JOURNAL OF CHEMICAL EDUCATION

pubs.acs.org/jchemeduc Article

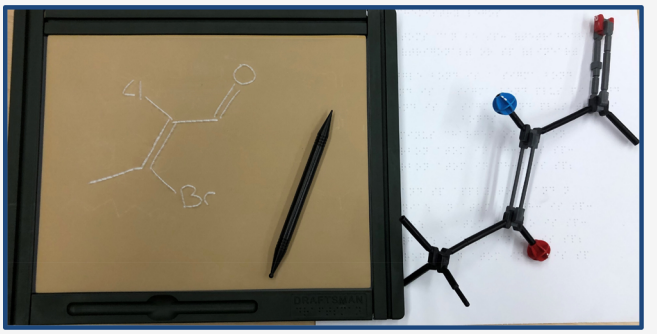
Introductory Organic Chemistry (First-Semester) for Blind and Visually Impaired Students: Practical Lessons and Experiences

Jon T. Njardarson*

Cite This: *J. Chem. Educ.* 2023, 100, 3960−3967 Read Online

ACCESS | Metrics & More | Article Recommendations

ABSTRACT: This article describes practical lessons and experiences acquired as part of a journey in teaching a blind student at The University of Arizona to master the written and graphical language of first-semester organic chemistry and its associated concepts. These practical lessons include details on how to adapt an organic chemistry model set (with simple, minimal modifications) to make it suitable for teaching organic chemistry to blind and visually impaired students and lesson examples of how the modified model sets are an indispensable tool to effectively teach a majority of foundational topics in first-semester organic chemistry in concert with a tactile drawing board. Printing chemical structures and text in braille, along with semester printing preparations to ensure smooth experiences for students, teachers, and support staff, is a recommendation, as is the prioritization of one-on-one teaching to ensure the best possible outcomes.



KEYWORDS: *Organic Chemistry, Visually Impaired, Blind, Model Sets, Tactile Drawing Board, Braille Printing*

INTRODUCTION

In the summer of 2022, for the first time in my career, I learned that I would be teaching a blind student how to master first-semester organic chemistry during the following semester. In the fall, I typically teach two large introductory organic chemistry classes (250−300 students each). I was excited about this teaching challenge and the learning experiences I would acquire along the way. At the same time, I was surprised that 18 years after I began my independent career and after having taught introductory organic chemistry to close to 7000 undergraduate students, this was the first time a blind or visually impaired student had enrolled in my classes. The class was a requirement for the student, and the student also took the accompanying organic chemistry lab section. Conversations with my senior University of Arizona organic chemistry colleagues in the Department of Chemistry and Biochemistry quickly revealed that none of them had taught a blind or visually impaired student. This perplexed me but at the same time made me extremely motivated to take on this journey and use a one-on-one teaching setting so that I could best serve and support the student, while at the same time learn as much as possible about unmet challenges, how best to instruct, and insights into advising that might account for these surprising statistics. I am writing this article to make the journey of preparing and running similar organic chemistry-focused courses hopefully easier to launch, run, and manage for other instructors by sharing what teaching tools were most effective for the student along with detailed insights into how I ran the course.

GETTING STARTED: ESSENTIAL TEACHING AIDS

I benefitted from reading and learning from a published account[1] and recommendations[2,3] from Dr. Supalo's time as an undergraduate and graduate student. Insights gathered from learning about the instructor's perspective also provided informative lessons, notably from Professor Poon,[4] Professor D'Agostino,[5] and Professor Tantillo.[6,7] Importantly, email and Zoom conversations with Professor Mary Watson (University of Delaware) provided me with invaluable insights and recommendations based on her recent experiences, which enabled me to get the semester off to a good start.

After going on this amazing teaching journey in Fall 2022, I concluded that, in addition to conducting the instruction in a critically important one-on-one teaching format, there are three specific teaching aids that are essential (and sufficient) for an instructor and student to realize full mastery of the content and concepts of first-semester organic chemistry without any *loss in*

