Describing and Analyzing the Gestures of Inorganic Chemistry Students Learning Symmetry and Group Theory

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THESIS

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To my wife, Kassandra, who has been an unending font of support and motivation. I could not have done this and accepted all of who I am without you.

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LIST OF ABBREVIATIONS

- GT&S - Group theory and symmetry
- CER - Chemical Education Research
- PER - Physics Education Research
- BER – Biology Education Research
- GSA – Gesture as Simulated Action

SUMMARY

This dissertation explores three different but related projects that all take place within the undergraduate inorganic chemistry classroom. The bulk of the work herein focuses either on gesture as a communicative and cognitive tool or on the literature or environmental support that justifies the focus on gesture as a phenomenon worthy of scholastic inquiry. But I think of this dissertation fundamentally as a story about communication. This arguably includes Chapter I which serves to communicate to the reader the frameworks which underpin the work discussed, including how gesture is a mode of communication and cognition, and a review of the literature of CER's relation to gesture. Chapter II describes the development and implementation of a group theory & symmetry (GT&S) activity. The activity was designed for use in an upper-level inorganic chemistry course and was developed in partnership with the instructors of the course as it is taught at the University of Illinois Chicago. It was during student interaction with this activity that we first observed spontaneous gestures being used in this context. Chapter III details the scheme I have developed to systematically describe gestures, and trends in the gestural forms and notions used by students in undergraduate laboratory and one-on-one interview settings. Chapter IV, following the challenges observed in gesturing about improper rotation and inversion operations, examines early work done to actively incorporate specific gestures in the lecture space to hopefully prompt students to mimic instructor gestures. Video data of students in undergraduate laboratory, one-on-one interview, and focus group settings are analyzed. The dissertation concludes with Chapter V, summarizing the previous chapters and the paths that CER scholars might walk in the future.

CHAPTER I.[1] LITERATURE REVIEW

Introduction

This dissertation primarily focuses on gesture as a communicative and cognitive tool as it appears in an inorganic chemistry classroom, and at times with its intersection with physical molecular models. This broad conception of gesture has been explored by some in the chemistry education research community. This chapter will review that literature to best contextualize the work ahead. Indeed, following that exploration is a detailed account of how gesture is framed in the work I have done. Of foundational importance is the work of Geneviève Calbris, which is described in this chapter after requisite contextualization. As my work is presently limited to the inorganic chemistry classroom and specifically only to the topic of group theory and symmetry (GT&S), this chapter will also briefly review GT&S' place in the broader chemistry curriculum.

Despite the focus of this dissertation being on gesture in chemistry, all of the original research work described herein occurred because of the GT&S activity described in Chapter II. As a result, the final section of Chapter I concludes with a discussion of the design principles and frameworks which structured the design of the activity discussed in Chapter II.

The work described in this dissertation had me operate in several different roles which I describe here to succinctly describe my own positionality. Though I describe this further in Chapter II, I had a direct impact on the education of the students who did (and did not) consent to my study as I designed the activity they were assigned during a laboratory section, as well as the suggested grading rubric. I also directly interfaced with students during: their laboratory sections

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as described in Chapters II, III, and IV; during one-on-one interviews as described in Chapters III and IV; and focus groups as described in Chapter IV. Though I always attempted to keep at the fore my role as a researcher unaffiliated with the inorganic chemistry course, I was at times a resource, a knowledgeable other, to the students akin to a Teaching Assistant. Finally, in Chapter IV I collaborated with the faculty teaching the inorganic chemistry course to design the gestures they would use in lecture. However, at no point did I have any influence over student grades. Conducting research in naturalistic settings will always result in complex working relationships with the stakeholders involved in those settings, but I have endeavored to ethically conduct the research described in this dissertation with the utmost respect for those stakeholders, and especially those who consented to participate in these studies. Some discussion of frameworks here has been published in the *Journal of Chemical Education* and has been reprinted here with permission from the American Chemical Society. Reprint permissions are listed in **Appendix A**.

Group Theory and Symmetry in the Inorganic Chemistry Curriculum

Inorganic chemistry is presently recognized by the American Chemical Society as one of five subdisciplines of chemistry required by to be taught by departments seeking ACS approval.[1] This has not always been the case as seen in Reisner et al.'s historical account, with this and other factors contributing to little standardization in the early inorganic chemistry curriculum.[2] There is still discussion in the literature as to what content should be taught and how it should be structured.[3-5] And while an extraordinary scope of topics has been taught over the years, with some topics comparatively falling to the wayside,[6] GT&S has consistently appeared on ACS exams[7] and in discussions regarding the curriculum.[5]

Despite the persistent appearance of GT&S in the inorganic curriculum, little is published regarding the depth to which GT&S is taught in inorganic chemistry classrooms. Undoubtedly this is in part due to the heterogeneity of the inorganic chemistry curriculum in the US[8,9] (saying nothing of curricula elsewhere) and due to the incredibly vast purview of the inorganic chemistry subdiscipline.[6,7] Curiously, looking at earlier literature in the *Journal of Chemical Education* shows that GT&S may have appeared in second year courses,[10] organic chemistry courses,[11] and even general chemistry.[12] More recently, GT&S is a topic largely for inorganic chemistry and we might look to treatments of the topic in popular inorganic chemistry textbooks to reasonably approximate how it is positioned in the upper-level undergraduate curriculum.[13-16]

The value of GT&S in these texts is presented primarily in two contexts: the ability to predict IR And Raman active vibrational modes, and in molecular orbital theory. This ultimately requires the student to have several skills,[17,18] including proficiency in identifying point groups to which a compound belongs. Fundamentally, the student requires competence in the language of, and distinction between, symmetry elements. The activity described in Chapter II attempts to address precisely this competence, while the gestures described in Chapters III and IV are physical, specifically manual, representations of these GT&S components.

A comprehensive introduction to GT&S for chemists can be found elsewhere,[11,19] but there are some few aspects of GT&S I would explicitly mention now that will be relevant later. Though neither of the primers by Zeldin or Orchin & Jaffe use the term, I define the “principal axis (of rotation)” as the highest order rotation axis.[13,14] Also, while the horizontal reflection plane and inversion operation are technically improper rotations, being S_1 and S_2 respectively,[11] I do not group them with higher order improper rotations of $S_{n>2}$ based on how these two operations are taught at the University of Illinois Chicago and in the texts commonly associated with UIC's undergraduate inorganic chemistry course.[14]

Gesture in Science DBER

Human beings communicate through various modes. The verbal and written modes are especially dominant in modern pedagogical practice and have been the focus of various groups in the Chemistry Education Research field.[20,21] Undeniably, the gestural mode, or communication via manipulations of the body, differs from the verbal or written modes in ways that have captured the attention of other CER scholars.[22-24] As Flood eloquently shared when describing classroom discourse involving gesture, "Where terminology in speech only conveys discrete meaning (e.g., an animal can be a sheep or a dog), gesture allows for the sharing of continuous, topological meaning such as paths of motion, like the trajectory of an electron circling a nucleus."[23] Indeed, it captured my attention and has led to the publication of scholarly work regarding gesture in inorganic chemistry where there previously was none.[25]

Gesture in Chemistry

There is some interest in gesture within the CER community, with several publications appearing in the *Journal of Chemical Education, Chemistry Education Research and Practice*, and other domain-general education journals. Much of this work is centered around organic chemistry[22,26,27] and stereoisomerism.[24,28] Some investigations also looked at general chemistry and molecular geometry,[23,29] and ion channels in biochemistry.[30] To my knowledge, no work has been published involving gestures in other subdisciplines such as analytical chemistry, physical chemistry, or radiochemistry.

Several of the gesture-related investigations in CER cited above have been quantitative in nature. With the exception of Kiernan and coworkers' recent publication,[29] these studies did not probe the characteristics of individual gestures and instead treat gesture as a condition by which to describe groups of students.[22,24,28] That said, this exception only went so far as to delineate gestures based on the primary function of the gesture using McNeill's terms.[31] While such a scheme is perfectly adequate for specifically designed investigations, the work described in this dissertation seeks to delve far deeper into the characteristics of individual gestures, even if it might complicate the ability to engage in rigorous statistical methodologies. I take a particular interest in *specific, individual* gestures because different gestures can have different meanings, just as different words can have different meanings.

In some ways, the work described in this dissertation is similar to that of Flood and co-workers, who previously explored the semiotic and communicative use of gesture in a general chemistry setting.[23] Notably, students used gestures to communicate notions that were otherwise cumbersome to elucidate verbally, e.g., the spatial arrangement of atoms in a trigonal bipyramidal compound, and when constructing meaning by themselves and with others. I share an interest in the pedagogical utility of gesture, but one of the hopes of my research work is that the manner in which we *describe* those gestures might be afforded some systematicity.

There is also a branch of the literature which concerns itself with gesture and gesture-based technology.[32-36] Educational technologies have considerable potential, and it is of interest to the broader education research communities to learn how best these technologies can be implemented. However, these considerations are beyond the scope of this dissertation.

Gesture in STEM Education Research

Scholarly gesture work also appears in other STEM education research communities. These include the physics education research (PER) community, biology education community (BER), and even in geology education.[37] I draw especially heavily from the physics education research community (specifically from Scherr and Gregorcic) in part because of the community's small but robust body of gesture scholarship.[38-42]

Aspects of Scherr's scholarship in some ways closely mirrors that of other gesture researchers. Much of her gesture-related work[42-44] examines naturalistic gestures in a social environment,[23,45] describes gestures in a narrative style replete with pictures,[46] and draws conclusions by examining episodes of gestures in great depth.[47] Her use of these methodological aspects in the PER space provided valuable inspiration and guidance for the initial methodological framing of my own work in Chapter III, which eventually led to my adoption and modification of Calbris' methodology.

Gregorcic's work cites Scherr at times, and consistently provides a strong foundation of frameworks on which their analysis builds.[48,49] Gregorcic and coworkers put forward a particularly compelling scheme by which semiotic resources such as gesture relate to disciplinary-relevant aspects of physics.[49] Similar to Scherr, they examine episodes in great detail, in this case focusing particularly on a coordinated movement similar to a dance from a popular film. The students used this dance to understand how the movement of two celestial bodies affect each other; in this way they come to learn about Newton's 2nd law, 3rd law, and law of gravitation without necessarily using such terms. To paraphrase their words, the dance serves as a nonpersistent coordinating hub the students can leverage to speak and gesture intelligibly, i.e. to learn.[49] Framing gesture in this way echoes Flood's comparison of the verbal and gestural modes,[23] and gives further validity to gesture as a phenomenon worth investigating for pedagogical purposes.

Unfortunately, gesture's presence in BER is limited. Sjøberg and coworkers present their investigation as one focused on students' meaning-making model-based reasoning.[50] They frame student talk, gestures, and drawings not only as evidence of students engaging with meaning-making but also as different forms of representations. The authors ultimately describe a cyclic process in which students utilize these three different representations to iteratively advance their understanding to a more complete and robust explanatory model. The only other publication I could find is the biochemistry education research by Randa and coworkers mentioned above.[30] I mention it again to draw explicit attention to the journal in which it was published, *CBE-Life Sciences Education*, as this journal is heavily used by the BER community. As only the second of these two publications was published in a strictly biology education journal and no further scholarly gesture work could be found in other BER journals such as *Biochemistry and Molecular Biology Education* or the *Journal of Biological Education*, it is reasonable to say that gesture is not presently very important to the BER community.

