 12 electrons in its valence shell. In this construction students largely ignore the number of valence electrons in each shell until they come to evaluate the model at the end of its construction. This leads to a "lightbulb" moment

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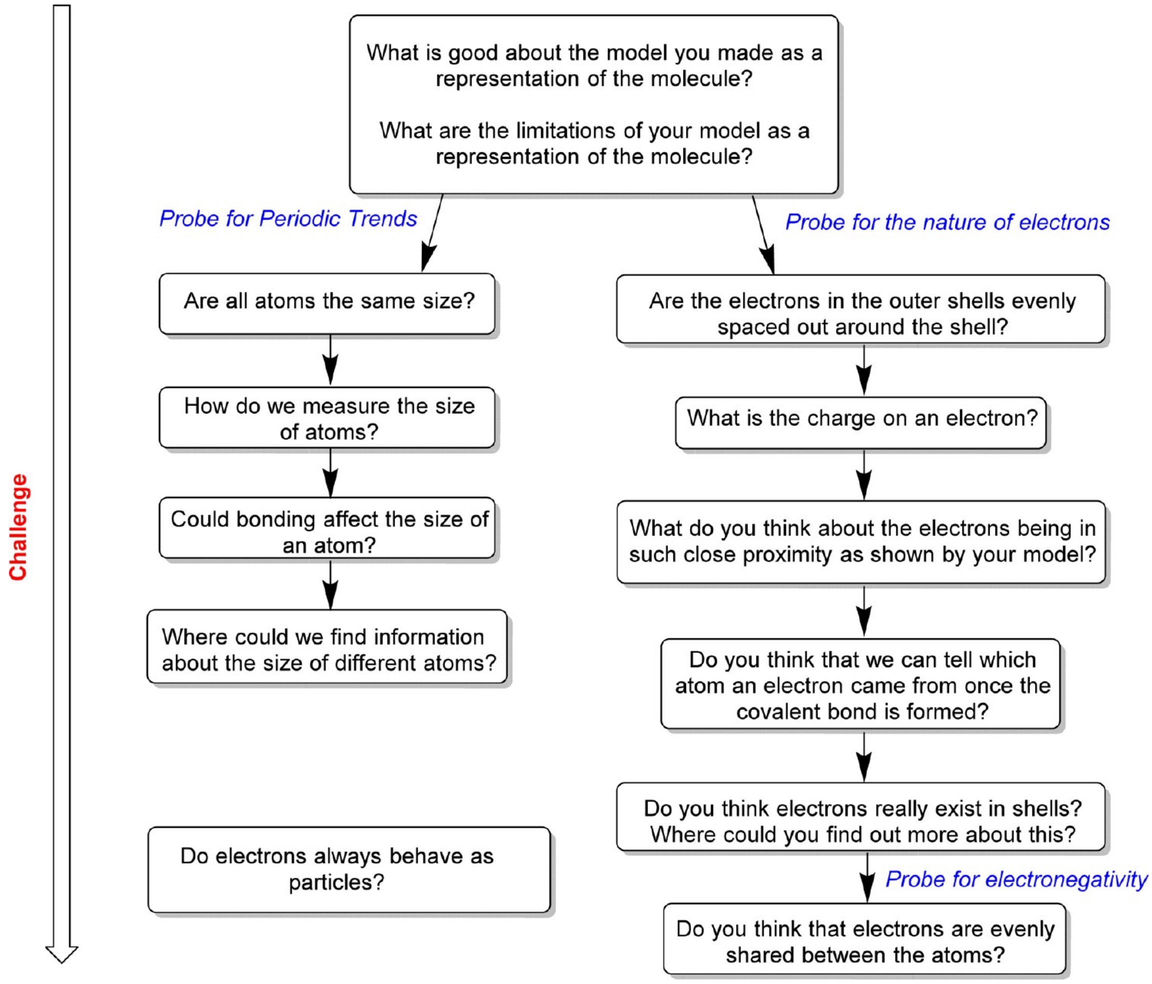

Figure 6. A schematic for discussion using the model as stimulus.

where they realize that not all the atoms have 8 electrons in their outer shell. This is a useful prompt to extend students' understanding of bonding theory and the usefulness of the octet rule. Teachers can then choose whether to probe this idea further or simply sow the seed for further learning, depending on the constraints of their curriculum.

■ LESSON PLAN: APPROACHING THE ACTIVITY FROM LEWIS STRUCTURES

This modeling activity can also be used as a supplementary lesson for students who already have a working knowledge of the nature of covalent bonds, either to reinforce understanding or to provide variety in a series of lessons. A suitable starter for the lesson would be to present students with the formulas of a number of covalent molecules and ask them to choose one to draw a Lewis diagram of. As with the previous approach, this activity can be easily differentiated through matching the choice of molecule to the abilities of the students (see Supporting Information, notes for instructors).

The students are then presented with the model making activity. For students with a good understanding of the chemistry it is possible to present them with the materials, explain what each represents, and allow them to construct their models through a process of trial and error. Students with less secure understanding will need some guidance, with the teacher leading the students through the development of some "rules" through discussion. Typical rules arising from such discussion include the following:

1. The outermost shell of electrons for each different element should be represented by a different colored pipe cleaner.
2. The valence electrons of each different element should be represented by a different colored bead.
3. For beads (electrons) contained in covalent bonds, the beads must be contained in both the pipe cleaner "shells" of the atoms forming the bond.
4. Each covalent bond must contain 2 or a multiple of 2 beads.
5. For diatomic molecules, different colors of pipe cleaner and beads should be used for each atom.