Received: June 26, 2023
Revised: September 4, 2023
Published: September 18, 2023

https://doi.org/10.1021/acs.jchemed.3c00616
J. Chem. Educ. 2023, 100, 3960−3967

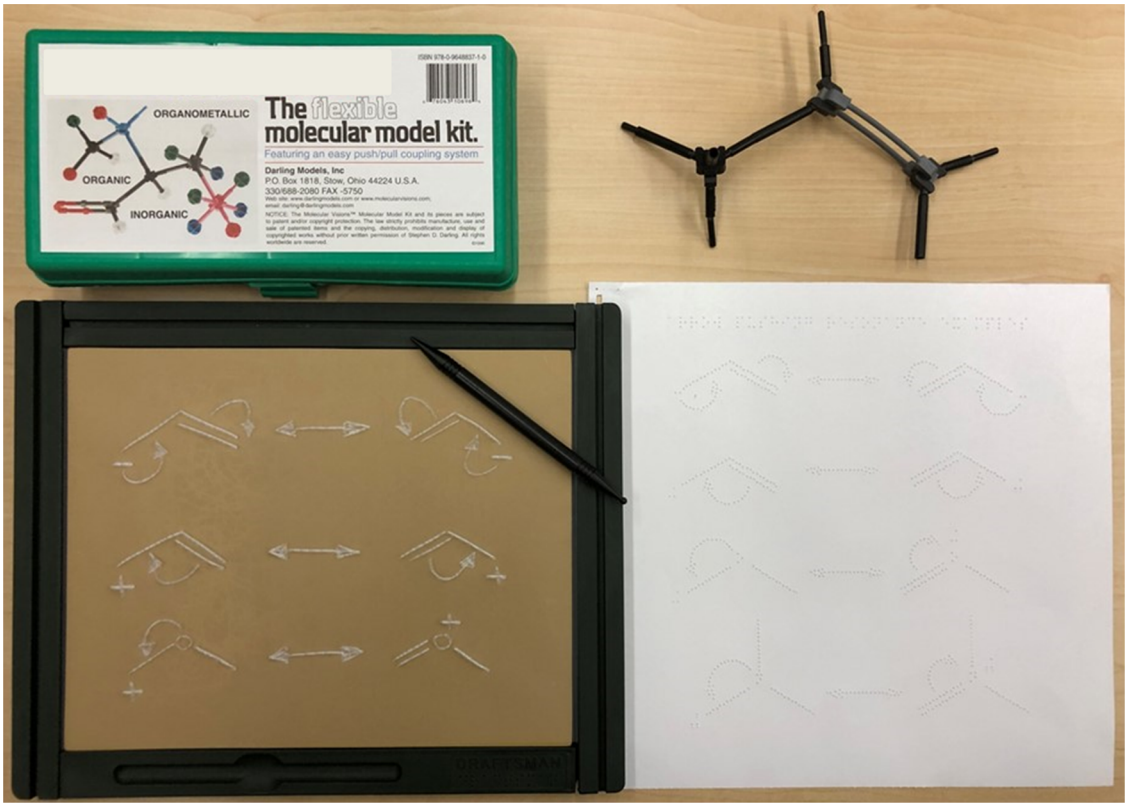


Figure 1. Essential teaching aids for organic chemistry: tactile drawing board, modified organic model kit, and braille printing output.

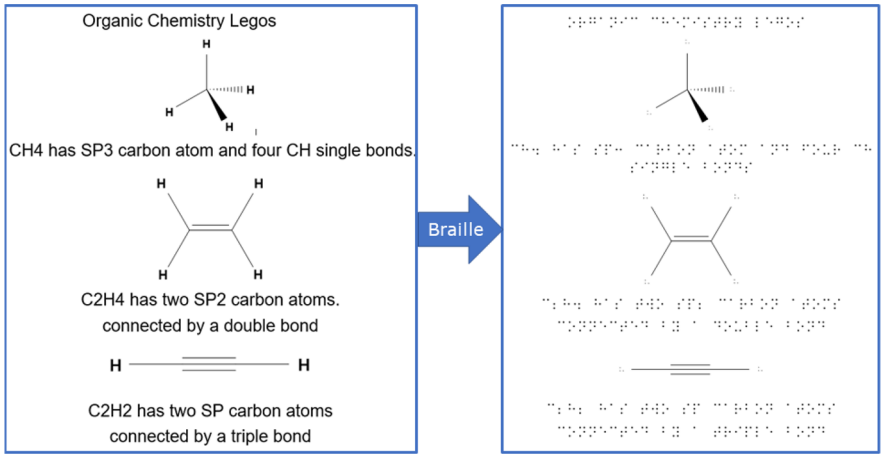


Figure 2. Example of carbon atom hybridization summary converted into a braille format for text and atom labels.

translation. Figure 1 displays these three critical teaching aids. First, a **tactile drawing board** is indispensable to allow the instructor and students to draw and show each other images in one-on-one teaching sessions. Second, a **modified organic model kit** ensures that the student can master the structural and three-dimensional (3D) language of organic chemistry and then communicate it on a tactile drawing board (vice versa). Third, access to a **braille printer and fonts** enables the printing of textbooks, custom teaching content, practice questions, and exams.

To create custom-support printed course material (notes, summaries, etc.), it is essential to install a font on your computer such as Braille29.ttf (ttf = TrueFont type), for use in Word, PowerPoint, ChemDraw, and other programs to convert written text and labels into printable braille fonts. In creating custom material for printing, it is important to remember that Braille printing paper is 11.5 in. × 11 in. in size. Once a page setup is complete, custom content text is created in regular fonts (I used Arial) and then converted into Braille29 font, at which point the final layout on the page is optimized since the final braille text invariably uses more space than the original font. In ChemDraw, all atom labels are created in large formats with special care for significant space between the end of a bond and the beginning of an atom label, which ensures that, once printed, it is easy to distinguish the braille-printed atom labels from the dots associated with bonds. Once atom sizes and positions are optimized, they are converted to Braille29 font, and the image is both copied into a Word document containing the associated text and scaled to ensure that the atom label dots are of appropriate size to be legible for printing. This might require