Gesture's Relation to Cognition and Communication

The work in this dissertation considers gestures as manipulations of the body that can be interpreted as utterances in discourse.[51-53] Just as an individual can respond to a question in verbal or written modes and signed language,[54] one's hands, facial expressions, and other manipulations of the body can serve as nonverbal forms of communication. Considerable research also shows the role gesture has in reasoning and cognition.[22,51,55,56] In chemistry education research, there has been an effort focused on gesture and problem-solving tasks in organic chemistry. Ping and co-workers examined how students used gesture when mentally manipulating stereoisomers[28] and generating a given compound's stereoisomer (if one existed).[24] Stieff, Lira, and Scopelitis demonstrated that gesture can support students when tasked with translating between Newman, Fischer, and dash-wedge representations comparable to using a model kit.[22] Many scholars, including some of these cited above[22,24,28] contextualize the relationship between gesture, cognition and communication using the popular philosophical framework, Embodied Cognition.

Embodied Cognition has been evoked in education research across disciplines including chemistry,[23,24] physics,[44,49] and mathematics.[57] Lawrence Shapiro has written extensively on Embodied Cognition, including a more full treatment of the framework[58] and other related thoughtful expositions.[59,60] To be brief, the central premise of embodied cognition is that learning and thinking about the world "... is grounded in the interactions our bodies… have with the world around us."[51] Since gestures are physical manifestations of Embodied Cognition, we can glean information about student cognition by examining how they use gesture during reasoning and communication tasks. As will be seen in Chapters III and IV, this includes tasks relating to symmetry and group theory in inorganic chemistry.

EC is a sufficiently vast framework that some scholars have sought to develop frameworks nestled within it to provide greater structure or facilitate more fine-grained analysis.[61] Gesture as Simulated Action (GSA), developed by Hostetter and Alibali, intends to address how gestures arise using Embodied Cognition as a basis.[62,63] While I do not specifically frame the results in Chapters III and IV using GSA, the framework does address several relevant considerations and limitations in this dissertation. As Hostetter and Alibali themselves put it in their revisitation of the framework, "… [T]he central idea proposed in the GSA framework – that gestures reflect embodied sensorimotor simulations – has been taken as a warrant for using gestures as evidence about the nature of underlying cognitive processes or representations…"[63] Indeed, this warrant lies at the heart of my scholarly pursuit of gestures, though the connection between gesture and underlying cognitive representations is specifically framed using metaphor as a framework, which is discussed later in this chapter. Beyond this, GSA has several tenets which comprise the framework. According to GSA, the likelihood a gesture will occur depends on three factors relevant to the person who would gesture; their mental simulation of an action or state relating to their perception, whether or not they are speaking, and the height of that individual's "gesture threshold". The "gesture threshold" is a construct within their framework that refers to how resistant an individual might be to produce a gesture at any given time. This is intended to account for a range of sociocultural and situational factors, such as the individual's perception of how polite the act of gesturing might be when speaking with a friend or a stranger with superior social status.[64] Based on these factors, GSA also makes six predictions about speakers and their gestures, though I will only supply two of them here. GSA predicts that people will gesture more frequently when the mental simulation involves some kind of transformation or manipulation (as opposed to a static image), and that the gesture should reflect the underlying mental simulation. The first of these predictions may explain why students learning GT&S may so readily gesture, while the second strengthens claims that these same gestures are indeed revealing information about students' underlying cognitive processes.[63]

Gesture can also function as a communicative mode.[56,65] Indeed, there is an enormous literature surrounding gesture's relation to communication and language. The body of scholarship includes investigations of gesture's communicative use across cultures[64,66,67], in relation to signs and sign languages,[27,45,52,68] dynamics between gesture and aspects of discourse such as the use of words implying specific points of view[69] or shared space and perspective,[70] and even the universality of gesture across *all* cultures.[71] Euler, Rådahl and Gregorcic reasonably connected this utility of gesture as a coordinating hub to social semiotics in their physics education setting,[49] but indeed this is not a strictly physics or STEM phenomenon but more broadly a human phenomenon.[47] This vigorously investigated aspect of gesture is a strong motivation for this dissertation's investigation into gesture as used by both students *and* instructors, especially in light of GSA's prediction that gestures should reflect the accompanying mental simulation as related to the gesturer's speech.[63] Indeed, gesture can even serve as a communicative form not just alongside but as *superior* to accompanying speech. Or, as Roth and Welzel elaborate, "[g]estures allow students to construct complex explanations even in the absence of scientific language."[39]

Classifying Gestures

This dissertation restricts the term "gesture" specifically to movement of the hand(s).[51] However, it is necessary to further still refine how we consider gesture considering the multitude of forms the hands might take or the meanings they might intend to convey. Two established views on gesture have had a profound influence on the gesture studies community over the past 30 years; those held by the late Adam Kendon and those held by David McNeill. While a more thorough discussion of the history of these different perspectives may be found elsewhere,[54] a brief overview will help contextualize the perspective used in the following chapters.

Adam Kendon's work on gesture was closely tied to the language and culture of the speaker, with common themes being the lexicalization of gesticulations into conventionalized signs and sign languages.[72,73] The gesture-sign continuum, sometimes referred to as "Kendon's continuum" though that term was not approved by Kendon himself, describes utterances as they proceed through the lexicalization process.[54] In this way, one could differentiate gestures by considering the phases of this continuum, with gesticulations and pantomime lacking conventionalization and linguistics properties, emblems expressing both of these properties in part, and proper signs in a signed language becoming fully conventionalized and sufficiently linguistic in character.[52,54]

David McNeill is also a widely known gesture scholar, known especially for his description of four properties that gesture might exhibit: iconicity, metaphoricity, deixis, and beat character . While they were once described by him as categories, they were later reconsidered instead as dimensions such that a given gesture might be, say, primarily iconic in nature but have also some deictic character.[31] These dimensions have been extensively cited in gesture-related CER work[22,26,28,29] and have been used and recategorized by other prominent gesture scholars. Indeed, Wakefield and Goldin-Meadow categorize co-speech gestures into representational and non-representational gestures, the former category housing iconic and metaphoric gestures and the latter beat and deictic gestures.[51] I adopt Wakefield and Goldin-Meadow's categorization of gesture insofar as they allow me to specify the kind of gestures of principal interest to my research. They also narrow their definition of gesture to movements specifically of the hands, excluding other parts of the body; I use this definition in my work.[25,51]

Much of the gesture literature, as evidenced above, is concerned with the *purpose* of a given gestural utterance. Gestures are examined and highlighted according to their function in a specific social context. These positions on gesture have been, and continue to be, indisputably influential to modern conception of gesture. That said, gesture is an observable phenomenon that physically exists in space that, to my knowledge, lacks a systematic method by which to characterize its *appearance*. Part of this dissertation, specifically Chapter III, seeks to address this perceived shortcoming. The philosophical foundation that supports this stems from the scholarly work of Geneviève Calbris, which is contextualized and then described in the following section, which frames gesture as metaphor.

Gesture as Metaphor

Metaphor is characterized by the mapping of features across different domains.[67,74] A well-known example, the metaphor "Love is a journey" has several mappings between the source domain (journeys) and the target domain (love), such as lovers being akin to travelers, difficulties in the relationship acting like obstacles during travel, and the goals of the lovers' relationship being the destination of the journey.[74] As such, metaphors establish an indirect relation between the source and target domains, and sense is made by contrasting and comparing the two domains.[75] While metaphor has traditionally been the domain of linguists,[74,75] it extends beyond the written/verbal mode and into gesture.[31,53,67]

Metaphor in STEM Education Research

Metaphor (and relatedly, analogy) and the target domain/source domain dichotomy has also been used in chemistry education research[76-81] and education research more broadly.[41,82-85] The source domain is sometimes referred to as the analog domain when working specifically with analogies,[84,85] though the source and target dichotomy otherwise remains.[74] Relevant to this dissertation, one instance in the literature was found where bodily involvement in analogy was mentioned,[86] though neither those authors nor do I describe that bodily involvement as gesture.

Calbris

Geneviève Calbris is a French gesture studies researcher and whose work has critically influenced this dissertation. While most of her work is, regrettably, in French, her book

"Elements of Meaning in Gesture" discusses much of her methodology and framing of gesture.[67] In this book, Calbris treats representational gestures as signs motivated by a physico-semantic link to a concept or object that the gesture represents; a view espoused by others in the gesture studies community.[53,54] In this frame, gesture serves a role as a nonverbal metaphor. She explicitly views this class of gesture as metaphorical in that "... using contemporary terms, a representational gesture is established by mapping from a source domain (physical experience) to a target domain (notion)."[67] In other words, one could come to know more about a concept through meaningful bodily motions, i.e., through gesture. Calbris rests this argument on the claim that our bodily experience with the physical world influences the quality and form of our gestures. Just as we might pinch our thumb and forefinger together to hold a small object like a needle, so too might we gesture with similarly pinched fingers to communicate the quality of smallness. Calbris uses this argument for other gestural forms and notions, such as a flat hand to indicate something being cut or otherwise ending.[87] This resembles a previously mentioned hypothesis from the GSA framework, and is the philosophical underpinning of the connections I make in Chapters III and IV between gestural forms and notions.

Calbris also describes a scheme by which to classify referential gestures based on *the physical component of the gesture*. In this scheme, several characteristics are important to consider such as the localization of a gesture to specific parts of the speaker's body (termed by Calbris as "body-focused gestures"), the form and direction of any present movement component, and the body part involved in the gesture. Do note that while I specifically focus on the hands, Calbris does include other body parts such as the head. Calbris's scheme also includes specific code systems. These include: Using numbers 0-36 to indicate body parts involved in gesture, and a mixture of the Greek alphabet, Latin alphabet, and common typographical symbols to indicate hand shapes (e.g., [⁋] for a closed fist, [H] for a flat hand with palm faced forward, etc.). Just as I use the specific word “notion” as Calbris does when referring to an abstract idea which serves as the target domain for a metaphoric gesture, so too do I adopt several of her hand shape codes, first seen in Chapter III.

