A Collaborative Model-Based Symmetry Activity for the Inorganic Chemistry Laboratory

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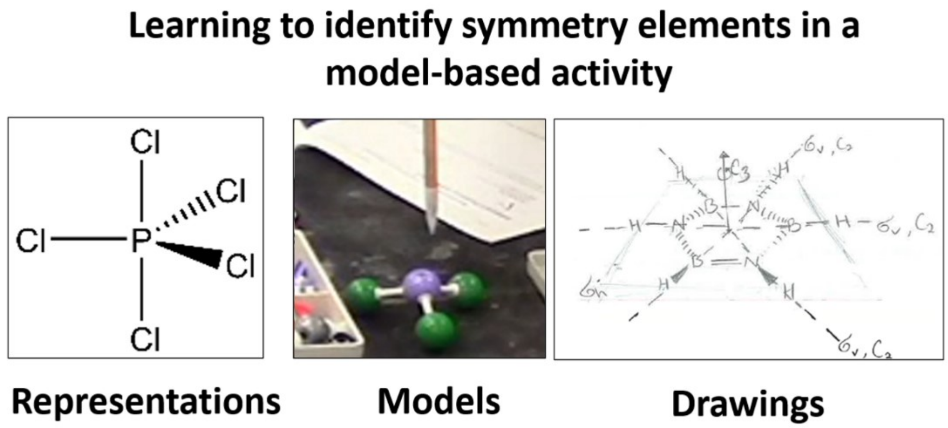
ABSTRACT

A symmetry activity using student-built models was developed in line with faculty-developed pedagogical goals and a collaborative learning framework. The activity took place in a 3-hour laboratory portion of an upper-division inorganic chemistry course. It required students to identify symmetry elements for seven molecules using common 2D representations, student-constructed 3D concrete models, and student-created drawings. Evidence indicates consistent student engagement with specific tasks in the activity and that these tasks provide utility in symmetry element identification. Data on how different parts of the activity contributed to students' increased ability to identify symmetry elements is presented.

KEYWORDS:

Upper-division undergraduate, inorganic chemistry, Hands-on learning/manipulatives, Group Theory/Symmetry, Collaborative/Cooperative Learning, Laboratory Instruction

GRAPHICAL ABSTRACT



INTRODUCTION

Symmetry and group theory are widely taught in inorganic chemistry courses and have been the subject of several papers in this Journal[1,2]. One published symmetry and group theory activity focused on constructing symmetry concepts using 2D geometric objects (i.e., triangles and trapezoids) and 3D molecular representations[3]. Another was centered on thinking critically about the definition of a symmetry element and its effect on a given compound.[4] Some authors have also created games to facilitate student learning of molecular symmetry.[5] Central to these activities is the ability to perceive and utilize the different kinds of symmetry elements involved in point-group symmetry. Here, we describe an activity that focuses on supporting student skills in symmetry element identification itself. To facilitate this, the activity leverages several evidence-based practices: collaborative learning[6], using concrete model kits[4], and drawing.[7]

The activity is designed to be accessible to any upper-level inorganic chemistry classroom and can be readily modified to address specific institutional needs and goals. We collected data in two successive semesters (Fall 2021 and Spring 2022). We analyzed the data for evidence of student learning as they move through different steps: from looking at 2-D representations, to building and manipulating concrete models, and finally to drawing and labeling molecules.

PEDAGOGICAL GOALS

The pedagogical goals for the activity, formulated as part of the learning objectives for a third-year inorganic chemistry course, include:

- Students should know the language of group theory.
- Students should use physical objects to model symmetry elements.
- Students should learn how to find perspectives to look at compounds, and to draw them from scratch.

These pedagogical goals guided the choice of frameworks and design principles for the structure of the activity. These frameworks and design principles, as well as the activity itself, are described further in the following sections.

The activity plays an important role in attaining the overall goals of an upper-level inorganic chemistry course: understanding functional behavior (e.g., reactivity, spectroscopy, color, magnetism, toxicity, etc.) of inorganic compounds from the perspective of their electronic structures, which in turn are partly dictated by local symmetry. As such, multiple learning objectives in the course depend critically on building and solidifying the understanding of structure and symmetry. Prior to this activity, the students typically undergo a brief review of molecular structures from the perspective of VSEPR theory, requiring them to both produce and interpret drawings of Lewis structures with canonical dash/wedge representations of 3-dimensional arrangement. This knowledge is reinforced by multiple components of this activity and represents a foundational skill to learn topics that are introduced in this course for the first time. Nearly simultaneous to this activity, the students undergo a lecture component accompanied by homework assignments that describe the framework of point group theory: identification of symmetry elements, comparisons of symmetry elements between molecules, classification of molecules into point groups, and interpretation of character tables. Progress toward these tasks is greatly facilitated by the familiarity with symmetry elements that the students gain during this activity. This content underpins multiple topics in the course, including vibrational spectroscopy, molecular orbital theory, and ligand field theory, because they are presented using approaches based on symmetry. This hierarchy makes it fundamental for students to master spatial visualization of simple molecules and to develop the ability to identify molecular symmetry elements and classify molecules into point groups.

