

# Illustrating Concepts in Physical Organic Chemistry with 3D Printed Orbitals

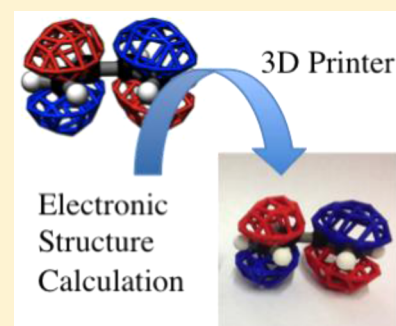
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**S** Supporting Information

**ABSTRACT:** Orbital theory provides a powerful tool for rationalizing and understanding many phenomena in chemistry. In most introductory chemistry courses, students are introduced to atomic and molecular orbitals in the form of two-dimensional drawings. In this work, we describe a general method for producing 3D printing files of orbital models that can be employed with most popular software packages for performing electronic structure calculations and molecular visualization. Methods for producing both solid and mesh orbitals are provided, including pointers for producing a model that is both informative and structurally sound. Finally, numerous examples of various systems of interest in physical organic chemistry are provided in the .stl format for 3D printing, as well as a fully illustrated tutorial for the process.

**KEYWORDS:** First-Year Undergraduate/General, Second-Year Undergraduate, Upper-Division Undergraduate, Graduate Education/Research, Physical Chemistry, Interdisciplinary/Multidisciplinary, Hands-On Learning/Manipulatives, MO Theory, Conformational Analysis, Molecular Properties/Structure



## INTRODUCTION

Since its development in the early days of quantum mechanics, orbital theory has provided crucial insight into the nature of chemical bonding,<sup>1</sup> reactivity,<sup>2,3</sup> conformations,<sup>4</sup> and more. The value of depicting these orbitals was recognized immediately, with the first of Linus Pauling's seminal papers on the nature of the chemical bond including a hand-drawn hybrid orbital.<sup>1</sup> With the advent of computers, methods were quickly developed to draw the contours of molecular orbitals in a plane. This led to computational methods for producing contour maps of molecular orbitals or electron density in one plane. Then in the early 1970s, the first accurate three-dimensional images of molecular orbitals were reported by Jorgensen and Salem.<sup>5</sup> Yet, until recently, options for three-dimensional physical models of molecular orbitals have been limited; a few commercial kits for demonstrating simple principles are available.<sup>6,7</sup>

Recent advances in 3D printing have allowed the technology to become highly accessible, with many universities owning at least consumer grade printers. The cost of having a model 3D printed commercially has also become quite reasonable. Consequently, several papers have documented the use of 3D printing in chemical education. Examples including teaching organic chemistry to the visually impaired,<sup>8</sup> illustrating concepts in crystallography and group theory,<sup>9</sup> in demonstrating potential energy surfaces in physical chemistry,<sup>10</sup> in modeling block copolymer nanostructures,<sup>11</sup> and in printing molecular structures from pdb files.<sup>12</sup> Further, a method for generating 3D print files of solid molecular orbitals with Gaussian and Jmol has been reported in a blog post and referenced in a book chapter on chemical instruction for "millennial" students.<sup>13</sup>

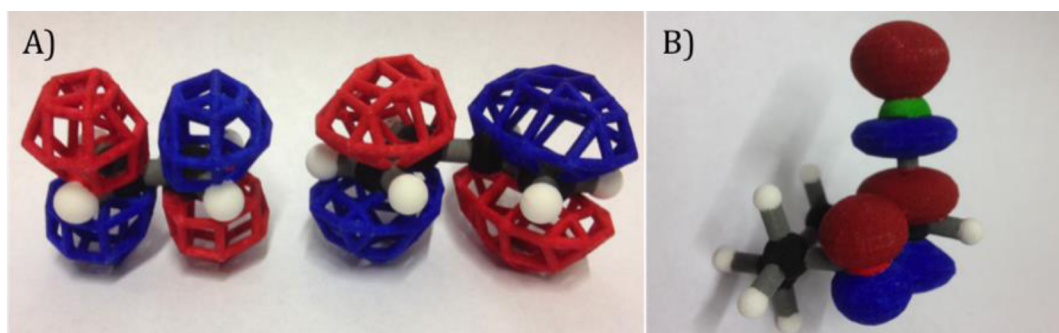
In this work, it is demonstrated how this process can be generalized to many popular electronic structure packages and molecular visualization programs, including free applications, for both commercial and consumer printing. Advice is provided for producing high quality solid and mesh orbital models (see Figure 1 for an illustration of both types). Finally, suggestions are made for physical organic chemistry concepts that can be best illustrated with these models, and preprepared 3D printing files are provided for several example systems.