Summary

While gestures can serve a wide variety of purposes, the gestures of interest in this dissertation are representational gestures.[51] I treat these gestures as metaphors[67,74] where the gestural form is the source domain and the abstract chemical or mathematical concept being conveyed is the target domain. Following Calbris’ stance and others’,[65,78] I treat in this dissertation the concept or object to which I infer a gesture is referring as a notion. Thus, gesture consists of two components: First, the gestural form that can be observed, which includes the physical form or motion enacted by the hands. Second, the cognitive notion(s) that is conveyed by the speaker and inferred by the observer. By treating the form a gesture takes (the source domain) as a separate construct from the notion we infer (the target domain), relational claims can be made between them, enabling an analysis of how particular gestural forms act as metaphors that express underlying cognition.[65]

In short, gesture is treated in this dissertation such that trends in gestural form-notion correlations ascribed to individuals are used as evidence in discussions surrounding the use of gesture in educational contexts, such as lecture or peer-peer interactions. Put another way, I use evidence stemming from the “inside-looking-out” point of view on gesture to discuss how we might engage with gesture in pedagogically-relevant environments from an “outside-looking-in” perspective.[88]

Activity Design Frameworks

The bulk of this dissertation is concerned with the gestures used by inorganic chemistry students who are learning about GT&S. Every one of these students had an important shared experience in that they engaged with a collaborative model-based symmetry activity which I had designed using literature-supported design principles.[89] Considering the foundational importance of this activity to this dissertation, it is only reasonable for me to describe the frameworks and design principles which I employed in the creation of the activity. These frameworks and design principles were chosen based on their alignment with the pedagogical goals of the instructors of the inorganic chemistry course. These pedagogical goals, and the activity more broadly, are described in Chapter II.

Collaborative Learning

The activity took place in a laboratory environment where students regularly worked in self-selected groups. It was important for us to not disrupt this classroom norm, especially in light of the immense body of research that supports properly structured group work.[90-95] As such, I decided to consider a framework such as collaborative learning[90,95,96] or cooperative learning.[91,92] While work in the areas of collaborative and cooperative learning evolved to the point where a distinction between the two is hazy,[97] others have continued to delineate them.[94]

While I make no strong claims here as to whether there *should* be a distinction between them, I do note key differences between two highly cited references that use specific language to refer to these frameworks as specific and distinct.[90,91] In Johnson & Johnson's Cooperative Learning framework, they cite five elements that must be present for group activity to be "cooperative". These include: positive interdependence between group members; individual accountability; the promotion of face-to-face interaction between group members; the development of social skills; and processing progress towards goals and maintaining working relationships.[91] While several of the principles that Panitz describes for Collaborative Learning echo those above from Johnson and Johnson, Panitz calls specific attention to *voluntary* participation and mentions nothing of the positive interdependence element. As such, there seems to be a strong difference in the rigidity or structure of the relationship between group members. Collaborative Learning explicitly promotes interdependence through grade incentives or group roles reminiscent of Peer Oriented Guided Inquiry Learning (POGIL).[98-100] Cooperative Learning recognizes that the social elements of group work are "idiosyncratic and unpredictable" and allows for students to enter or leave groups by their own volition.[90]

Ultimately, the activity I designed more specifically cited the collaborative learning framework as the underlying pedagogical and organizational framework.[89] As the students who would complete this activity were adults who, we assumed, were acclimated with the academic institution and had clear understandings of the course expectations and their own learning needs, the instructors and I elected to utilize the collaborative learning framework. This would afford the students greater freedom to accomplish the tasks of the activity while still promoting social interactions for theoretically increased learning gains. In other words, we wanted to give students the opportunity to work individually if they thought interacting with their peers might result in the formation of a detrimental learning group.[91]

Use of Concrete Models

The activity also needed to position students to interact with physical objects with hopes that doing so would promote the learning of GT&S. The physical objects in this context were concrete model kits purchased from Duluth Laboratories, specifically the MM007 molecular model set.[101] Concrete models, or "physical 3D models that represent the 3D spatial relations between atoms in a molecule”,[102] are widely used in general,[103-105] organic,[102,106] and inorganic[12,99,107-109] chemistry classrooms. The potential utility of model kits is supported by a significant body of literature, both specific to chemistry[110] and beyond,[60,111] that supports the link between cognitive processes and actions or perceptions of the body. Beyond the use of the molecular model kit and upon suggestion by one of the inorganic chemistry faculty, we did further include blank 3” by 5" notecards as a potential physical proxy for mirror planes, with writing implements, such as pens and pencils, brought and used by the students to complete the activity serving as similar proxies for rotational axes.

Drawing for Educational Purposes

A key purpose for the inclusion of concrete models was their potential utility for students in finding different perspectives, which is detailed further in Chapter II. The incorporation of drawing was meant to further emphasize the importance and provide tangible evidence of these perspectives. This emphasis was intended to have students pay closer attention to spatial features and the relations between atoms which may then cause students to become adept at identifying these relations in other contexts later, such as on exams and in the research literature for inorganic chemistry. That drawing can provide such educational utility is supported by research,[112-114] though the potential boons of drawing require proper scaffolding.[115] Specifically, students need to be instructed to limit what they include in their drawings and focus on specific features, and the drawings should prompt self-reflection and self-regulation.[116] How these design principles are leveraged in the design of the symmetry activity is discussed further in Chapter II.

CHAPTER II.[2] DEVELOPMENT AND IMPLEMENTATION OF A MODEL-BASED SYMMETRY ACTIVITY IN INORGANIC CHEMISTRY

Introduction

GT&S has had a stable presence in the inorganic chemistry curriculum for decades[2,6] and has been the subject of several academic publications and published learning activities. 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.[117] Another was centered on thinking critically about the definition of a symmetry element and the respective operation's effect on a given compound.[99] Some authors have also created games to facilitate student learning of molecular symmetry.[118] Indeed, it is also a topic taught in the inorganic chemistry curriculum at UIC which, at time of writing, has involved for several years a laboratory activity component.

This chapter was born from a decision to develop an activity that used evidence-based design principles supported by the literature to enhance student learning regarding GT&S. Specifically, this activity leverages collaborative learning,[95] using concrete model kits,[99] and drawing,[116] and was intended to be accessible to any upper-level inorganic chemistry classroom.

The activity was first implemented in Fall 2021 and has been used every Fall and Spring semester since, with data being collected in two successive semesters (Fall 2021 and Spring 2022) to judge the suitability of the activity's design. Data was analyzed in pursuit of evidence for student learning as students moved through different steps: from looking at 2D

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representations, to building and manipulating concrete models, and finally to drawing and labeling molecular representations. This work has been published in the *Journal of Chemical Education*[89] and has been reprinted here with permission from the American Chemical Society. Reprint permissions are listed in **Appendix A**.

Situational Context

This activity was implemented at UIC, a large, federally designated Hispanic-serving urban research university in the Midwest United States. The course in which the activity was implemented is an upper-division one-semester inorganic chemistry survey course with lecture and laboratory components. It is the only undergraduate inorganic chemistry course the institution offers. The laboratory section in which the activity was implemented occurs weekly and lasts for approximately 3 hours. Prerequisites for the course include two semesters of general chemistry and one semester of organic chemistry lecture with the associated laboratory, though most enrolled students have had a full year of organic chemistry, one semester of organic chemistry laboratory, and a semester in analytical chemistry. As such, enrolled students are typically at least in their 3rd year. The course typically serves between 60 to 75 students.

Though the instructor of record and the syllabus for CHEM 314 changes by semester, there are certain topics consistently covered in the course. A review of key general chemistry topics such as periodicity and orbitals often start the course. This is consistently followed by a review of Valence Shell Electron Pair Repulsion theory which then leads to GT&S. Typical course topics following GT&S include molecular orbital theory, spectroscopy, redox chemistry, and basic coordination chemistry.

Activity Design

As I am a graduate worker and not an instructor of record for the inorganic chemistry course, my position naturally put me as an outsider to the classroom; I did not have a stake in the course outside of this activity. As such, I took care to develop and organize the activity to synergistically incorporate instructor-developed pedagogical goals with literature-based design principles and frameworks. Ultimately, the product I was creating would be used by others who graciously but temporarily invited me into their space. As such, the design of the activity proceeded iteratively with me providing to the instructors a bare skeleton of the activity, elucidating their pedagogical goals, and discussing with them potential design elements from the literature. Thus, the activity in its published form is the result of a collaborative effort with key stakeholders where their considerations were incorporated.[89]

Pedagogical Goals

The activity is situated in a course where GT&S plays an important role in attaining several learning goals: understanding functional behavior (e.g., reactivity, spectroscopy, color, magnetism, toxicity, etc.) of inorganic compounds from the perspective of their electronic structures, which in turn is partly dictated by local 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, students experienced a lecture component accompanied by homework assignments that described 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 might 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 develop the ability to classify molecules into point groups, and thus identify molecular symmetry elements.

Considering GT&S had a very particular place in this curriculum, it was necessary to consult the instructors to establish what exactly they wanted students to know about GT&S to best serve broader curricular goals. As this activity was precisely about GT&S, incorporation of these pedagogical goals was paramount. Discussions with the instructors led to the consensus that students should:

1. Know the language of group theory.
2. Use physical objects to model symmetry elements.
3. Learn how to find perspectives to look at compounds and to draw them from scratch.

Establishing these pedagogical goals led to a discussion of the theoretical frameworks and design principles that would underpin this activity. Three key frameworks and design principles were chosen for the design of this activity. Specifically, they are: collaborative learning, use of concrete models, and the incorporation of drawing for educational purposes. These frameworks are discussed in Chapter I.

Activity Components

With the pedagogical goals and theoretical frameworks set, the specific components of the activity were refined to compose a cohesive activity. Specifically, the goals and frameworks influenced the compounds which the students would investigate and the structure of the tasks the students would perform.

Activity Outline

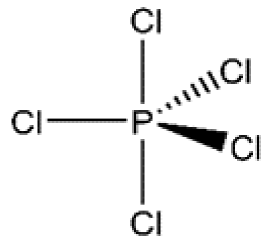
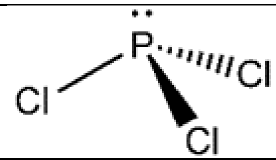
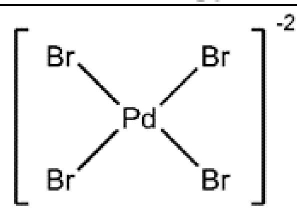
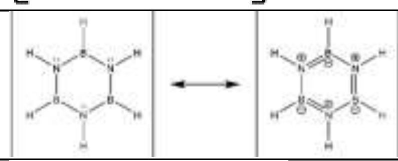
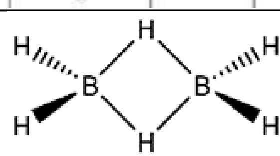
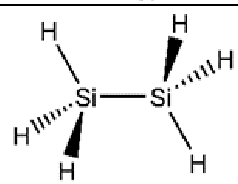
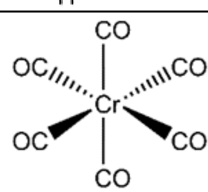
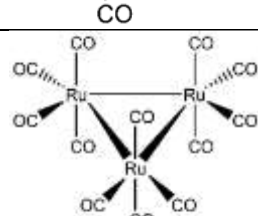
The activity has students answer three sets of questions for each of seven inorganic compounds, with one additional compound provided with all questions answered to serve as an example of expectations. A copy of the activity in full is provided in **Appendix B**. Compounds were ordered according to expected 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**. 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[101] 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.