https://doi.org/10.1021/acs.jchemed.3c00616
J. Chem. Educ. 2023, 100, 3960−3967

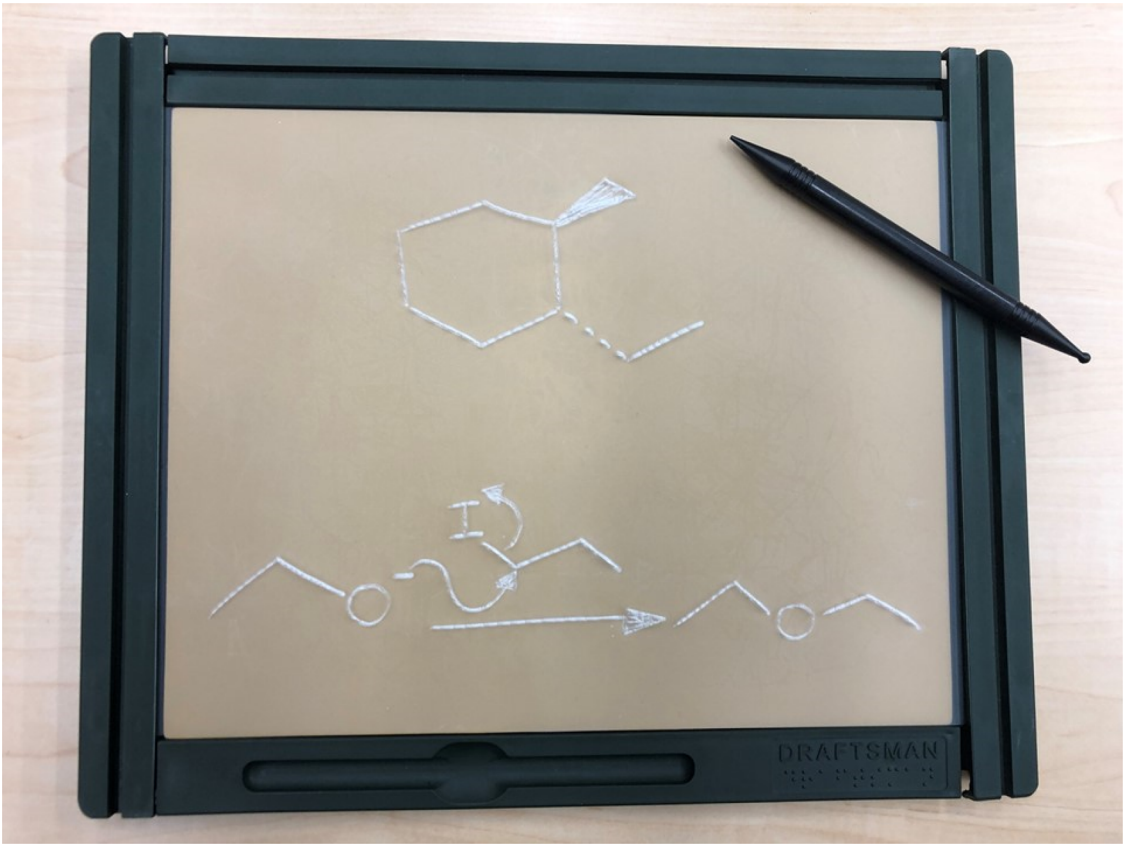


Figure 3. Drawing example using a draftsman tactile drawing board, tactile drawing film, and a marking pen.

some minimal experimentation, which is simply done by having the student read the content and confirm that nothing is lost in translation. Once that is settled, you are ready to go with a format for converting text and chemical structures into the braille format for the rest of the semester. Figure 2 is an example of a one-page summary detailing carbon atom hybridization with the *left* panel created in Word (Arial font) and the *right* panel created in ChemDraw representing the same information content after braille font conversion for both the Word text and atom labels in ChemDraw.

A tactile drawing board is a vital tool for one-on-one teaching to ensure a clear understanding of the content covered in a lecture in printed braille material (textbook and custom content) as well as to confirm between the student and instructor a better understanding of organic models and their conversion from 3D models to two-dimensional (2D) representations on paper. Discussions with the student and other experts quickly pointed to the Draftsman Tactile Drawing Board from the American Printing House as the best-suited product for the organic chemistry drawing tasks required to achieve full mastery. This tactile drawing board is incredibly easy to use, and I found it to be indispensable in our one-on-one communications and in realizing the semester teaching goals. A tactile drawing film is first placed and secured on the drawing board, and then a marking pen is used to draw images (apply force) on the film (Figure 3). It is important to first optimize the size of images that are easy for students to read. This is simply done by drawing several sizes and asking the students to indicate which size is easiest for them to read. Ensure that bonds represented by wedges/dashes (stereochemistry) are clearly drawn and readily distinguishable from in plane bond lines and each other, atom labels are separated from the end of lines, and the arrowheads are substantial in size. An important added benefit of using a tactile drawing board is that each completed film (sheet) can then be removed as a permanent note page for the student to keep, revisit, and review later. In my experience, I found that it is better to not overfill each sheet and instead aim for clarity and graphical minimalism when communicating concepts and content.

■ ORGANIC CHEMISTRY MODEL

Organic model kits are important to achieve full mastery of the 3D structural language of organic chemistry and the graphical conversion of these structures onto 2D surfaces. In service of blind and visually impaired students, instructors have explored various approaches to tackle this communication challenge, such as toy building blocks,[8] magnet-models,[9] innovative and affordable homemade models,[10] cleverly designed 3D-printed molecular models[11,12] including ones with different textures for different atom types,[13] a chemoinformatic approach to read structure names aloud,[14] and creative contributions for biomacromolecules that use the mouth for sensing.[15]

For many years, one of the most affordable and useful organic molecular models that I have recommended for my classes is the Molecular Visions plastic model kit. These models are lightweight, flexible, and easy to use, and they turned out to be vital to the success of teaching the class while also making it more enjoyable for the students and myself. The sizes of assembled molecules using this model kit are in my opinion particularly well suited to feel and touch by hand, which enables the student to easily distinguish structural differences and then move onto more challenging tasks like conformations and