## METHODOLOGY AND APPLICATIONS

### Generation of 3D Print Files

The first step in preparing a 3D print file of a molecular orbital is to prepare a .cube file, which contains the values of a molecular orbital at each point in space ( $x,y,z$ ) over some region. Many common electronic structure packages, including Gaussian<sup>14</sup> and ORCA,<sup>15</sup> are capable of generating cube files from the results of a single-point energy calculation for any desired molecular orbitals. One should consult the manual for the preferred QM program for directions in generating .cube files. It is also necessary to generate a file containing the coordinates of the atoms in the molecule upon which the calculations are being performed, preferably in pdb format.

Although many principles can be illustrated with the MOs resulting from a QM calculation, for some concepts involving complicated molecules, the actual molecular orbitals may be difficult to interpret. To prepare a clean, simple model, in some cases, it may be necessary to employ natural bond orbital



**Figure 1.** Photographs of (A) 3D printed molecular orbitals for the LUMO of ethene and the HOMO of 1,3-butadiene generated as meshes and rendered as a .wrl in PyMOL and converted to a .stl in Chimera. (B)  $\pi$  lone-pair HOMO of water and  $\sigma^*$  LUMO of chloromethane superimposed on 2-chlorotetrahydropyran to illustrate the anomeric effect. This was prepared in Chimera as a .stl file. Both models were printed with the commercial service Sculpteo in white polyamide plastic and painted by hand.

analysis (NBO)<sup>16</sup> or simply superimpose orbitals from simpler molecules onto the more complex one. Examples of this will be provided for illustrating the anomeric effect in 2-chlorotetrahydropyran.

Once a .cube and coordinate file have been prepared, they should be opened with a molecular visualization program capable of reading .cube files and rendering a 3D printing formatted output file. Choices include VMD,<sup>17</sup> PyMOL,<sup>18</sup> Chimera,<sup>19</sup> and Jmol,<sup>20</sup> with each software offering different advantages and disadvantages. VMD and Chimera, for example, are able to produce .stl files, one of the most common 3D printing formats that should work with most consumer grade 3D printers. As of the time of this publication, PyMOL can only produce .wrl files, which can be used by commercial 3D printing companies and can contain information for printing in color, but may not be compatible with consumer machines (.wrl files can be converted to .stl files). PyMOL does, however, visualize meshes as three dimension objects rather than lines, allowing the meshes to be rendered when a 3D printing file is prepared.

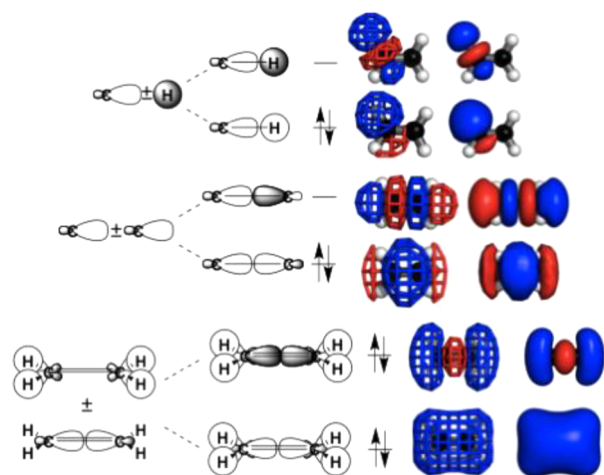
With a cube file and 3D coordinates loaded into a molecular visualization program, one must first produce the desired orbitals by generating an isosurface, the surface at which the molecular orbital function in the .cube file has a given value. The exact method for generating the surface should be provided in the documentation for the visualization software being employed. Typically, a positive and a negative isosurface will be necessary to represent both phases of the molecular orbital. If one is desiring to produce an orbital with a mesh surface, the resolution of the grid in the cube file and/or in the visualization software must be considered carefully. Too wide of a spacing in the mesh will lose information about the exact shape of the orbital, including a loss of symmetry in some cases. A mesh with very fine spacing will have the same visual effect as a surface. In the molecular orbitals provided in the [Supporting Information](#) that are depicted as meshes, care was taken to attempt to find a mesh spacing as wide as possible without too much distortion. However, it is up to the individual to determine the best grid spacing for their particular model and the size they intend to print. It should also be noted that the width of the mesh should be fairly wide to provide sufficient structural integrity to the model. This is especially true if printing in color, as at the time of this publication the most popular material used to print multicolor models predominately consists of calcium sulfate hemihydrate, that is, plaster of Paris. This material is very brittle and weak,<sup>21</sup> potentially causing structural integrity issues when the orbitals are represented as meshes. Printing in white plastic and painting is highly recommended for