Compounds of Interest

Carefully selecting the compounds for which students would practice identifying symmetry elements was crucial; if they were too easy then we would be wasting potential student growth, but if they were too difficult then students might rely on methods not directly in line with the pedagogical goals. The compounds listed in **Table 1** were presented to students in the order listed on the basis of increasing expected difficulty and important spatial features.

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. Reprinted with permission from *J. Chem. Educ.* **2023**, 100, 1633-1640. Copyright 2023 American Chemical Society.

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 *C₂'* 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

The first compound on the activity had all answers completed so as to give clear expectations for the forms answers should take. In the Fall 2021 implementation of the activity, water was used as the sample compound but this was then changed to phosphorus pentachloride. This was done as the VSEPR geometry of phosphorus pentachloride, trigonal bipyramidal, is familiar to students from their general chemistry coursework but the relative three-dimensionality of the compound (compared to water, which has all atoms existing in a single plane) allowed for images with greater contrast between perspectives.

Phosphorus trichloride (point group: C_{3v}) was the first compound students did themselves. It is geometrically very simple and has low symmetry, which allowed for students to become familiar with the instructions. The second compound, tetrabromopalladate (point group: D_{4h}) is also fairly simple geometrically but belongs to a more complex point group. However, its planar nature, even-ordered principal axis of rotation, and inversion center coinciding with an atom all contributed to its inclusion to the activity as a comparatively easier compound. In contrast, the third compound, borazine (point group: D_{3h}) does not have a principal rotation axis coinciding with an atom and so was deemed more challenging. Diborane (point group: D_{2h}) and disilane (point group: D_{3h}), the 5th and 6th compounds, were introduced later in the activity due to their aplanarity, the presence of rotational axes that did not pass through atomic centers, and by virtue of having improper rotations (diborane- S_2; disilane - S_3).[119] The last two compounds were deemed the most difficult for different reasons. Chromium hexacarbonyl belongs to the very highly symmetric O_h point group and has several obscure symmetry elements that novices are likely to overlook. Meanwhile, triruthenium dodecacarbonyl (point group: D_{3h}) has a comparatively large number of atoms to manage during symmetry operations which may make it difficult to justify the existence of more complex operations. For both of these complexes containing carbonyls, the carbonyls were not fully built due to limitations of the molecular kits.

Incorporating Design Principles into Specific Questions

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,[90] 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.[91] 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. Others have previously noted that students often did not spontaneously engage with concrete models in their research environment.[102] 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 effective. Specifically, instructions for drawing tasks must constrain the kinds of features to be depicted.[115,116] 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. It should be noted that students were also exposed to virtual simulations in lecture via the Symmetry@Otterbein Web site, but these were not assigned for use during the activity.

Implementation

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 additional instruction to take pictures of the constructed models.

First Implementation: Fall 2021

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 **Appendix B**), 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 to 4 students during the activity itself.

After all students completed the assignment, the collected audio and video recordings of all 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 work analyzed, others elected to give consent to only one (or neither) of these requests. Recordings of and work submitted by students who did not consent to be part of the study were not analyzed.

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, nonplanar borazine, and bent carbonyl ligands for chromium hexacarbonyl. Constructed model accuracy is further discussed in the Results section.

Furthermore, student use of the language of group theory was problematic, especially when it came to differentiating types of mirror planes and axes perpendicular to or including the principal axis of rotation (though students did consistently identify the principal axis of rotation). That said, some difficulty was expected considering other reports noting the problematic linguistic complexity of group theory.[108,119,120] 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 taught 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.

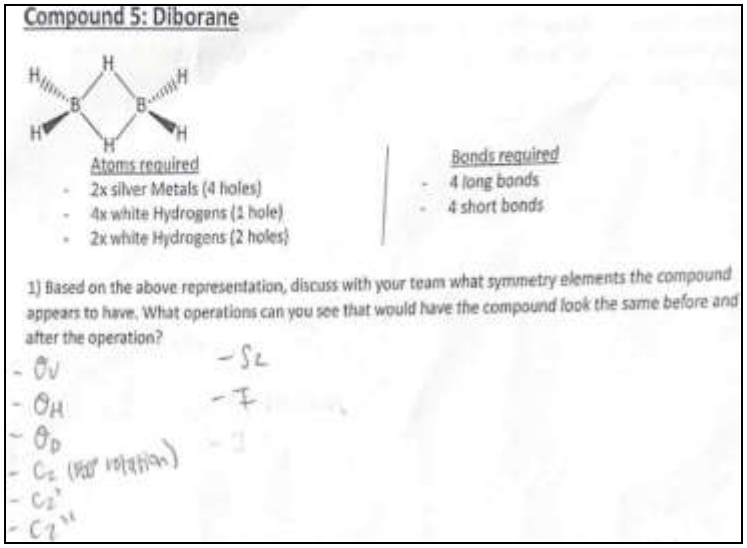


Figure 1 Student identification of symmetry elements in diborane (*D_{2h}*). As the highest order rotational axis has n=2, non-degenerate *C_2* axes should be differentiated by axial orientation and not arbitrary prime denotations. Reprinted with permission from *J. Chem. Educ.* **2023**, 100, 1633-1640. Copyright 2023 American Chemical Society.

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.

Table 2 Completion of Question 3 Drawing Task for consenting students who provided their completed activity. Reprinted with permission from *J. Chem. Educ.* **2023**, 100, 1633-1640.

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

Revisions Prior to Spring 2022

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 often 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.

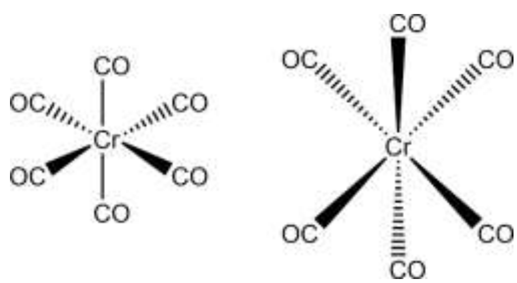


Figure 2 Both provided perspectives of $Cr(CO)_6$ (left, at the start of the section; right, in Q3). The perspective on the right is tilted downward to emphasize the trigonal relationship between sets of carbonyl ligands. Reprinted with permission from *J. Chem. Educ.* **2023**, 100, 1633-1640. Copyright 2023 American Chemical Society.

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 and 14 students at any given time, with student groups ranging from 2 to 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 **Table 3** and **Table 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 min; Spring 2022 video length range: 64−82 min). 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**.

Unfortunately, students still seemed to have difficulties with 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 nonstandard notations such as “perpendicular” and “parallel”.

Table 3 Constructed model accuracy for 18 students in 6 groups. Of these groups, 2 shared a laboratory section. Reprinted with permission from *J. Chem. Educ.* **2023**, 100, 1633-1640. Copyright 2023 American Chemical Society.

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. No groups were in the same laboratory section. Reprinted with permission from *J. Chem. Educ.* **2023**, 100, 1633-1640. Copyright 2023 American Chemical Society.

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

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 are tabulated in **Table 3** and **Table 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 **Table 3** and **Table 4** show that model accuracy improved between semesters, possibly because of the probing questions about molecular geometry priming students to 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 the 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.

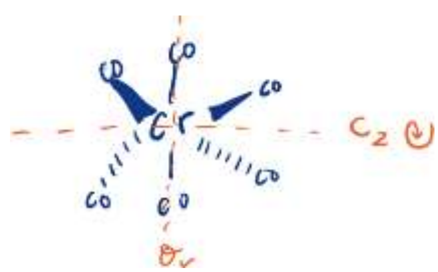


Figure 3 Student work that satisfied both criteria for **Table 2**. Reprinted with permission from *J. Chem. Educ.* **2023**, 100, 1633-1640. Copyright 2023 American Chemical Society.

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. **Figure 4**, **Figure 5**, and **Figure 6** summarize which symmetry elements were identified by whom and at what point in the activity. These data provide 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 **Appendix C**, while the tabulated results of this coding process for all consenting students in the Fall and Spring semesters is listed in **Appendix D**.

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 GT&S had been covered in lecture by this point. The "Not Found" designation indicates the symmetry elements not identified at any point by that student. Incredibly, 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.

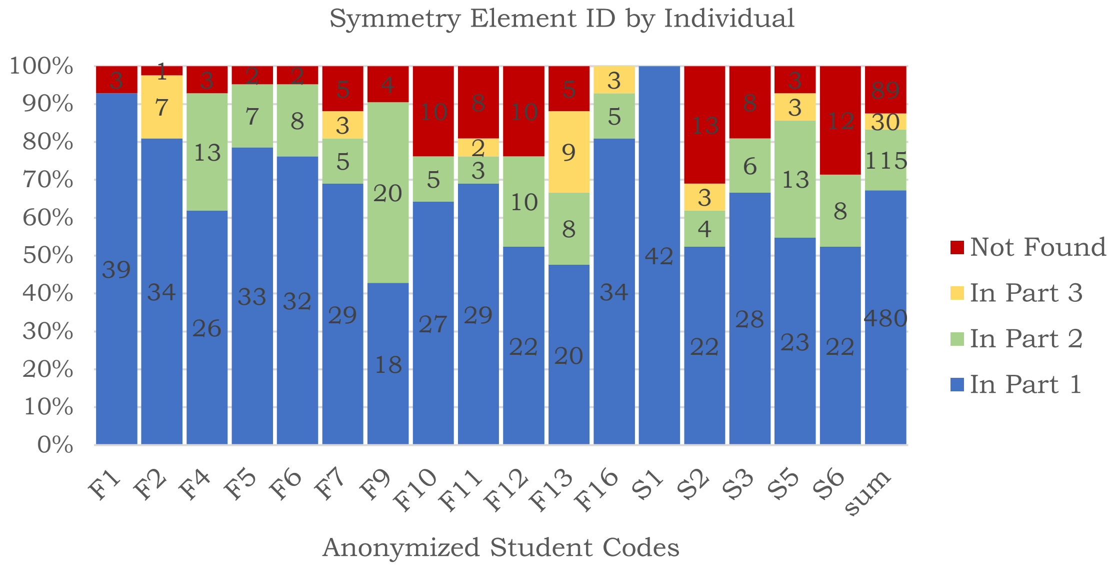


Figure 4 The number of symmetry elements students found in each part of the activity. Symmetry elements found in part 1 were found using only the provided 2D representation; those found in part 2 utilized the 3D model; and those in part 3 were found after completing the drawing prompt. Reprinted with permission from *J. Chem. Educ.* **2023**, 100, 1633-1640. Copyright 2023 American Chemical Society.

Figure 5 and **Figure 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.[121] Finally, it is clear that the model building step was especially important in identifying improper rotation axes, where present.