https://doi.org/10.1021/acs.jchemed.3c00616
J. Chem. Educ. 2023, 100, 3960−3967

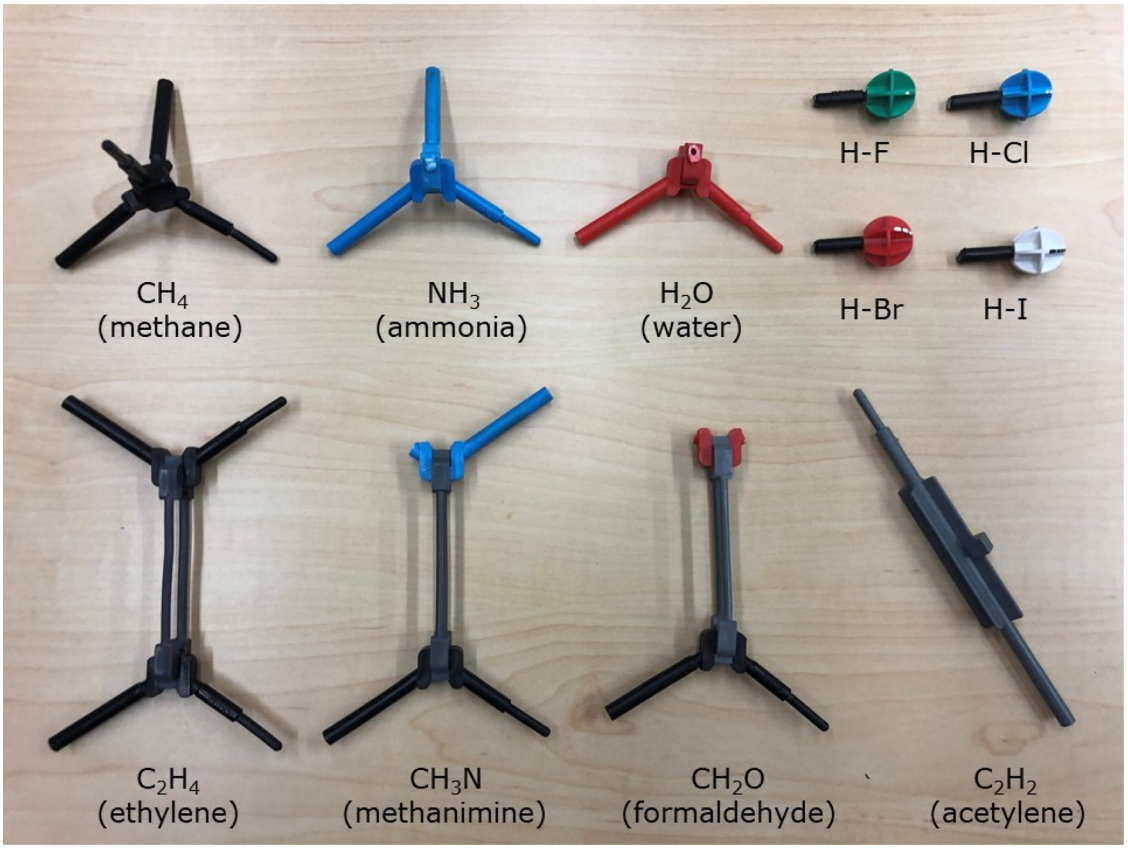


Figure 4. Organic chemistry building blocks: hybridization of carbon, oxygen, and nitrogen and designer halogen labeling.

explanations of reaction outcomes. Organic chemists' work has many similarities to how architects, engineers, and builders use their craft and tools to realize designer houses and other products.[16] Organic chemists do the same thing but at the smallest scale on which one can build complex designer molecular architectures in this world, using atoms for construction with a primary focus on the key elements of life, namely, carbon (C), hydrogen (H), oxygen (O), and nitrogen (N).

I made simple adaptations to this standard molecular kit to make it well suited for teaching visually impaired/blind students (Figure 4). I began by adapting the model kit to display sp^3-hybridized nitrogen, oxygen, and halogens (Figure 4, top row). In the case of nitrogen (*blue*, NH_3 = ammonia), I used scissors to cut off one of the bonds and then assembled a tetrahedron missing one bond (representing a lone pair) to represent the sp^3-hybridized nitrogen atom. Similarly, for oxygen (*red*, H_2O = water), I cut off both bonds of one molecular fragment and then assembled a tetrahedron missing two bonds (representing two lone pairs) sp^3-hybridized oxygen atom. For the halogens, different adjustments had to be made to realize the desired model kit communication goal. The attachment of labels, including ones with braille lettering, turned out to be cumbersome and the outcome undesirable. Fortunately, the Molecular Visions kit comes with differently colored spherical units that have single bond attachments, which seemed like a great fit to represent halogens. Furthermore, the colors of these spherical units served the added purpose of differentiating the halogens for an instructor. The final key adjustment was realized by applying Tulip *Puffy Paint* to make different number marks on the spheres that could be felt by touching. As in Figure 4, one mark was chosen to indicate fluorine (HF shown), two marks for chlorine (HCl shown), three marks for bromine (HBr shown), and four marks for iodine (HI shown). These marks allowed the student to easily differentiate the halogens on any structure.

In the case of sp^2-hydridization (Figure 4, bottom row), formaldehyde (CH_2O) and methanimine (CH_3N) are examples of how the model adaptations made for the sp^3-case also fit perfectly for the sp^2-case and without further changes (one arm cut off the blue and two arms cut off the red model building blocks, respectively) as double bonds are provided as part of the model kit. With this model kit, alkynes (sp-hybridization, Figure 4, bottom row) can be shown for carbon but not for nitrogen. Given that 99%+ of the molecules used in teaching organic chemistry rarely use sp-nitrogen (except for N_2 and CN = nitrile), it is a reasonable minor compromise that can readily be addressed by the use of a tactile drawing board drawing of such structures when relevant. It is worth noting that the Molecular Visions kit models, as for a vast majority of the available organic models, do not display heteroatom lone pairs (O, N, F, Cl, Br, and I). Indeed, the models would become too cumbersome and complex, which is also consistent with how professional organic chemists draw organic structures: lone pairs are rarely displayed unless they are needed to highlight reaction mechanisms or specific interactions beyond displaying the standalone structure. As part of one-on-one discussions and with a custom braille write-up, the student is taught that the lone pairs are there, even if they are not displayed. Our model adaptations make it easy to identify what atoms are in play and thus, in turn, where lone pairs are.

The model adjustments in Figure 4 proved to be an excellent and essential teaching tool throughout the semester by