THEORETICAL FRAMEWORKS

Based on the pedagogical goals, we chose three frameworks to support the design of this activity: collaborative learning, concrete model kits, and drawing.

Collaborative -learning[6,8] serves as a pedagogical framework and organizational lynchpin. The activity encouraged students, via written and verbal instruction, to work with their peers, as they typically do in other experiments.

Concrete model kits enjoy widespread use in general[9,10,11], organic[12,13], and inorganic[4,14,15,16,17,18] chemistry classrooms. We use the term “concrete model” to refer to “physical 3D models that represent the 3D spatial relations between atoms in a molecule.”[12] In this case, we used Duluth Labs’ MM-007 molecular model set[19] in both iterations of this activity. Students were also exposed to virtual simulations in lecture via the Symmetry@Otterbein website, but these were not assigned for use during the activity.

Other publications in this journal have noted the difficulty for novices in identifying symmetry elements[16,20], especially for complex compounds belonging to certain dihedral point groups.[21] The potential utility of model kits is supported by a significant body of literature, both specific to chemistry[22] and beyond[23], that supports the link between cognitive processes and actions or perceptions of the body.

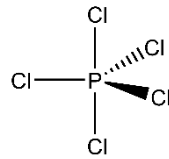
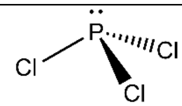
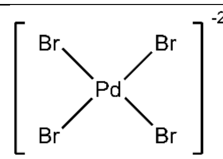
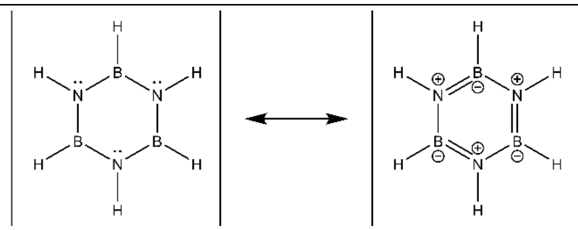
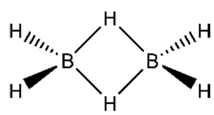
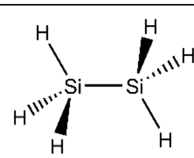
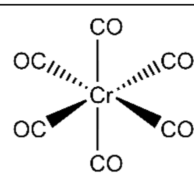
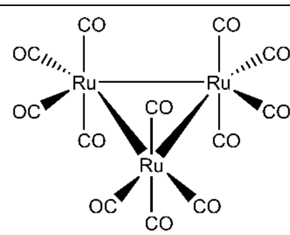
The final pedagogical goal was for students to find perspectives which would then facilitate identification of symmetry elements. While the use of concrete models was crucial to this goal, we further wished to incorporate drawing into the activity for this same purpose. The utility of drawing has been discussed in science education at length.[7] The rationale here is that students, in drawing these unique perspectives, must focus on spatial features and relations which may cause students to more easily explore and identify these relations in future contexts, such as on exams and in the research literature for inorganic chemistry.

ACTIVITY DESIGN PRINCIPLES AND DEVELOPMENT

The activity was designed for implementation in an upper division one-semester inorganic chemistry survey course with lecture and lab components. Prerequisites for the course are two semesters of general chemistry with lab and one semester of organic chemistry lecture, though most students have a full year of organic chemistry, one semester of organic chemistry lab, and a course in analytical chemistry. The course covers topics such as molecular orbital theory, coordination chemistry, and redox chemistry.

The course has a weekly 3-hour laboratory section in which the activity was implemented. The activity has students answer three sets of questions for each of seven inorganic compounds, with one additional compound provided with all questions answered to serve as an example of expectations. Compounds were ordered according to expected difficulty (order of the point group, number of unique operations, etc.) and the relevance of spatial features (i.e., the presence or absence of certain symmetry elements) as summarized in Table 1.