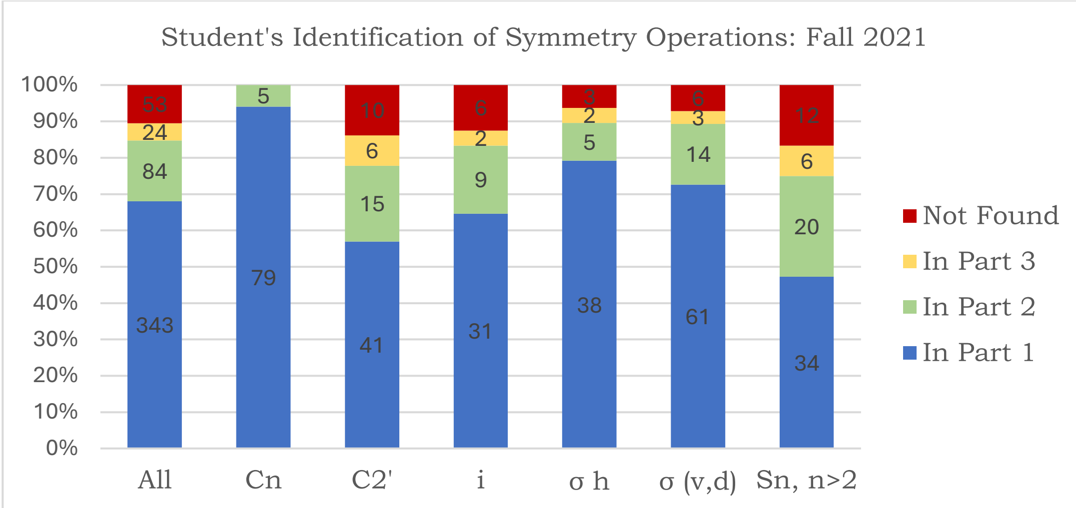


Figure 5 A count of symmetry elements identified by students in Fall 2021 distinguished by the type of symmetry element. Symmetry elements found in part 1 were found using only the provided 2D representation; those found in part 2 utilized the 3D model; and those in part 3 were found after completing the drawing prompt. Reprinted with permission from *J. Chem. Educ.* **2023**, 100, 1633-1640. Copyright 2023 American Chemical Society.

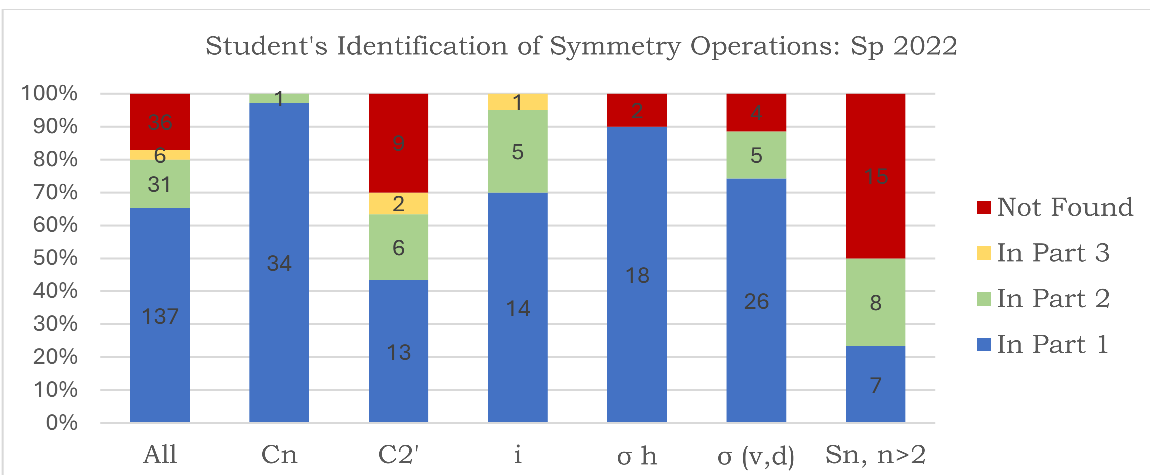


Figure 6 A count of symmetry elements identified by students in Spring 2022 distinguished by the type of symmetry element. Symmetry elements found in part 1 were found using only the provided 2D representation; those found in part 2 utilized the 3D model; and those in part 3 were found after completing the drawing prompt. Reprinted with permission from *J. Chem. Educ.* **2023**, 100, 1633-1640. Copyright 2023 American Chemical Society.

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 published activity seemed to fulfill its pedagogical purposes. Though the activity will be further refined, especially as related to the pedagogical goal of accurate terminology use, my co-authors and I believed that iteration was sufficiently developed for adoption at other institutions. Minor adjustments may be necessary to fit institution-specific curricula, pedagogical goals, and student prior knowledge.

That student engagement with the activity consistently included gestures prompted further investigation into this manual phenomenon. This investigation is described in Chapter III.

CHAPTER III.[3] SYSTEMATICALLY CHARACTERIZING AND ANALYZING GESTURES WITH A NOVEL GESTURE CHARACTERIZATION SCHEME

INTRODUCTION

What topics commonly appear in inorganic chemistry curricula has changed significantly over the past century.[3,4,6,8,9] However, GT&S is one topic that continues to be widely covered in inorganic chemistry curricula.[12,89,99,107,117,120,122,123] Publications involving symmetry and group theory, which largely focus on in-classroom activities, suggest that this topic is uniquely challenging for students. Several publications describe students struggling with observing certain symmetry elements[12,108,124] determining point groups [108,125] or using general visualization skills. [109,123,125,126,]

In response to these difficulties, researchers detailed how using certain pedagogical approaches,[99,117,127] 3D models,[108,109] or other tools[107,118,126,128] can help students become adept at skills relevant to GT&S. In our own published activity using concrete models and other frameworks to accomplish this same goal,[89] we noted students additionally using gestures when engaging with GT&S. In the process, our observation of students showed that, in addition to analyzing 2D representations, building models, and drawing, students used gestures with their hands as part of their communication and, possibly, reasoning about symmetry. This prompted us to examine the role of gesture more rigorously, drawing on frameworks of embodied cognition in general and with gesture specifically. The work described in this chapter has been published in the *Journal of Chemical Education* and is reprinted here with permission from the American

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Chemical Society. Reprint permissions are listed in **Appendix A**. This work's position with respect to embodied cognition and gesture as metaphor are detailed in Chapter I. Central to this work is the idea that gesture can be described in terms of how it physically exists in the world (gestural form) and the meaning underpinning the gesture (notion). This relationship is described in **Figure 7**.

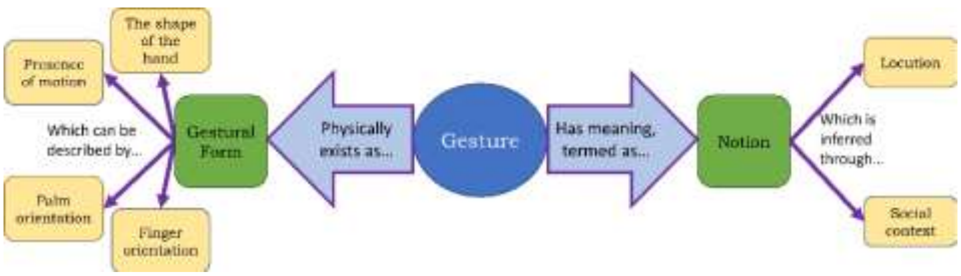


Figure 7 Gesture has two key components. The gestural form is the physical manipulation of the body (or in our framework, specifically of the hand). The notion is the meaning which is being conveyed by that physical manipulation in a particular context. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

Our work examines gestures in an inorganic chemistry context as participants reason about symmetry and group theory. With considerable literature support of gesture's relation to reasoning and cognition, especially with spatial tasks, we sought to investigate what meaning students ascribed to their gestures. To accomplish this, we have developed a scheme to succinctly but comprehensively code individual gestures so that we might ascertain not only what gestures are most used but also the notions these gestures convey. What is novel in our approach is the application of the source/ target domain frame specifically to gestures in a chemistry setting, as well as the scheme by which we systematically describe gestural forms.

RESEARCH QUESTIONS

This work was motivated by observations of students completing the symmetry activity described in Chapter II, which has been published elsewhere.[89] In that work, students gestured frequently and with similar gestural forms despite having no explicit prompt to gesture. Inspired by these observations and the literature that supports gesture as having cognitive and communicative utility, we proposed the following research questions:

1. What gestural forms are inorganic chemistry students employing as they explore symmetry and group theory?
2. Are there certain notions which are typically associated with certain gestural components?

To address these questions, we examined video data from one-on-one interviews with inorganic chemistry students. We then systematically coded the gestural forms students used and the notions we inferred to identify when these constructs temporally aligned. Finally, we looked for patterns in the components of gestural forms individual students used and tabulated the critical gestural components used across all students for our notions of interest. We hope our work can guide further chemistry education research in this modality and inform pedagogical practice.

METHODS

This study took place in the Midwest United States at a large, federally designated Hispanic-serving urban research university. Participants were recruited from the only undergraduate inorganic chemistry course that the institution offers, in both the Fall 2022 and Spring 2023 semesters. Approximately 60−75 students take the course each semester, and most are third-year students. The instructor for the course rotates among the institution's inorganic faculty. The Fall 2022 and Spring 2023 offerings of the course had different instructors. While both instructors used gestures during their lectures, they did not call out that the gestures themselves were to be followed. Instructor gestures were outside of the scope of our data collection protocols and, as such, were not included in our analysis. All offerings of the course include three 50-minute lectures by a faculty member and a laboratory section led by a Graduate Teaching Assistant (TA) each week. Symmetry and group theory was covered first in the lecture and then in the laboratory portion of the course, using the activity previously described.[89]

This study analyzed one-on-one interviews with students after they had completed the laboratory activity. Interviews occurred 2−9 weeks after completion of the activity. Consent procedures and interview protocols were approved by the university's Institutional Review Board (ID: 2021-1273). Consenting students were assigned an alphanumeric identifier to protect their identities and were compensated with $25 for their time.

Interviews were conducted in Fall 2022 and Spring 2023. Interviews took place in person and outside of regular class hours. The interview format was semi-structured and included six phases (see **Appendix E** for the protocol). The first phase reiterated the purpose of the interview and asked the interviewee if they still provided consent. Phase two probed the interviewee's familiarity with symmetry operations. We then asked the interviewees in phase three to identify the symmetry elements for four compounds. In this phase, preconstructed molecular models were provided for two of the four compounds. Interviewees freely gestured throughout the first three phases. The fourth phase had the interviewer mimic some of the gestures produced by the interviewee and ask questions about the meaning and origin of those gestures. The fifth phase had the interviewer produce gestures from a list and ask the interviewee to interpret those gestures. Interviewees were reminded that there were no wrong interpretations and that a gesture having no meaning to them was acceptable. The sixth phase gave room for the interviewee to share any final thoughts before departing.

Interviews in Fall 2022 were recorded on a tripod-mounted video camera, while interviews in Spring 2023 were recorded both on a tripod-mounted video camera and by a webcam on the first author’s laptop. In total, seven interviews were analyzed. Two of these interviews were conducted in Fall 2022 (participants Fa1 and Fa2) while the remaining five were conducted in Spring 2023 (participants Sp1 through Sp5).