these to produce the most robust, classroom-friendly models. However, recent technological advances, including the development of full color plastic printing,<sup>22</sup> should provide direct printing of color mesh orbitals in the near future.

Once the isosurface or isomesh is finished, the molecule itself needs to be rendered. The classic ball and stick model works particularly well, but care should be taken in ensuring the bonds are wide enough for good structural integrity. Finally, if any of the orbitals do not physically connect to another part of the model, it will be necessary to draw struts connecting any disjointed pieces. This is again something most programs can do. For example, in PyMOL, a cylinder can be drawn between two points in Cartesian space with a desired width and color by using the command `cmd.load_cgo`. As soon as the model is finalized, one simply has to save the work as a .wrl, .stl, or other compatible file depending upon what is available with the molecular visualization program being used and the desired method of printing. Some 3D modeling programs, as well as Chimera, are capable of converting from one file format to another. The 3D print files prepared by these modeling programs may still have errors that could complicate printing. Many commercial printing companies will repair the models when they are uploaded automatically. If using a consumer printer, it may be necessary to use a free service like Microsoft 3D model repair to fix any issues.<sup>23</sup> A full pictorial walkthrough of this process with Gaussian and PyMOL is provided in the [Supporting Information](#).

### Example 3D Models for Concepts in Physical Organic Chemistry

There are several concepts in physical organic chemistry that can be readily explained with the aid of three-dimensional models of molecular orbitals. First, atomic orbitals for hydrogen ([Supporting Information Figure S1](#)) can be printed to supplement the introductory quantum chemistry portion of undergraduate general chemistry. These can then be built upon to demonstrate how bonding orbitals are generated from atomic and hybrid orbitals. An example is provided in [Figure 2](#), where the C–H and C–C  $\sigma$  bonding and antibonding orbitals are depicted for ethene. These orbitals were generated in Gaussian with HF/3-21G calculations, and NBO analysis was used to produce localized orbitals. Small basis set calculations are usually sufficient for producing 3D orbital models. Also included in [Figure 2](#) is an example of how the C–H and C–C bonding orbitals combine to make two of the ethene molecular orbitals, which come directly from HF/3-21G calculations. The 3D print files themselves were rendered in PyMOL, and .stl files for



**Figure 2.** Diagram depicting how to construct (A) a C–H  $\sigma$  bonding and antibonding orbital from an  $sp$  hybrid orbital from a carbon atom and an  $s$  orbital from a hydrogen atom, (B) a C–C  $\sigma$  bonding and antibonding orbital from two  $sp$  hybrid orbitals, and (C) ethene molecular orbitals from the linear combination of four C–H  $\sigma$  bonds and one C–C  $\sigma$  bond. Each of these principles is then represented for ethene in a 3D print file. C–H and C–C orbitals were generated by performing NBO analysis.