https://doi.org/10.1021/acs.jchemed.3c00616
J. Chem. Educ. 2023, 100, 3960−3967

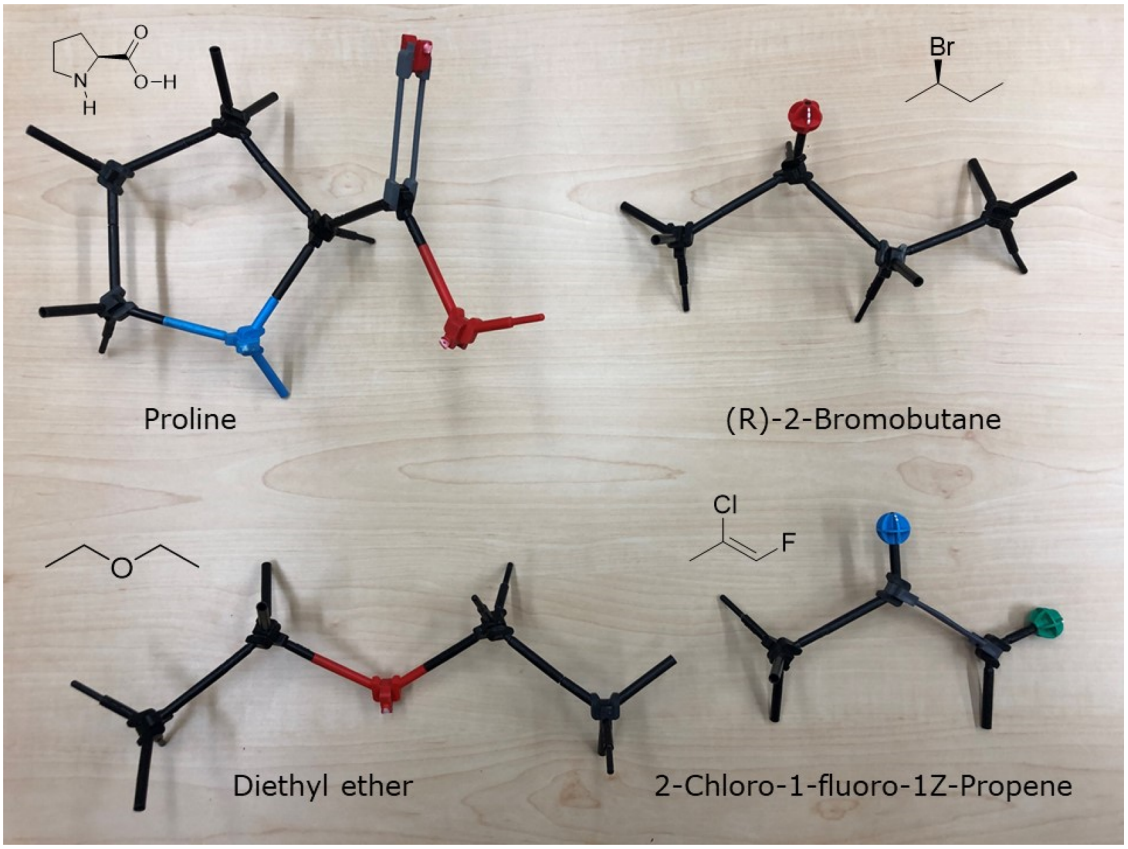


Figure 5. Examples of cyclic, acyclic, and chiral organic structures with a modified organic model kit.

providing the blind student with the exact same level of detailed structural experience and mastery of the material that I delivered to the rest of the students in the class. It is my sincere opinion that it is not possible to adequately teach organic chemistry to blind or visually impaired students without the help of a model kit. Figure 5 shows examples of additional structures used during the semester along with their names and ChemDraw structures, which further highlight applications of the model adjustments I made.

■ ORGANIC CHEMISTRY CONCEPT LESSON EXAMPLES.

The blind student enrolled in one of my 300-person first-semester organic chemistry courses in the Fall of 2002. The class meets three times a week (Monday−Wednesday−Friday) for a 50 min lecture along with office hours. Before the semester started, I contacted the University of Arizona Disability Resource Center (DRC) to set up the braille printing of the course textbook and to ensure that the printing of each chapter would be complete in a timely fashion for the student to follow the exact flow of material covered in a lecture. The DRC also printed all of the custom braille content material I created during the semester as well as the exams in braille. I quickly realized that the only way I could ensure that the student received the best possible teaching experience and that I would learn as much as possible from this experience was by instructing the student in a one-on-one teaching format. By consulting with the student and being respectful of the student's schedule, a successful weekly schedule was established wherein the student (and support dog) attended lectures with the rest of the class, listened to the lecture, and captured as much of the language content as possible. Immediately after a lecture, three times a week, I walked the student over to my office, and with three University of Arizona preceptors (all of whom had taken this exact course with me the year before), we met for about an hour during which we covered and tested organic chemistry content and concepts. We used the modified organic model kits, the tactile drawing boards, and the braille printouts to ensure that the student could master and enjoy all aspects of learning the wonderful language of organic chemistry. For exam review sessions and extra problem sessions, the preceptors met additionally with the student for 1−2 h. This schedule and approach enabled us to remain in sync with the class in our coverage and achieve the exact level of mastery for the student. The midterms and final exam were conducted in my office, where I provided custom created braille-printed exam questions, and the student used the tactile drawing board and model kit to communicate their answers to me one-on-one. This exam format worked fantastically well, ensured that nothing was lost in *translation*, and gave the student opportunities to clearly communicate their mastery of the subject matter. I went to great lengths to recreate the exact same exam questions at the same level of difficulty as those presented to the sighted students to ensure that grading was equitable.

For the class, I use the Smith Organic Chemistry textbook (3rd−6th editions).[17] The class has four midterm exams of which the grades from three midterms count toward the final grade and a final comprehensive exam. In the sections below, I discuss broadly how the topics and concepts for each midterm exam were taught and tested by using the tactile drawing board, model kit, and braille-printed content in a one-on-one teaching format.

https://doi.org/10.1021/acs.jchemed.3c00616
J. Chem. Educ. 2023, 100, 3960−3967

Midterm 1

For midterm one, I covered chapters 1 (structure and bonding), 2 (acids and bases), and 4 (alkanes). I began the class by using the model kit and the tactile drawing board to explain the building blocks of organic chemistry, namely, sp^3-, sp^2-, and sp-hybridization and σ- and π-bonds for carbon, and how these apply to oxygen, nitrogen, and the halogen atoms. An important part of this task was to build and touch the structures and then to master the crucial task using the tactile drawing board to convert these 3D objects into clear 2D images through wedges and dashes that indicate atoms/objects further away or closer, respectively. It is critical when displaying with a tactile drawing board or braille-printed images to communicate organic structures that chemical bonds whose stereochemistry is represented by wedges and dashed are exaggerated in size and filled in well and that the lines are well spaced out for dashes to ensure that they are easily distinguished by touch from bonds in the plane.

It is important to ensure that the student quickly comprehends structure and bonding and how to clearly communicate using the models and then translate the model structure to a drawn structure and vice versa. Practice extensively until the student is happy, and it is clear to them and you that they have established fluency in using the model kit and communicating those structures clearly and precisely on the tactile drawing board. Early mastery of structure and bonding with these tools impacts the success of teaching everything that follows for the rest of the semester.