Coding Referential Gestures Based on their Physical Components

To answer our research questions, we needed a systematic way to describe the observed gestures. Other authors in the field of gesture studies developed schema and discussed how they classify gestures.[46,52,53,129] But to our knowledge there are no schemas that relate to the question of molecular structure or symmetry elements, nor that succinctly and systematically describe gestures. Most schema describe gestural forms with full sentences in a narrative fashion,[52,53] though sometimes these are partially abbreviated.[46] We initially developed a similar coding scheme that explicitly described gestural forms in a seminarrative fashion (e.g., “Point with Index Finger”). Unfortunately, this scheme quickly became unwieldy for anything beyond the simplest gestural forms. Instead, we moved to a form of symbolic notation that indicated if a gesture was of a static physical form or was associated with motion, inspired by Calbris’ methodology.[67] We also developed a way to describe components of the gestural form, such as the orientation of the palm or fingers or the type and direction of motion in the case of gestures, which included motion. This scheme uses the anatomical planes and axes of the body in **Figure 8** for clarity and uniformity.

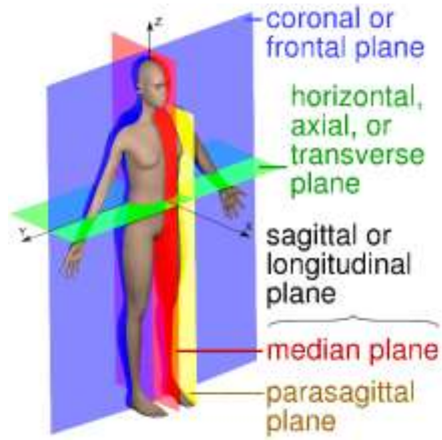


Figure 8 Anatomical planes and axes of the body. Image created by David Richfield, Mikael Häggström, M.D. and CMG Lee. Reproduced with permission, CC BY-SA 4.0.<File: Human anatomy planes>[130]

Following Calbris,[67] our coding scheme captures all the relevant physical details of a gestural form in a single code rather than having distinct codes for individual components of a gestural form (i.e., hand shape, orientation, etc.). We categorized gestural forms in a hierarchical fashion based on if they embodied notions purely through gestural form ("F" or form-dependent gestures), or if there was also a movement component ("M" or motion-dependent gestures). Our coding scheme is described in **Figure 9**.

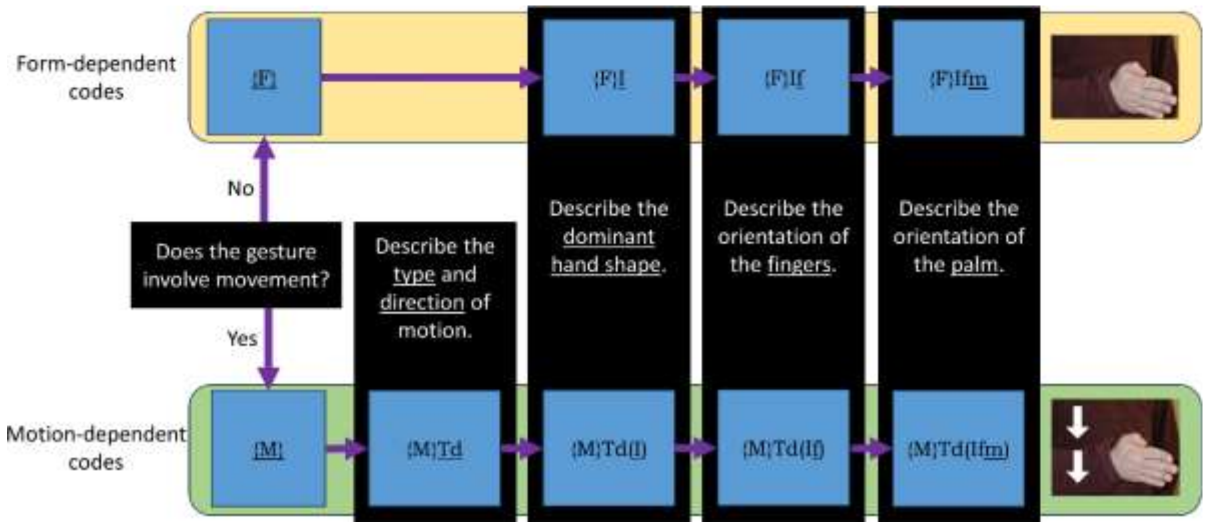


Figure 9 Hierarchal description of gestures with syntax. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

Form-Dependent Gesture Code Syntax

Gestures that conveyed notions purely through their gestural form were described as form-dependent gestures. We used a base four-letter code for these gestures with the following syntax:

{F}Abc

Where "{F}" simply indicates this as a form-dependent code, "A" indicates the hand shape, "b" describes the orientation of the fingers with respect to the planes and axes of the body, and "c" describes the orientation of the palm.

Figure 10 illustrates this scheme. In this and other gesture photos, we have recreated our participants' original gestures with a new photograph for clarity. The original photos are shown for comparison in **Appendix F**. Without our scheme, this gesture may be described as "a hand oriented parallel to the midsagittal plane of the body with all fingers pointing forward and the palm facing the midsagittal plane." While this form can be thoroughly described in those 23 words, it would be very time-consuming to similarly describe all 218 unique gestural forms we observed in the data corpus.

Figure 10 A **Form-dependent ({F})** gesture that was produced by Participant Sp3, with a flat hand oriented here parallel to the midsagittal plane **(I)**, fingers pointed forward **(f)**, and palm faced medially **(m)**. This is coded as {F}Ifm. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

With our scheme, the form of this gesture is coded as {F}Ifm. The "{F}" designation indicates that this gesture does not involve movement. The "I" hand shape code, borrowed from Calbris' designation for the same shape, indicates a flat-hand shape oriented in a nonspecific vertical fashion (i.e., not parallel to the transverse body plane). The third letter, "f", indicates that the fingers are facing forward, while the last letter, "m", indicates that the palm is facing medially. Thus, we describe the physical form of a gesture in 6 characters instead of 23 words.

Motion-Dependent Gesture Code Syntax

Gestures perceived as having a critical movement component are motion-dependent gestures and use the following syntax:

{M}De(Abc)

Where "{M}" indicates this as a motion-dependent code, "D" indicates the type of motion involved (translational or rotational), and "e" further specifies the direction of the motion. The hand shape component ("A") and orientation components ("b" and "c") from the form-dependent gesture syntax are also utilized for motion-dependent gestures but are placed in parentheses to better distinguish them from the characters specifying the type and direction of motion.

Figure 11 shows a recreation of a motion-dependent gesture produced by participant Sp1. Throughout the duration of the movement, the hand shape and orientation are constant. In our scheme, this would be coded as {M}Td(Imb) as the gestural form has a clear and deliberate motion component ("{M}") wherein the hand translates ("T") downward ("d"). The hand shape is a vertically oriented flat hand ("I") with the fingers oriented toward the medial body plane ("m") and the palm facing back toward the gesturer ("b").

Our scheme also accommodates cases where the hand changes shape or where both hands are involved. If both hands are used for a single gesture, the hands are described separately within parentheses with the left-hand being described first. This allows for the addition of a motion code in front of the parentheses in case one (or both) hand moves throughout the gesture. If the motion, shape, and/or orientation of the hand changes during the gesture, the greater-than symbol (">") is used to separate the codes which describe the initial and final states of the gestural form. A list of abbreviations used in this syntax is provided in **Appendix G**.

Figure 11 A **Motion-dependent ({M})** gesture that was produced by Participant Sp1, where the hand translates downward **(Td)**. The hand's shape is flat and parallel to the coronal plane **(I)** with fingers pointed medially **(m)** and palm faced back **(b)**. This is coded as {M}Td(Imb). Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

Student Actions Beyond Gestures

Some students communicated in modes beyond locution and gesture. Occasionally, participants used objects when discussing relevant concepts, such as pens to model axes, notecards as analogues to mirror planes, and rotations of molecular models to communicate a specific rotation operation. Though we might learn much about the participants' thought processes, we elected to restrict our analysis only to the performed gestures as defined in our frameworks. Additionally, students performed deictic gestures that point to a referent that is not represented by the hand itself. These were also not examined in our study.

Establishing Relationships Between Gestural Forms and Notions

We began this investigation intending to make relational claims between gestural forms and notions as has been done elsewhere.[52,65,67] We took as evidence the temporal overlap between an expressed notion and a gestural form as a correlation between them.

The frequency of overlaps between gestural form and notions codes were tabulated for each individual. For sufficiently populated notions of interest, we then looked for patterns not in the entire gestural form but in the components of the gestural form associated with that notion. By observing patterns across individuals, we can make claims that certain gestural components typically convey certain notions in this local environment. Note that we did not expect (nor does the data suggest) that there exists a one-to-one unique relationship between just one gestural form and one notion. But it is the case that certain gestural components, such as specific hand shapes or orientations, were more commonly associated with certain notions.

DATA ANALYSIS

Coding Interview Videos for Gestural Forms

All interviews were transcribed with timestamps and coded for gestural forms and notions in MaxQDA 20.4.2. Codes were created as new gestural forms were documented. In total, 218 unique gestural forms were observed across the seven coded interviews. The Supporting Information of the associated publication[25] has the full list of these gestures and has not been included in the appendix of this dissertation due to the sheer size of the table. The frequency at which gestural forms were enacted was tabulated to address Research Question 1, which asked what gestural forms were being used by inorganic chemistry students as they explored symmetry and group theory.

Coding Interview Videos for Notions

We began coding notions based on patterns observed in the transcription process, as participant locution was a major evidence source for this component of our coding. We developed codes distinguishing rotational symmetry operations (“C2 ”and “C3”), rotational symmetry elements (“Principal Axis of Rotation (Axis)”), and beyond. These included codes such as “Inversion”, “Improper Rotation”, “Mirror Plane”, and the specific mirror planes “Vertical”, “Horizontal”, and “Dihedral”. We also observed notions describing qualities of symmetry elements such as specific rotation angles, motions embodied by operations (“Flipping”, “Folding”, “Translational motion”), and even notions describing the molecular entity under examination (“Straight object”, “H2O”). Our data contained instances of gestures alongside verbal utterances describing the “flatness” of planes and planar molecules, the “flipping” of objects undergoing rotations, or objects being “cut” when discussing mirror planes. Thus, our notion codebook includes a range of codes that broadly encompass how our participants reason about symmetry and group theory. By the end of the coding process, we had generated a total of 51 notion codes. Again, due to the size of the tabulated data, the full notion codebook is provided in the Supporting Information elsewhere.[25]

Notions were coded predominantly based on participant locution and social context. Participant locution was used as evidence, whether unprompted or in response to our dialogue. For example, when participant Sp1 was given a molecular model of benzene and prompted to identify symmetry elements, she flattened her hand parallel to the transverse body plane with her palm facing down and fingers facing medially while moving her hand forward, away from her (coded as {M}Tf(Hmd) (see **Figure 12**, left). She simultaneously stated, “It’s just very flat, and so that’s where you get your horizontal mirror.” She next raised a finger up through the middle of the model (palm facing medially, coded as {F}2um) (see **Figure 12**, right) while stating that, “The principal axis is actually straight through here.” In this example, the time frame in which the first gesture occurred had notion codes for “Flatness” and “Horizontal”. The second gesture’s time frame had a "Principal Axis" notion code. Instances where the participants gestured with little to no locution could still receive notion codes based on context.