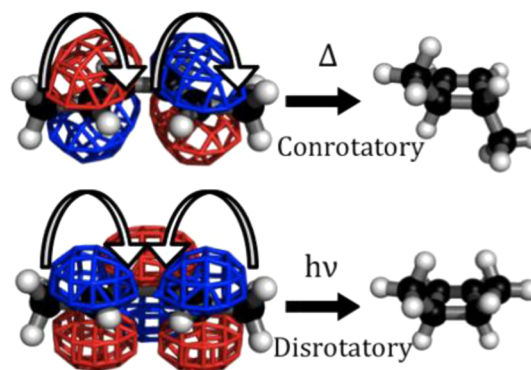
each of these models are available online as described in the [Supporting Information](#).

More advanced concepts that can be illustrated by 3D printing of molecular orbitals include conformational phenomena like the anomeric effect in carbohydrate chemistry. The anomeric effect is caused by the orbital mixing of high-energy lone pair orbitals on the ring oxygen of sugars with low-energy unoccupied molecular orbitals for adjacent electronegative substituents. This mixing can only occur when the orbitals are properly aligned, as they are in 2-chlorotetrahydropyran when the chlorine is in the axial position. This causes the axial position for the chlorine to be favored by 1.8 kcal/mol in chloroform, whereas for chlorocyclohexane, the equatorial chlorine conformer is preferred by 0.6 kcal/mol.<sup>24</sup> The model of this phenomenon in [Figure 1](#) was prepared by overlaying the HOMO of water and the LUMO of chloromethane on the structure of 2-chlorotetrahydropyran; however, similar results can be obtained with NBO analysis. Also illustrated in [Supporting Information Figure S2](#) are models prepared with the same orbitals and the chlorine equatorial, and an example of the more general gauche effect for 1,2-difluoroethane.

Pericyclic examples also lend themselves well to demonstration with 3D printed orbital models. An example appropriate for introductory organic chemistry classes would be for the Diels–Alder reaction between ethene and 1,3-butadiene showing the HOMO/LUMO match. Printed example models of this Diels–Alder reaction are shown in [Figure 1](#). Physical models of orbitals can be used to explain the stereochemistry of electrocyclic ring closing and opening reactions. The model of the HOMO of 1,3-butadiene, for example, can illustrate for students the conrotatory nature of the thermal ring closing, whereas a model of the LUMO can demonstrate the disrotatory photochemically induced reaction. It may prove beneficial to add substituents and to print a model of the substituted product to assist students in understanding the stereochemical outcome ([Figure 3](#)).

## CONCLUSION

In this work, a general procedure for generating 3D models of molecular orbitals was presented and several potential uses for



**Figure 3.** Demonstration of how 3D printed orbitals can be used to demonstrate the stereochemical outcomes of electrocyclic reactions. To generate these models orbitals for the HOMO and LUMO of 1,3-butadiene from HF/3-21G calculations were overlaid on the structure of substituted 1,3-butadiene.

these models in the chemistry classroom were suggested. These are just a few possibilities of the many phenomena that can be illustrated with 3D printed orbitals, spanning not just physical organic chemistry but extending into other areas of chemistry as well. Inorganic chemistry in particular offers numerous examples of coordination complexes involving higher angular momentum orbitals. These techniques can also be extended beyond molecular orbitals to other molecular surfaces. Electronic structure packages can often also generate cubes of electrostatic potential and electron density from the results of a QM calculation. Further, properties can be mapped onto surfaces as color gradients, for example, the electrostatic potential at each point on a molecular orbital can be mapped out onto it in color. This could then be printed in full color, providing a captivating representation of the ESP along a molecular orbital. Even the maps from an X-ray diffraction experiment can be loaded into a program like PyMOL to generate a model of the experimentally measured density for a crystal structure. 3D printing has allowed for high quality bespoke models for use in chemical education to become a reality.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available on the [ACS Publications website](#) at DOI: [10.1021/acs.jchemed.5b00682](https://doi.org/10.1021/acs.jchemed.5b00682).

A document containing figures of 3D printed atomic orbitals and further examples of the anomeric and gauche effect, as well as a fully illustrated tutorial for producing files with Gaussian and PyMOL. 3D models in the .stl file format are available free of charge via the Internet at [traken.chem.yale.edu](http://traken.chem.yale.edu). (PDF)

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### Notes

The authors declare no competing financial interest.

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