For chapter 2 (acids and bases), use of the tactile board and supporting braille-printed content is critically important as the first class of reactions (acid base reactions) and movement of electrons using arrow pushing is introduced, along with a discussion of resonance and analysis of conjugate bases and the significant role atoms, atom size, resonance, and inductive effects play in this context. It is important that all images be of good size, use large arrowheads for reaction arrows, and have atom labels and atom charges (plus and minus) that are clearly readable and separated in space from the end of bonds to avoid confusion when the student reads the tactile drawing board of braille-printed content.

In chapter 4, the naming of alkanes is covered (usually C1−C10, methane to decane), along with the conformations of acyclic and cyclic alkanes. In mastering the content, the model set is again an indispensable teaching aid as it allows the student to build their own structures and get an actual feel for conformations by learning how to rotate bonds and how the size of atoms impacts conformations. We started with ethane, progressed to butane, and moved into discussions of cycloalkenes with a primary focus on cyclohexanes, chair conformations, and the differences between axial and equatorial positions. These lessons involved starting with a braille-printed or tactile board drawn 2D structure and then building the model to match it or the reverse where the student received an assembled model structure and had to demonstrate and then draw its lowest conformation on the tactile drawing board.

On the first braille-printed exam, the student was asked to communicate their expertise to the instructor by (1) analyzing the hybridization of a complex molecule; (2) drawing the reaction mechanism for making the conjugate acid and base of a structure with multiple heteroatoms; (3) identifying the most acidic hydrogen atom in multiple diverse organic structures; (4) providing exact names for organic structures; (5) drawing conjugate base and resulting resonance forms of structure with two different carbonyl groups; (6) using the molecular model to build a specific disubstituted cyclohexane and then demonstrate the best and worst chair conformations using the model; (7) building a specific 2,3-disubstituted butane structure and demonstrating its lowest energy conformation using the model; and (8) drawing the structures of all constitutional isomers of a small haloalkane (C_3H_6BrF).

Midterm 2

Organic chemistry, unlike other early subjects in college, is always comprehensive, as the new concepts and topics that are progressively presented throughout the semester build upon what was covered earlier. For midterm 2, I expanded the coverage to include chapters 5 (stereochemistry) and 7 (alkyl halides and nucleophilic substitution). Stereochemistry is challenging to explain in this context, as some of the typical analogies one might use (mirror image, etc.) are not that helpful, while terms such as "handedness" are more useful and relatable. Again, the modified organic model kit was a true *lifesaver* in teaching this centrally important concept for chapter 5. I first built enantiomers of a simple structure containing a single stereocenter and allowed the students to compare them and figure out exactly how they differed from one another. Once the difference was established and understood, the definitions of enantiomers, stereoisomers, and *R*/*S*-naming could proceed. This concept was then practiced extensively by analyzing structures and making sure that mastery of translation from a chiral structure model to the tactile board was accomplished (and vice versa) by precisely using wedges and dashes in drawings. From there, we proceeded to discuss diastereomers and meso-compounds and finished by discussing other curious forms of chirality (allenes and axial chirality).

We then transitioned to chapter 7 and the first reaction class categories, namely, nucleophilic substitutions (S_N2 and S_N1), with a focus on alkyl halides (chlorides, bromides, and iodides) that involved the expansion of naming to include alkyl halides. These discussions focused on the size of atoms, functional groups, molecular structures, partial charges, the definition of a leaving group, trajectory of attack in an S_N2 reaction, and the formation and stability of carbocations in the context of S_N1 reactions. In one-on-one sessions, the models and the tactile drawing board were indispensable in covering the reactions in detail by building structures and getting an actual feel for differences in atom and substituent sizes, presenting how exactly a nucleophile approaches an electrophile in an S_N2 reaction, and demonstrating changes from sp^3 to sp^2 as a carbocation forms and the impact of neighboring atoms on the stability of carbocations. The hybridization of carbocations was presented as well as details about how the size of a neighboring or adjacent atom and substituents impacts the preferred product outcomes, particularly in cyclic structures. The significance of the size of directly attached or neighboring atoms and substituents and their electronics on the success of the S_N2 and S_N1 reactions was discussed.

On the second braille-printed exam, the student was asked to communicate their expertise to the instructor by (1) assigning *R*/*S* stereochemistry of the highlighted stereocenters of the US FDA approved drug (2022) ganaxolone; (2) providing exact names for three chiral compounds (one a cycloalkane and two acyclic compounds with 2−3 stereocenters); (3) drawing the chemical structures of compounds corresponding to specific names; (4) indicating if a molecule is chiral or not (four examples); (5) comparing a reference structure to three others and indicating if

https://doi.org/10.1021/acs.jchemed.3c00616
J. Chem. Educ. 2023, 100, 3960−3967

the structures are enantiomers, diastereomers, or the same; (6) building the structure of natural carbohydrate glucosamine (structure provided) and demonstrating with the model its most stable chair conformation; (7) identifying the most acidic proton of a chiral molecule and using its conjugate base to draw (or build) the structure of the resulting intramolecular S_N2 reaction; (8) drawing the structures of the products resulting from possible S_N2 or S_N1 reactions (six examples); and (9) demonstrating the reaction mechanism for a specific S_N1 reaction and showing all possible products (resonance involved).

Midterm 3

For midterm 3, the coverage expanded to include chapter 8 (alkyl halides and elimination reactions), chapter 9 (alcohols, ethers, and epoxides), and naming only from chapter 10 (alkenes). With chapter 8 covering the *other side* of substitution reactions, namely competing elimination reactions, I discussed β-hydrogen atoms and their relationship to the nucleophile in an E2-reaction for which the model kit was indispensable in precisely conveying this information. The impact of different leaving groups was presented, as well as impacts from the size and electronics of the substrate and base and examples of how (in the context of E2-reactions) specifically changing the size of the base drastically enables the control of the least- or most-substituted double bond product. Chapter 9 revisits S_N2, S_N1, E1, and E2 reactions for different functional groups (alcohols and epoxides) with a discussion of how these functional groups can be converted into leaving groups using protonation or designer reagents (phosphorus and sulfur reagents $POCl_3$, PBr_3, $SOCl_2$, and TsCl) capable of delivering specific S_N2, S_N1, E1, and E2 reaction outcomes. Finally, the names of the alkenes were carved from chapter 10 for testing.