Table 1: Compounds used in the activity in the order given, as well as key spatial features to justify their inclusion. The 2D representations listed are identical to those used in the activity

Compound Name	Given 2D Representation	Key Spatial Feature(s)
#1: Phosphorus pentachloride (completed for students)		Two types of mirror planes, perpendicular axes
#2: Phosphorus trichloride		Low order, no perpendicular axes, no improper rotations
#3: Tetrabromopalladate		Planar compound which introduces all types of symmetry elements. Simple shape and few atoms to keep track of (compared to borazine)
#4: Borazine		Planar compound with many atoms to keep track of during symmetry operations. Principal axis does not pass through an atom
#5: Diborane		Unusual geometry, one rotation axis does not pass through an atom.
#6: Disilane		Improper rotation without horizontal mirror plane, unusual C_2' axes
#7: Chromium hexacarbonyl		Common highly symmetric geometry. Several examples of all types of symmetry operations (e.g., S_3, S_6, C_2, C_4)
#8: Triruthenium dodecacarbonyl		Same point group as borazine but very high number of atoms to track during symmetry operations

Each compound was presented with three tasks: (1) The students were asked to identify symmetry elements from a typical 2D representation (shown in Table 1); (2) Students then used a kit from Duluth Labs[18] to assemble a concrete model to identify symmetry elements in the model, in some cases noticing some of the symmetry elements for the first time after doing so; (3) Students drew their constructed models with an emphasis on drawing perspectives that they felt highlighted symmetry elements that were difficult to perceive. A copy of the activity in full is provided as Supporting Information.

Implementing Design Principles of Group Work, Model Use, and Drawing

Students were encouraged to work together through verbal prompts in the activity (e.g., "You may work with your partners if you want") and initial questions such as "1a) Based on the above representation, discuss with your team what symmetry elements the compound appears to have and record them here." and "2b) Using your constructed model, list any symmetry elements present in the compound that your team didn't see in question #1." This fits with our approach to collaborative learning,[8] specifically to encourage but not force students to work together. In our implementations, we saw most students work in groups of 2-4 while a few chose to work largely by themselves. By not forcing this social collaboration, we hoped to avoid the formation of detrimental learning groups.[24] That is, we trusted students in a 300-level course to work individually if they thought interacting with their peer(s) might be personally unproductive.

The use of concrete models was critical for this activity. Thus, it was crucial to ensure that students interacted with the models. Stull *et al.* previously noted that students often did not spontaneously engage with concrete models in their research environment.[12] To maximize student engagement with this tool, we created questions such as question Q2a, which explicitly prompts students to: "Construct the compound using the model kit. Take two pictures of the model you've assembled."

Reviews of the literature on drawing to promote learning indicate that the task of drawing must be guided by certain principles to be effectual. Specifically, instructions for drawing tasks must constrain the kinds of features to be depicted.[7] In line with the third pedagogical goal, question Q3 for each of the compounds asks students to produce drawings with unique perspectives and then to connect them to the previous questions by labeling identified symmetry elements on their drawings.

IMPLEMENTATION

This activity was implemented at UIC, a large, Federally designated Hispanic-serving urban research university in the Midwest United States. This course, which is the only undergraduate inorganic course the institution offers, was largely populated by third-year students with no prior experience with group theory. From available data, over 70% of students in the course in Fall 2021 and Spring 2022 were biochemistry majors, while approximately 13% were chemistry majors. The remaining students declared other majors typically associated with intentions to apply to medical school (e.g., public health, biological sciences, etc.) and were likely pursuing a chemistry minor.

The activity was introduced during Fall 2021 in a face-to-face setting. Class observations, initial data analysis, and faculty feedback led to changes including brief notes to guide the model construction process and an additional instruction to take pictures of the constructed models.

Fall 2021 Implementation

The Fall 2021 semester marked the first implementation of this activity. Approximately 70 students were enrolled in the course. Teaching Assistants (TAs) were provided with an extensive key (see Supporting Information), and the intention of the activity was discussed at length in a TA meeting prior to student engagement with the activity. Due to the COVID-19 pandemic, each laboratory section had only half of the students in person each week. This reduced the number of students in the classroom to 5 to 8 students, with student group sizes typically ranging from 2-4 students during the activity itself.

After all students completed the assignment, the collected audio and video recordings of consenting students, as well as the work they uploaded to the university's learning management system, were reviewed. While some students consented to both being recorded and having their uploaded work analyzed, others elected to give consent to only one (or neither) of these requests.