The students can then gather their materials and construct their models. During this time the teacher circulates around the class to assist students and provide prompts for further discussion. Once constructed the students can then take them around the class and ask others to predict the molecule by counting the beads in each pipe cleaner "shell". If a display is to be made from the models, then students can also produce a backing card (Figure 5) for their molecule with some facts about it.

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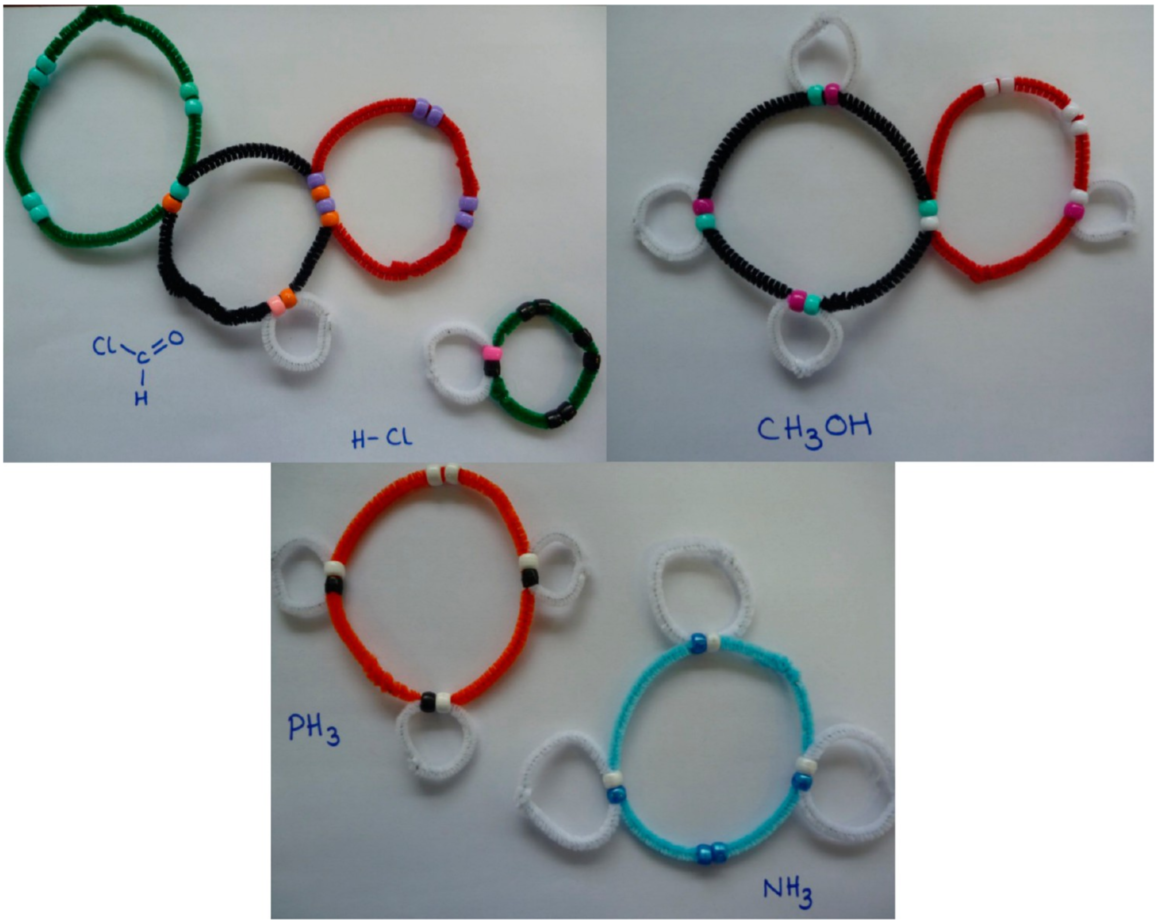

Figure 7. Some models constructed using the CPK color system.

■ EVALUATION OF MODELS THROUGH DISCUSSION

This activity provides a useful stimulus for discussion to elucidate students' understanding of the concept of covalent bonding. There is a rich literature illustrating the misconceptions that students hold with respect to covalent bonding at various points in their academic careers. The most prevalent of these is a secure attachment to the octet rule as previously discussed. This activity is designed to be used with students at the very start of their instruction in chemical bonding, when they have little understanding of what the term "bond" means. It can therefore be used as a physical stimulus for discussion with a role in preventing misconceptions (or preventing them becoming too securely held) rather than addressing misconceptions already held. Figure 6 shows a schematic for use in discussing aspects of covalent bonding using the model as a stimulus. These can be used in teacher−student discussion or handed out on cue cards for student paired discussion.

■ INCREASING FAMILIARITY WITH THE IUPAC ACCEPTED COLORS FOR ELEMENTS IN MODELS

Students may have a familiarity with the colors assigned to particular elements from the use of molecular modeling kits. All modeling kits use the CPK coloring system (designed by chemists Robert Corey and Linus Pauling, and improved by Walter Koltun).[16] Pipe cleaners are available in most of the CPK colors. Figure 7 shows some models made using pipe cleaners with CPK colors. This increases the cost of the activity (as packs of single color pipe cleaners are more expensive than mixed packs); however, it is a useful approach to produce models analogous to those constructed with 3D molecular models, especially with older students, and can help the modeling process "feel" more familiar.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00981.

Lesson plan (PDF, DOCX)
Instructions for instructors (PDF, DOCX)
Wall display (PDF, DOCX)
Examples of student work (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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