Figure 12 (Left) A gesture that was produced by Participant Sp1 where the hand is parallel to the transverse plane of the body ("H"), with fingers faced towards the midsagittal plane ("m") and palm faced downward ("d"). The motion would start close to the body and move linearly away in the +x direction ({M}Tf). This gestural form is coded as {M}Tf(Hmd). (Right) A gesture that was produced by Participant Sp1, the model is held with the left hand while the right hand gestures. The gestural form, coded as {F}2um, has the second finger ("2") pointed upward ("u") while the palm is faced roughly medially ("m"). Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

Eliminating Notions from Final Analysis

We ultimately arrived at 51 notion codes and 829 gestural form-notion overlaps. We removed 29 notions based on two criteria to obtain a list of 22 notion codes. First, some notions were too far removed from symmetry and group theory and instead described notions more closely related to spatial reasoning (e.g., "Origin (Cartesian)"), the entities which we analyze with symmetry and group theory (e.g., "H2O", "2D Object"), or motion and orientations (e.g., "Translational motion", "Upward, up"). Second, other notions, like "Reflection (Operation)" and the three codes for planes described by pairs of Cartesian axes (e.g., "XY Plane"), were comparatively undersampled. As our analysis relied on finding patterns across gestures with the same notion, undersampled notions could prove problematic. To keep a notion code, we required a minimum of three gestural form-notion overlaps for at least three individuals (with the sole exception of notions related to improper rotations; see Results). Finally, we determined some notions to be sufficiently similar and elected to combine them. Notions that we did not deem appropriate to combine and were undersampled were eliminated from further analysis.

The 22 remaining codes were further grouped into 10 notions for analysis, with 4 of these being composites of similar notions. The final set of 10 notions still accounts for 590 gestural formnotion overlaps, or 71% of the original data set. The six singular notions, or those notions which are not composites of other notions, are Inversion, Principal Axis, Rotation, Dihedral, Horizontal, and Vertical. The other four notions, Mirror Plane, Proper Rotation, Axis, and Improper Rotation, are composites of several notions. We refer to these composites as parent notions, while the individual component notions are referred to as subnotions. For example, the subnotions of C_2, C_3, C_4, and C_n were judged as sufficiently similar and grouped into the Proper Rotation parent notion. The six singular notions and four parent notions constitute our main analytical framework and are listed alongside descriptions of the notions in **Table 5**. This tabulated data regarding the final set of 10 notions is shown in **Appendix H**.

Table 5 Ten notions composing analytical framework. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

Notion codes	Description
Inversion	Movement of an object(s) through a central point.
Principal axis	The axis which allows for the largest rotation.
Rotation	Generic code for movement in a radial manner.
Dihedral	Mirror plane coincident with the principal axis and C_2'' (if present)
Horizontal	Mirror plane perpendicular to the principal axis
Vertical	Mirror plane coincident with the principal axis and C_2' (if present)
Mirror plane (parent code)	Generic code for mirror planes with *no specification* of type
Proper Rotation (parent code)	Rotation that is specifically in line with a proper rotation axis
Axis (parent code)	Generic code for a one-dimensional object (about which rotation *may* occur)
Improper rotation (parent code)	Operation consisting of a rotation and a mirror perpendicular to that axis

Extracting Critical Gestural Components from Gestural Form-Notion Correlations

With the final set of notions determined, we extracted key physical feature(s) of gestures that overlapped with these notions to address Research Question 2, where we inquired as to possible relations between certain notions and certain gestural components. We did this by examining heat maps showing the number of instances in which a participant enacted a gestural form that had a temporal overlap with a given notion. **Table 6** is an abridged frequency table for participant Sp1 that only includes gestural forms that conveyed the “Mirror plane” parent notion code (among other notions). Full gestural form-notion heat maps for all participants can be found in **Appendix I**. The frequency table here shows the significant breadth of participant Sp1’s gestures, with some notions highlighting several gestural variants or different gestural forms referring to the same notion (e.g., {F}Hfd, {F}Ium, and {M}Td(Ifm) all communicating “Mirror

Plane”, see **Figure 13**). Additionally, certain gestural forms exhibited polysemy, such as {F}Ium at different times conveying specifically the “Principal axis” notion, the generic “Axis” parent notion, the “Vertical” mirror plane notion, as well as the notion of a generic mirror plane with no specified relation to a principal axis.

Table 6 Frequency table of gestural form codes overlapping with notions for participant Sp1. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

Gestural form codes	Principal axis	Dihedral	Horizontal	Vertical	Mirror plane (Parent)	Cn Rotation (Parent)	Axis (Parent)
{F}Hfd	0	0	2	0	2	0	0
{F}Hmd	0	0	7	0	2	1	0
{F}Iaf	0	0	0	0	2	0	0
{F}Idb	0	1	0	1	2	0	0
{F}Ifm	0	0	0	5	14	0	0
{F}Imb	0	1	0	2	7	0	0
{F}Ium	3	0	0	5	4	0	1
{M}(Guu)Ta(Guu)	0	0	0	0	1	0	0
{M}Td(Ifm)	0	0	0	0	3	0	0
{M}Tf(Ium)(Ium)> Tb(Ium)(Ium)	0	0	0	0	1	0	0
{M}Tm(G12uu) (Ium)	0	0	0	0	1	0	0
{M}Tu(Ium)(Ium)> Td(Ium)Ium)	0	0	0	0	1	0	0
{M}R+x(2db)(Ifm)	0	0	0	0	1	0	0
{M}R-x(Hfd)	0	0	1	0	1	1	0
{M}R+z(Ifm)	0	0	0	0	2	0	0
The “Inversion”, “Rotation”, and the parent “Improper Rotation” codes were removed from this table as there were no gestural form codes which overlapped with those presented.							

Figure 13 (Left) A gesture that was produced by Participant Sp1, where the hand is held parallel to the transverse plane of the body ("H") with fingers forward ("f") and palm down ("d"). There is no motion associated with this gesture ("{F}"). This is coded as {F}Hfd. (Middle) A gesture that was produced by Participant Sp1, where the hand is parallel to the medial plane ("I") with fingers upward ("u") and palm faced medially ("m"). There is no motion associated with this gesture ("{F}"). This is coded as {F}Ium. (Right) A gesture that was produced by Participant Sp1, where the hand is parallel to the medial plane ("I") with fingers pointed forward ("f") and palm faced medially ("m"). The hand also translates downward in the -z direction indicated by the white arrow ("{M}"Td"). This gesture is coded as {M}Td(Ifm). Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

It was occasionally necessary to return to the video recordings to understand seemingly irregular codes. For example, most of the gestures that participant Sp3 enacted when conveying the "Horizontal" mirror plane notion involved the "H" gestural form code. However, they enacted a gesture we coded as {F}Ifm when asked about a hypothetical gesture that would distinguish between σ_v and σ_h. They explained,

> *"You would have to first establish what the molecule, where it is in three-dimensional space [sic]. If you have the molecule slanted or perhaps on a different axis, then those planes would change. Because this (gesture) means vertical, diagonal, and horizontal at the same time if I didn't specify where the molecule would be positioned."*

RESULTS

Common Gestural Forms

As described in the methods, to address the forms gestures may take as stated in Research Question 1, we identified 218 unique gestural codes from our observations of the students. From those, there were 180 gestural form codes observed to overlap with the 10 notions in our analytical framework. Tabulated gestural form-notion overlap data is presented in **Appendix H**.

We have listed the 12 most common gestures, their most associated notions, and depictions of the gestural forms in **Table 7**. The most common gestures use either a flat hand shape that is oriented parallel to the transverse body plane (i.e., using the “H” hand shape code) or perpendicular to that plane (i.e., using the “I” hand shape code). Gestures using these hand shapes are predominantly associated with notions involving mirror planes, with the former often referring to horizontal mirror planes and the latter to vertical mirror planes.

Interestingly, the “Ifm” gestural form, where a flat hand is oriented vertically with the fingers facing forward and palm facing medially, appears twice in **Table 7**: in a stationary form as {F}Ifm and in a form involving a linear downward movement as {M}Td(Ifm). As both gestures have similar notion associations, we take this as evidence that the translational motion in the latter gesture is further emphasizing the critical gestural component; the flat hand embodying the plane.

Table 7 Most common gestures across participant interviews Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

Gestural Form code	Frequency	Most Common Notion	Depiction
{F}Ifm	43	Mirror plane (parent) (27/43)	
{F}Ium	32	Mirror plane (parent) (14/32)	
{F}Hmd	27	Horizontal mirror plane (13/27)	
{M}Td(Ifm)	26	Mirror plane (parent) (14/26)	
{F}Imb	24	Mirror plane (parent) (16/24)	
{F}2db	17	Axis (parent) (10/17)	
{F}Hfd	16	Mirror plane (parent) (8/16)	
{F}2fm	13	Axis (parent) (10/13)	
{F}2ub	13	Axis (parent) (8/13)	
{F}2mb	12	Axis (parent) (11/12)	
{F}2fd	11	Principal Axis (3/11) or Axis (parent) (3/11)	
{M}Td(Imb)	11	Vertical (6/11)	

There are also several gestural forms in **Table 7** that invoke a hand shape where the index finger is pointing in some direction, i.e., using the “2” hand shape code. The most common of these, {F}2db, has the index finger pointing downward while the palm is facing back toward the body of the speaker and appears to invoke the unidimensionality of axes. Indeed, several participants directly confirmed this perspective during the interviews. Participant Sp1, for example, said, “… [T]o me, axes of rotation are more one-dimensional so I like to use a finger…”. In a different interview, participant Fa2 recognized that fingers are literally three-dimensional objects but that a pointing finger “gets the point across”, and that other analogs like a pencil might be used to physically represent an axis but that, “…it’s the same as a finger in [Fa2’s] mind.” Similar confirmations occurred in every other interview, except with participant Fa1.

Correlation of Gestural Features to Specific Notions

For Research Question 2 our analysis focuses on the notions expressed by students and the relationship that those have to their gestures. **Table 8** shows the frequency and spread of the 10 notions that constitute our analytical framework throughout the seven interviews. The full table which includes the 16 subnotions is present as Supporting Information in the associated publication.[25] Every one of these notion codes is covered by at least five of our participants, except for the Improper Rotation parent code.