The activity seemed to have mixed success based on observations of the recordings and work uploaded by consenting students. While student use of the model kits was consistent and frequent, some students struggled to construct geometrically accurate models. Common inaccuracies included T-shaped phosphorus trichloride, non-planar borazine, and bent carbonyl ligands for chromium hexacarbonyl. Constructed model accuracy is further discussed in the Results section below.

Furthermore, student use of the language of group theory was exceptionally problematic, especially when it came to differentiating types of mirror planes and axes perpendicular to or including the principal axis of rotation. That said, some difficulty was expected considering other reports noting the problematic linguistic complexity of group theory.[15,21,25] One such recurring example involved diborane (Molecule 3 in Table 1), which contains no principal rotation axis, as is often the case with molecules with three perpendicular but unique 2- or 4-fold axes. Figure 1 shows an example of student work for this, which includes annotations for a vertical, horizontal, and dihedral mirror plane (e.g.: pedagogical goal #1 and Figure 1). As there is no single principal axis of rotation, the assignment of certain axes as perpendicular (i.e. C_2' and C_2'') and mirror planes using the $\sigma_{(h,v,d)}$ convention is incorrect. However, this distinction was not specifically instructed about in the lecture. Therefore, the effort the student made here represents their effort to extend a concept beyond the scope of the course learning goals.

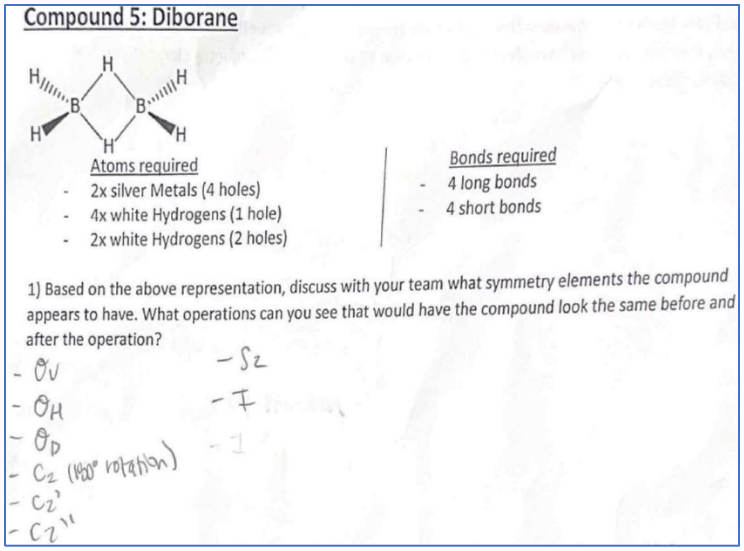


Figure 1. Student identification of symmetry elements in diborane (D_{2h}). As the highest order rotational axis has n=2, non-degenerate C_2 axes should be differentiated by axial orientation and not arbitrary prime denotations.

Generally, students did engage consistently with the first two questions in the activity, though not always with the final drawing task. This may have been due to insufficient scaffolding as the students were simply instructed to "… come up with ways to draw the compound that better shows some of the symmetry elements… you find particularly difficult to see." Many students opted to not complete this portion of the activity, especially for the larger compounds. Table 2 shows the number of students who created sufficiently satisfactory drawings. Only students who consented to having their lab report analyzed *and* uploaded their work to the course's learning management system were considered. The criteria for a satisfactory drawing are discussed in greater detail in the Drawing – Engagement section below.

Table 2: Completion of Question 3 Drawing Task for consenting students who uploaded activities to the course's learning management system.

Compounds with Drawings for Question Q3				
	0-2	3-4	5-6	All 7
Fall 2021 (N=12)	2	1	3	6
Spring 2022 (N=5)	0	0	0	5

Activity Modifications for Spring 2022 Implementation

Several modifications were made in response to these observations and faculty feedback. For one, additional questions about the geometry of the compound were added to the task for phosphorus trichloride, borazine, and tetrabromopalladate (compounds 2-4) to address problems students had in model construction. These additions were intended to promote recall of VSEPR theory knowledge and explicitly drew attention to critical structural features (e.g., Br-Pd-Br bond angle for planar, not tetrahedral, $PdBr_4^{2-}$). Furthermore, the drawing prompt for these compounds was revised to point students to the completed phosphorus pentachloride example; the purpose of this example was to clarify expectations in case of student confusion.