On the third braille-printed exam, the student was asked to communicate their expertise to the instructor by (1) naming molecules containing double bonds in acyclic and cyclic structures; (2) drawing the chemical structures of double bond-containing compounds corresponding to specific names; (3) drawing the structure of the resulting product when a specific starting material is treated with 1 equiv of a specific nucleophile; (4) drawing the major product resulting from treating a specific structure (chiral cyclohexane with two alcohols) with excess amount of $POCl_3$ in pyridine (E2-question); (5) using the model kit to build a specific cyclohexane structure (tetrasubstituted cyclohexane) and demonstrating its lowest energy conformation; (6) drawing the structure of the major product formed when (shown) epichlorohydrin is reacted with an excess of a (shown) hydroxide nucleophile to form the product (glycerol); (7) drawing the different major elimination products that would result when a cyclohexane starting material containing a tertiary halide leaving group (structure shown) is treated with a small or large base, for both cases; (8) drawing the major S_N1 and E1 products, as well as the major E2 product, that would result upon treating the structure provided (a cyclohexane with two adjacent stereocenters of which one is a tertiary center having a leaving group) with water and hydroxide ion, respectively; and (9) drawing the major products that would result when an alcohol starting material (a chiral cyclopentane structure with a secondary alcohol) is treated separately with H_2SO_4, $POCl_3$ in pyridine, $SOCl_2$ in pyridine, and PBr_3 and TsCl in pyridine.

Midterm 4

For midterm 4, chapters 10 (alkenes), 11 (alkynes), and 12 (oxidation and reduction) were completed. Models again proved critical in communicating the difference between *E*- and *Z*-alkenes and in precisely building and drawing the starting materials and products. Alkene addition reactions were discussed, including halogen additions, halonium ions, and their stereochemical outcomes. The first syn addition reaction was introduced in chapter 10 (hydroboration oxidation), with multiple other syn addition reactions added in chapters 11 and 12. A carbocentric definition and discussion about oxidations and reductions were presented, with reactions highlighting the manipulations of double and triple bonds and alcohols, as representative significant redox reaction classes.

On the fourth braille-printed exam, the student was asked to communicate their expertise to the instructor by (1) drawing the structures of the products that would result when a specific linear alkyne is treated separately with (a) BH_3 and H_2O_2, (b) H_2SO_4 in H_2O, (c) Na in NH_3, (d) H_2 and Lindlar catalyst, and (e) H_2 and Pd/C catalyst; (2) drawing the structure of the major product that would result when a specific chiral cyclohexene structure is treated with OsO_4, and then building the model and demonstrating its most stable chair conformation; (3) drawing the major product that would result when the provided starting material (a chiral cyclopentene structure) is treated separately with (a) OsO_4, (b) H_2 and Pd/C catalyst, and (c) O_3, and (d) m-CPBA; (4) drawing the product that would result from each reaction step when the starting material (1-pentyne) is treated sequentially with the following reagents, NaH then CH_3CHO (step 1), H_2 and Pd/C catalyst (step 2), and CrO_3 in pyridine (step 3) with $C_7H_{14}O$ provided as a hint for the product's molecular formula; (5) drawing the product that would result from each reaction step when the starting material (ethylene glycol) is treated sequentially with the following reagents, PBr_3 (excess used, step 1), NC^- (cyanide, excess used, step 2), and H_2 and Pd/C catalyst (step 3), with $C_4H_{12}N_2$ provided as a hint for the product's molecular formula; (6) drawing the product that would result from each reaction step when the starting material (symmetrical *E*-alkene structure) is treated sequentially with the following reagents, (1) O_3 (step 1), and (2) $NaBH_4$ (step 2); (7a) identifying the structure of the product that results from treating the structure provided (a chiral terminal epoxide) with $LiAlH_4$; (7b) drawing the products that would result by reacting the structure (cyclohexanones with a double bond) separately with $NaBH_4$ and m-CPBA; (7c) drawing the products that would result by reacting 1-butyne separately with BH_3 and H_2O_2 or H_2SO_4 in H_2O; and (8) drawing the reaction mechanism that explains how a specific reaction proceeds (a chiral cyclohexene reacted with Cl_2 in H_2O with the product structure shown) using arrow pushing, and showing the structures of all reaction intermediates. The final two lectures of the semester, before the final comprehensive exam, focused on using all of the reactions covered to discuss target synthesis, how to analyze structures, and how to plan their assemblies.

CONCLUSIONS

In conclusion, I hope the above practical lessons and experiences serve as resources to help instructors get their semester off to a great start when teaching first-semester organic chemistry to blind or visually impaired students. Organizing the braille printing setup before the semester starts is critical, with early chapters of the textbook ideally being printed in advance. Access

https://doi.org/10.1021/acs.jchemed.3c00616
J. Chem. Educ. 2023, 100, 3960−3967

to an on-campus braille printing setup is important for the real-time printing of class notes, custom support materials, and exams. Using organic model kits and tactile drawing boards in one-on-one teaching settings is critical for students to achieve full mastery of the material. I cannot emphasize enough how effective and satisfying it was to teach one-on-one: something I strongly recommend for anyone teaching blind or visually impaired students organic chemistry for the first time. Next time, I will ensure to have my class notes preprinted in braille and to create more custom braille-printed content that summarizes the concepts as well as additional problems to work on beyond those in the textbook.