Another change was to make phosphorus pentachloride the example compound instead of water. The alternate perspectives possible in a D_{3h} compound are more visually distinct, highlight different symmetry elements, and better demonstrate how the same symmetry element might appear differently based on the chosen perspective. Further, drawings of the example compound with labeled symmetry elements provided a more detailed demonstration of what was expected in the drawings.

Additional and visually distinct representations of chromium hexacarbonyl and triruthenium dodecacarbonyl (Compounds #7 and #8) were provided. This was done to both promote student interaction with the drawing portion for these compounds and to focus them on important alternative perspectives for these compounds. For example, the second perspective provided for chromium hexacarbonyl (Figure 2) emphasizes the oft missed S_4 and S_6 symmetry elements. Finally, a direct instruction for the students to check in with the TA was removed. Instead, we communicated to the TAs an expectation that they initiate this step.

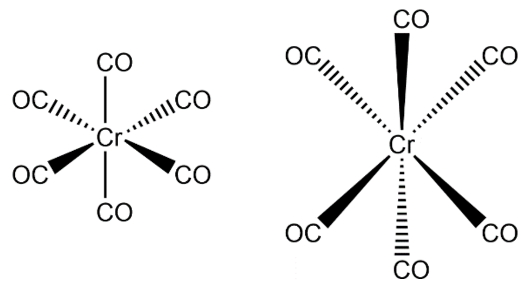


Figure 2. Both provided perspectives of $Cr(CO)_6$ (left, at the start of the section; right, in Q3). The perspective on the right is tilted downward to emphasize the trigonal relationship between sets of carbonyl ligands.

Spring 2022 Implementation

The Spring 2022 semester saw similar enrollment numbers and laboratory section populations compared to Fall 2021. In this semester, laboratory sections were *not* split as pandemic restrictions had been partially relaxed. Therefore, sections had between 10-14 students at any given time, with student groups ranging from 2-5 students during the activity. Student groups were now usually adjacent to one another, with more discourse between groups.

Review of audio and video recordings of consenting students in this semester showed fewer problems in model construction. While some instances of incorrect model construction were still present, the data in Tables 3 and 4 indicate that constructed model accuracy improved. It is also interesting to note that student groups in Spring 2022 completed the activity faster based on recording length (Fall 2022 video length range: 85-164 minutes; Spring 2022 video length range: 64-82 minutes). This may be because of greater student numbers during lab, which seemed to promote talk between student groups. Additionally, students more consistently engaged with the drawing prompt as seen in Table 2.

Table 3: Constructed model accuracy coded for 18 students in 6 groups. Only 2 of these groups were in the same laboratory section.

Constructed Model Accuracy – Fall 2021			
Compound	Initially Correct	Revised and Corrected	Incorrect
PCl_3	6	9	3
$PdBr_4^{2-}$	13	2	3
Borazine	16	0	2
Diborane	13	2	3
Disilane	8	8	2
$Cr(CO)_6$	14	0	4
$Ru_3(CO)_{12}$	14	0	4

Table 4: Constructed model accuracy for 11 students in 3 groups. None of the groups were in the same laboratory section.

Constructed Model Accuracy – Spring 2022			
Compound	Initially Correct	Revised and Corrected	Incorrect
PCl_3	11	0	0
$PdBr_4^{2-}$	11	0	0
Borazine	6	5	0
Diborane	11	0	0
Disilane	11	0	0
$Cr(CO)_6$	11	0	0
$Ru_3(CO)_{12}$	11	0	0

Unfortunately, students still seemed to have difficulties with the some of the language of symmetry elements, similar to the students in Fall 2021. While there appeared to be use of fundamental terms (e.g., rotation axis, mirror plane, C_n, etc.), more advanced distinctions were largely absent (e.g., identification of mirror planes as vertical, horizontal or dihedral). Interestingly, there was consistent discussion, and occasional written responses, involving point group identification even though the activity does not include a prompt for that. Future iterations intend to address this directly during the meeting with TAs, reinforcing the focus on symmetry elements. Specific discussion of vertical, horizontal, and dihedral mirror plane notation and identification may also be added, to overcome confusion by non-standard notations such as "perpendicular" and "parallel."

RESULTS

Though no surveys were collected to gauge student affect or engagement with the activity, video data and student assignments provide insights into the student experience.

Student Group Size

Though group formation was not required, every consenting student captured in video across both semesters was involved in a group. A small minority of students were observed to work entirely alone or with infrequent discussion. These observations were taken to support the claim that the "encourage, but don't force, group work" design aspect was successfully implemented.

Concrete Model Building – Engagement and Accuracy

Problematic model construction has been previously mentioned. Data regarding model construction accuracy is tabulated in Tables 3 and 4. Both tables represent only those students who gave consent to being recorded during their laboratory section and were observed in video (18 students for Fall 2021 and 11 students for Spring 2022). If individuals collaborated during model construction, the accuracy of that model was counted for all involved. Models were coded as "initially correct" if the attempt resulted in a model that accurately reflected the compound's geometry. If the model did not meet this criterion, it was coded as "incorrect" unless the model was revised, with or without outside assistance, which was then coded as "Revised and Corrected".

The data in Tables 3 and 4 show that model accuracy improved between semesters, possibly because of the additional probing questions about molecular geometry priming students to more closely consider what geometry the models *should* have. The only model construction issue seen in Table 4 in Spring 2022 stemmed from students using model atoms with the incorrect number of holes with borazine. Though this was also a very frequent occurrence in Fall 2021, it extended beyond borazine in that semester and was particularly troublesome for phosphorus trichloride model construction; these issues were confined to borazine in Spring 2022.

Drawing – Engagement

Arguably the most difficult task for this activity was question three, which had students draw unique perspectives of compounds that highlighted specific symmetry elements. Table 2 details the number of students who provided satisfactory drawings.

Drawings were deemed satisfactory if they met two criteria: 1) the drawing modeled a perspective dissimilar to provided representation and 2) the drawing had clearly labeled symmetry elements. Meeting both criteria was taken as sufficient evidence that they had given consideration to the goal of identifying unique perspectives (see Figure 3). Drawings were deemed insufficient if they were absent, did not appreciably differ from the provided representation, or lacked clearly labeled symmetry elements.

Though relatively few consenting students submitted activities for analysis in Spring 2022, that every student included at least one drawing for *every* compound does lend credence that the additional scaffolding was effective.

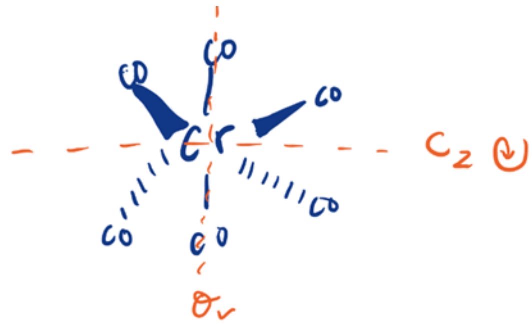


Figure 3: Student work that satisfied both criteria for Table 2.

Progressive Student Success with Symmetry Element Identification

Students are specifically asked in the activity to identify symmetry elements, first relying only on a 2D structure and then on the 3D model they constructed. Figures 4-6 below summarize *which* symmetry elements were identified *by whom* and *at what point* in the activity. This data provides unique insights into the struggles students had with the central task of identifying symmetry elements and what parts of the activity facilitated their success. The identity operation, *E*, was excluded given its unique function in group theory.

Each activity had seven molecules (Table 1) for analysis. Across these seven molecules, there were 42 unique symmetry elements. Figure 4 displays how many of the 42 unique symmetry elements students found during each question across the activity. Degenerate symmetry elements (e.g. each C_2' in borazine) were counted together. An example of this coding process for work submitted by student S5 can be seen in the Supporting Information. That almost every student except for students F13 and F9 in Fall 2021 could find over half of the symmetry elements in Part 1 is reasonable given that symmetry and group theory had been covered in lecture by this point. The "Not Found" designation indicates the symmetry elements not identified at any point by that student. Only one student identified all symmetry elements based only on the image given in Part 1. Across all students, approximately 15% of symmetry elements were identified only after construction of the models in question 2, which demonstrates the utility of the models for learners in this task. And for some students the models were especially important since they identified fewer than 25 symmetry elements during Part 1 alone.