AUTHOR INFORMATION

Corresponding Author

Jon T. Njardarson − *Department of Chemistry and Biochemistry, University of Arizona, Tucson, Arizona 85721, United States;* orcid.org/0000-0003-2268-1479; Email: njardars@arizona.edu

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.3c00616

Notes

The author declares no competing financial interest.

ACKNOWLEDGMENTS

I am grateful to the National Science Foundation for continued support of our diverse educational contribution efforts (CHE-2153657 and DMREF-2118578) and to Cassidy L. Zimmerman, Palmer H. Grabner, and Jillian Sweetland (University of Arizona) for being key players in this journey as preceptors for my class. My biggest thanks and gratitude go to Evamaria Tanori Contreras for taking me on this rewarding and enjoyable teaching journey, and for her positive spirit and honest feedback that enabled the real-time optimization and improvements of teaching. The purchase of critically important tactile-drawing boards was made possible by financial support from the University of Arizona DRC, the College of Science, and the Department of Chemistry and Biochemistry (CBC). I am indebted and thankful to Barbara Lopez, Dawn Hunziker, and Annissa Stout from the University of Arizona DRC for ensuring the braille printing of the textbook and my custom support material was done efficiently and in sync with class coverage for a smooth student experience. Special thanks and gratitude are to Professor Mary P. Watson (University of Delaware) for providing and sharing critical information and experiences, which were essential for catalyzing the success of this teaching endeavor. Finally, I would like to thank Professor Craig A. Aspinwall (CBC) and Dr. Deirdre Belle-Oudry (CBC) for their support.

REFERENCES

(1) Supalo, C. Techniques to Enhance Instructor's Teaching Effectiveness with Chemistry Students Who are Blind or Visually Impaired. *J. Chem. Educ.* **2005**, *82*, 1513−1518.

(2) Supalo, C. A.; Kennedy, S. H. Using Commercially Available Techniques to Make Organic Chemistry Representations Tactile and More Accessible to Students with Blindness or Low Vision. *J. Chem. Educ.* **2014**, *91*, 1745−1747.

(3) Supalo, C. A.; Isaacson, M. D.; Lombardi, M. V. Making Hands-On Science Learning Accessible for Students Who are Blind or Have Low Vision. *J. Chem. Educ.* **2014**, *91*, 195−199.

(4) Poon, T.; Ovadia, R. Using Tactile Learning Aids for Students with Visual Impairments in a First-Semester Organic Chemistry Course. *J. Chem. Educ.* **2008**, *85*, 240−242.

(5) D'Agostino, A. T. Accessible Teaching and Learning in the Undergraduate Chemistry Course and Laboratory for Blind and Low-Vision Students. *J. Chem. Educ.* **2022**, *99*, 140−147.

(6) Laconsay, C. J.; Wedler, H. B.; Tantillo, D. J. Visualization Without Vision − How Blind and Visually Impaired Students and Researchers Engage with Molecular Structures. *J. Sci. Educ. For Students with Disabilities* **2020**, *23*, 1−21.

(7) Wedler, H. B.; Cohen, S. R.; Davis, R. L.; Harrison, J. G.; Siebert, M. R.; Willenbring, D.; Hamann, C. S.; Shaw, J. T.; Tantillo, D. J. Applied Computational Chemistry for the Blind and Visually Impaired. *J. Chem. Educ.* **2012**, *89*, 1400−1404.

(8) Melaku, S.; Schreck, J. O.; Griffin, K.; Dabke, R. B. Interlocking Toy Building Blocks as Hands-On Learning Modules for Blind and Visually Impaired Chemistry Students. *J. Chem. Educ.* **2016**, *93*, 1049−1055.

(9) Boyd-Kimball, D. Adaptive Instructional Aids for Teaching a Blind Student in a Nonmajors College Chemistry Course. *J. Chem. Educ.* **2012**, *89*, 1395−1399.

(10) Fernandez, G. A.; Ocampo, R. A.; Costantino, A. R.; Dop, N. S. Application of Didactic Strategies as Multisensory Teaching Tools in Organic Chemistry Practices for Students with Visual Disabilities. *J. Chem. Educ.* **2019**, *96*, 691−696.

(11) Singhal, I.; Balaji, B. S. Creating Atom Representations Using Open-Source, Stackable 3D Printed Interlocking Pieces with Tactile Features to Support Chemical Equation Writing for Sighted and Visually Impaired Students. *J. Chem. Educ.* **2020**, *97*, 118−124.

(12) Singhal, I.; Balaji, B. S. Open-Source, Tactile 3D Printed Interlockable Tiles Incorporating Valency, Bonding, and Hybridization for Molecular Representation for Sighted and Visually Impaired Students. *J. Chem. Educ.* **2022**, *99*, 1708−1714.

(13) Lounnas, V.; Wedler, H. B.; Newman, T.; Schaftenaar, G.; Harrison, J. G.; Nepomuceno, G.; Pemberton, R.; Tantillo, D. J.; Vriend, G. Visually Impaired Researchers Get Their Hands on Quantum Chemistry: Application to a Computational Study on the Isomerization of a Sterol. *J. Comput. Aid. Mol. Des.* **2014**, *28*, 1057−1067.

(14) Kamijo, H.; Morii, S.; Yamaguchi, W.; Toyooka, N.; Tada-Umezaki, M.; Hirobayashi, S. Creating and Adaptive Technology Using a Cheminformatics System to Read Aloud Chemical Compound Names for People with Visual Disabilities. *J. Chem. Educ.* **2016**, *93*, 496−503.

(15) Baumer, K. M.; Lopez, J. J.; Naidu, S. V.; Rajendran, S.; Iglesias, M. A.; Carleton, K. M.; Eisenmann, C. J.; Carter, L. R.; Shaw, B. F. Visualizing 3D Imagery by Mouth Using Candy-Like Models. *Sci. Adv.* **2021**, *7*, No. eabh0691.

(16) Trauner, D. The Chemist and the Architect. *Angew. Chem., Int. Ed.* **2018**, *57*, 4177−4191.

(17) Smith, J. G. *Organic Chemistry*, 6th ed.; McGraw Hill: New York, NY, 2020.