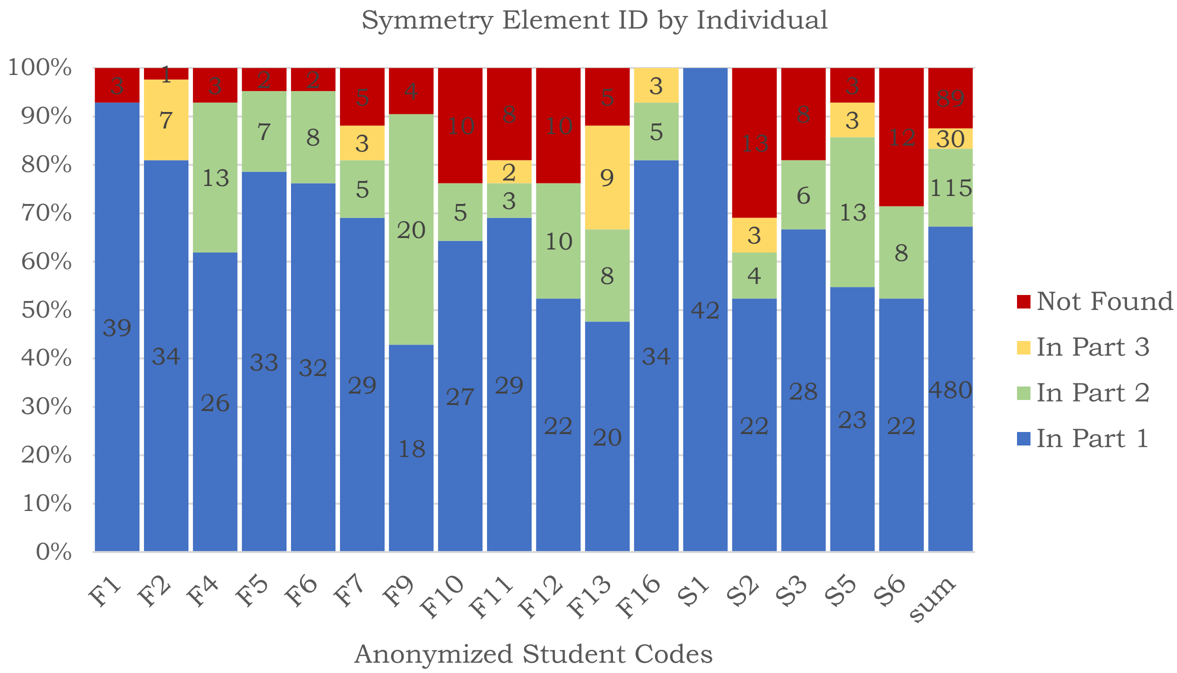


Figure 4: The number of symmetry elements students found in each part of the activity. Symmetry elements found in part 1 were found using only the provided 2D representation; those found in part 2 utilized the 3D model; and those in part 3 were found after completing the drawing prompt.

Figures 5 and 6 highlight aggregated data on *which* symmetry elements were identified, and when identification occurred. It is unsurprising that nearly every principal rotational axis C_n was identified in Part 1 since these elements are often the first focus of students who are thinking about point group identification. In contrast, the C_2', σ_h and $\sigma_{(v,d)}$ symmetry elements were identified less frequently based on the drawing but more consistently in the model building step; these symmetry elements are of particular importance as they feature prominently in Carter's flowchart[26]. Finally, it is clear that the model building step was especially important in identifying improper rotation axes, where present.

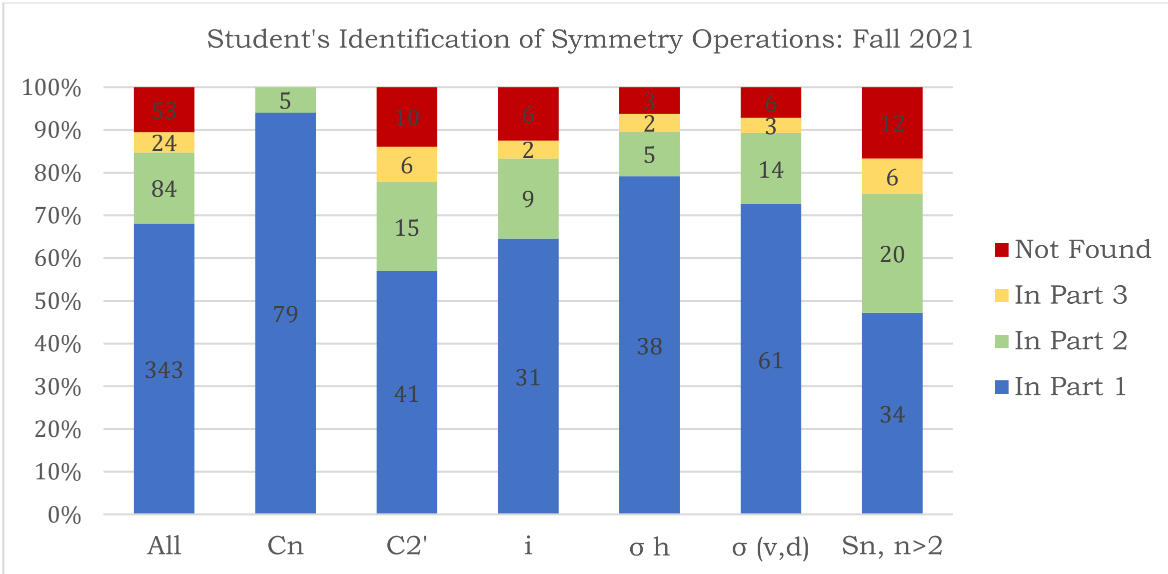


Figure 5: A count of symmetry elements identified by students in Fall 2021 distinguished by the type of symmetry element. Symmetry elements found in part 1 were found using only the provided 2D representation; those found in part 2 utilized the 3D model; and those in part 3 were found after completing the drawing prompt.

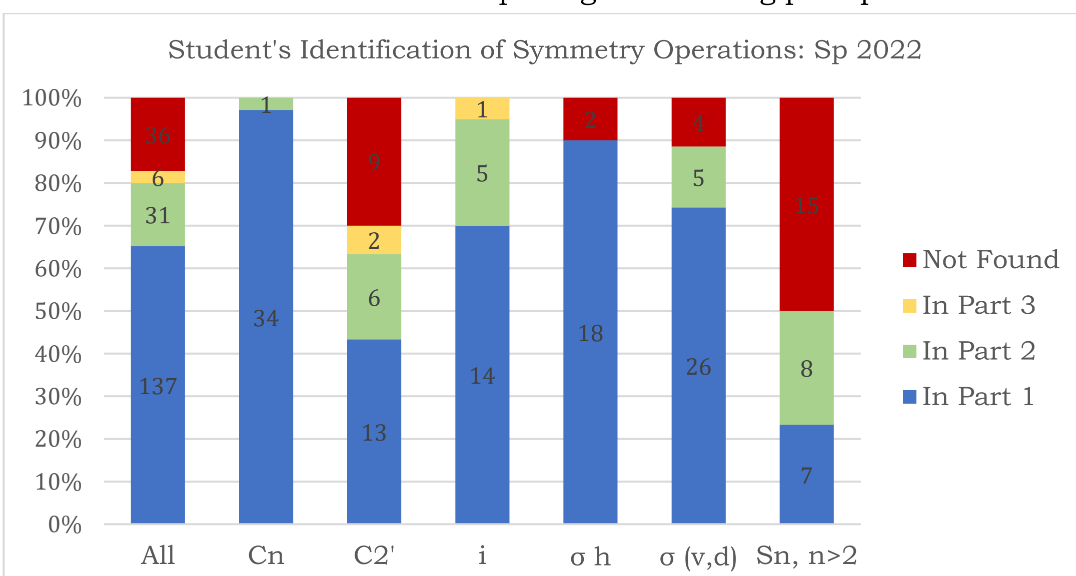


Figure 6: A count of symmetry elements identified by students in Spring 2022 distinguished by the type of symmetry element. Symmetry elements found in part 1 were found using only the provided 2D representation; those found in part 2 utilized the 3D model; and those in part 3 were found after completing the drawing prompt.

CONCLUSION

The activity described here was intended to meet pedagogical goals and to use evidence-based practices and real student experiences in the design and revision process. That additional symmetry elements were consistently found after model construction and (to a lesser extent) after drawing implies that these design principles provided the intended utility to students. Furthermore, that a majority of students worked in groups of variable, self-chosen size also indicates the successful implementation of that design principle from the Collaborative Learning framework.

Given these observations and data, the current iteration seems to fulfil its pedagogical purposes. Though the activity will be further refined, especially as related to the pedagogical goal of accurate terminology use, the authors believe that the present iteration is sufficiently developed for adoption at other institutions. Minor adjustments may be necessary to fit institution-specific curricula, pedagogical goals, and student prior knowledge. It is our hope that the design shared here will serve as one example for implementing laboratory activities based on department-derived pedagogical goals and literature-supported design principles.

ADDITONAL INFORMATION

Consent acquisition and the recording process was done with approval by the institution's IRB (ID: 2021-1273).

ASSOCIATED CONTENT

Supporting Information

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

File containing the list guidelines and directions for instructors and students for the activity (DOCX).

File containing data on symmetry elements identified by students as related to Figures 4-6 (XLSX).

Example completed student activity with author codes indicating symmetry elements identified by students (PDF).

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Notes

The authors declare no competing financial interest.

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