Table 8 Notion code counts by participant and in total. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

Notion codes	Sp1	Sp2	Sp3	Sp4	Sp5	Fa1	Fa2	Total
Inversion	6	3	2	6	5	2	1	25
Principal Axis	17	0	3	6	7	0	5	38
Rotation	24	5	8	11	11	2	12	73
Dihedral	5	1	4	1	1	0	4	16
Horizontal	14	9	12	6	8	3	6	58
Vertical	23	13	5	10	11	0	7	69
Mirror Plane (parent)	44	11	25	14	30	6	8	138
Rotation (parent)	16	0	4	2	1	7	9	39
Axis (parent)	29	9	31	16	12	13	10	120
Improper Rotation (parent)	0	0	0	9	0	0	5	14
SUM	178	51	94	81	86	33	67	590

To address Research Question 2, we sought correlations between specific notions and components of gestures. **Table 9** summarizes critical gestural components in gestural form-notion overlaps for all seven interview participants. To extract a "critical gestural component", we required that the student use three or more unique gestural forms for that notion. Furthermore, the critical gestural components presented in **Table 9** for a given notion had to account for at least 50% of the total overlaps with that notion for that individual. For example, participant Sp4's heat map indicated they used five unique gestural forms to communicate the "Vertical" notion. Three of those gestural forms were used by Sp4 only once ({F}Imb, {F}Iub, and {F}Iuf), while another was used twice ({M}Td(Imb) and another five times ({F}Ium). We judged that the critical gestural component for Sp4 when engaging with the "Vertical" notion was {F}I, as that gestural form occurred in 80%, or 8 out of 10, instances when a gesture occurred.

Table 9 Critical Gestural Components by Notion and Participant. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Sp1	Sp2	Sp3	Sp4	Sp5	Fa1	Fa2
Principal Axis	{F}2--	None (0)	None (2)	{F}2--	{M}Td(2--)	None (0)	None (1)
Axis*	{F}2--	{F}I-- {M}T-(I--)	{F}2-- {M}--(2--)	{F}2--	{F}2-- {M}Td(2--)	{M}T-(2--)	{F}2d- {M}T-(2d-)
Proper Rotation*	{M}R--(---)	None (0)	{F}2-- {M}--(2--)	None (2)	None (1)	{F}I-- {M}Td (I--)	{F}2--
Rotation	{M}R-z(---)	{M}R--	{M}R--	{M}R-(---)	{M}R-(--) {M}O-(--)	None (2)	{M}R-z(---)
Mirror Plane*	{F}I-- {F}H--	{F}I-- {M}T-(I--)	{F}H-- {F}I--	{F}H-- {F}I--	{F}I-- {M}T-(I--)	{F}I-- {M}Td (I--)	{F}I-- {F}H--
Horizontal	{F}H-d	{F}H-- {M}T-(H--)	{F}H-- {M}T-(H--)	{F}H--	{F}H-- {M}T-(H--)	{M}T-(-md)	{F}H-- {M}--(H--)
Vertical	{F}I--	{F}I-- {M}T-(I--)	{F}I-- {M}T-(I--)	{F}I--	{F}I-- {M}Td(I--)	None (1)	{F}I-- {M}T-(I--)
Dihedral	{F}I--	None (1)	{F}I--	None (1)	None (1)	None (0)	{F}I-- {M}T-(I--)
Improper Rotation*	None (0)	None (0)	None (0)	{M}--(---)	None (0)	None (1)	{M}--(2mm)
Inversion	{F}Gmm	None (2)	None (1)	{M}--(G--)--(G--)	{M}T-(Gmm) T-(Gmm)	None (2)	None (1)

Parent notions are denoted with an asterisk. Notions for which no critical gestural component was discerned are marked as “None” with the total number of unique gestures used by that participant to indicate that notion. A dash (-) is used as a wildcard in the gestural form syntax when a part of a gesture (e.g., finger orientation) was not deemed critically important.

Several interesting trends emerge from this table. We coded the principal axis of rotation as a separate notion from generic axes because the principal axis is significant for defining mirror planes and point groups. Despite this, there are several similarities between the two notions. All three participants who consistently gestured the “principal axis” notion used their index finger, denoted in our coding scheme as “2”; the remaining four did not communicate this notion with sufficient frequency to enable analysis. Similarly, six out of the seven participants used their index finger to indicate a generic axis with the “axis” parent notion. We interpret this as strong evidence that the index finger can serve as an embodied metaphor of an axis. Conversations during interviews also clarified that gestures using the index finger to communicate notions about axes, using forms such as {F}2db in **Table 7**, were not deictic; participants were not pointing to the axis but were having their finger embody the axis.

There were also often similarities between the “Rotation” notion, used when the participant was indicating a generic rotation, and notions indicating rotations with specified angles (i.e., those with the “Proper Rotation” parent code). The critical feature for most participants for rotation notions was that some part of the hand rotated, although participants Sp1 and Fa2 did typically gesture with rotations specifically along the z-axis. Participant Sp3 emphasized the pointing index finger ({F}2– and {M}--(2--)) for both the “Proper Rotation” parent code and “Axis” parent code. This could imply that, in instances where Sp3 was discussing rotations, they were doing so mentally while physically embodying the axis by which they did the rotation.

For most individuals, differentiating between the horizontal and vertical mirror planes involves a planar hand shape that is parallel and perpendicular to the transverse plane of the body, respectively. Indeed, both hand shape codes appear as dominant features for nearly all participants when indicating a generic mirror plane, as seen in the “mirror plane” parent notion. Participant Fa1 deviated interestingly when communicating the “horizontal” notion, however, as the critical gestural component was a translation of the hand where the finger(s) were pointing medially and the palm was facing down as if they were using their hand to trace the plane regardless of the shape their hand took.

We note that the "dihedral" plane notion was indicated less often not only because of the scarcity of dihedral planes in the molecules studied but because they are treated as functionally identical to vertical mirror planes in the undergraduate inorganic chemistry course at this institution; when dihedral planes appeared, they were simply referred to as vertical planes.

Participants Rarely Gestured about Improper Rotations and Inversions

Improper rotations and inversions (which are S_2 rotations) were discussed far less often by participants than the C_n and σ operation classes. Participants seemed less likely to gesture about improper rotation and inversion operations even when they were brought up in conversation, leading to a smaller sampling for these notions, as seen in **Table 8** and **Table 9**. There are several possibilities for why these notions may be undersampled. For one, there are indications elsewhere in the literature that students have difficulties with these operations.[12,89,108,119,124] Thus, participants may be gesturing about these operations and elements less frequently because their underlying conception is uncertain. It is for this reason alone that we elected to present data regarding the "Inversion" and "Improper Rotation" notions in **Table 8** and **Table 9** despite undersampling. A review of the instructional material given to the participants in their respective inorganic chemistry courses indicates that instructors did value knowledge of these operations. Both operations appeared in lecture materials, homework, exam materials, and the symmetry and group theory model-building activity given to students during their laboratory course component. However, identifying these symmetry elements is not necessary when determining molecular point groups using common flowcharts,[121] and so they may be implicitly deemphasized as students progress through the course. Furthermore, improper rotations are typically described during instruction as two operations in one; a proper rotation followed by a reflection in the perpendicular plane. It is possible that this composite nature renders these symmetry elements too complex for individuals still learning the material to consistently gesture.

Evidence of a Zipfian Distribution in Gestural Forms Used

Of the 180 unique gestural forms in our data, 85 of them only occurred once while an additional 47 occurred twice. That is, 73.3% of the observed gestural forms accounted for only 30.3% of gestural form-notion overlaps. In contrast, the 18 most common gestural forms, only 10% of all unique forms, accounted for 49.8% of overlaps. Analysis presented in **Appendix J** indicates that the gestural forms used in this environment follow a Zipfian distribution. Similar distributions have been observed in many languages such as English[131] and in various sign languages.[68]

DISCUSSION

From an embodied cognition perspective, our data (especially **Table 7** and **Table 9**) might suggest that our physical experience can both support and hinder student understanding of symmetry and group theory concepts. This is most plausible when considering the link between the “Horizontal” plane notion and flat-handed gestures with orientations parallel to the transverse plane (e.g., with the “H” orientation code) and “Vertical” plane notions with gestures that have flat hand orientations in the coronal or frontal planes (e.g., with the “I” orientation code).

That gestures with the “H” orientation code are often associated with the “Horizontal” notion is unsurprising, as we perceive the horizon as splitting the sky above from the earth below. Thus, a horizontally oriented gestural form, such as {F}Hmd or {F}Hfd in **Table 7**, would split a compound into top and bottom halves. Similarly, our own physical verticality involves the z-axis of the body, and planar gestures using the z-axis would thus be inherently vertical. Unfortunately, these rationalizations stemming from embodied experiences are problematic considering the proper mathematical definition of the horizontal and vertical mirror planes. Horizontal planes must be perpendicular to the principal axis of rotation. Thus, a hypothetical compound's horizontal mirror plane would not be aligned with the horizon if its principal axis was not coincident with the z-axis of the body (see **Figure 14**). This creates a contradiction, wherein a horizontally aligned gesture does not coincide with a mathematically defined horizontal mirror plane. This contradiction has been observed several times over multiple semesters wherein students insist that a given mirror plane is defined as horizontal or vertical based on their perspective, which becomes embodied as they gesture. Similarly, as vertical mirror planes must be coincident with the principal axis of rotation, nonconventional orientations such as the one seen in **Figure 14** would pose a similar issue. Thus, when gesture functions successfully as an analogy then productive understanding might be enhanced (e.g., hands as planes and fingers as axes) and when the analogy breaks, conception might be hampered (e.g., horizontal planes not aligning with the horizon/ transverse plane of the body).

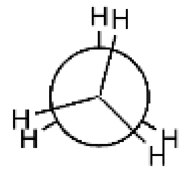


Figure 14 Newman projection of eclipsed ethane where the principal axis is coming out of the page. Thus, the horizontal mirror plane is the plane of the page and runs counter to embodied intuition that the horizontal mirror plane must be oriented with the horizon. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

CONCLUSIONS

Implications for Instruction

There is copious evidence that gesture is an efficacious communicative medium,[27,33] including in educational environments.[22-24,28,44,49,51,55,57] We suggest the reader actively consider how they use gesture when they communicate, whether that be as scholars at conferences or as instructors in classrooms. We have several suggestions for using gesture in symmetry and group theory instruction based on our data. While **Table 9** implies that planar hand shapes parallel to the transverse body plane typically convey the notion of a horizontal mirror plane (and planar hand shapes that are not parallel to that plane as implying vertical mirror planes), **Table 7** further indicates that certain gestures may have better communicative power based on the argument that they were used more often. For gestures implying vertical planes specifically, using a flat hand with palm facing medially and fingers pointing either forward or upward (that is, {F}Ifm and {F}Ium, respectively) may be best. Keeping one's hand flat with palm facing down and fingers facing medially (i.e., {F}Hmd) may be effective for communicating horizontal mirror planes, with a reasonable alternative changing the orientation of the fingers from medial to forward (i.e., {F}Hfd). Similarly, there is evidence in these tables that the index finger is uniquely useful for embodying axes, with **Table 7** indicating that having the finger pointing downward with the palm back toward the speaker may be particularly useful.

It is more difficult to suggest gestural forms to employ when discussing notions that were undersampled here such as the improper rotation and inversion notions. If the cause for the dearth of gesturing is the difficulty of these specific concepts, then learning may be supported by the deliberate incorporation of gestures during instruction followed by observation of how students employ or modify those gestures. In this way, the meaning of gestures becomes co-constructed to the benefit of both the instructor and students.[23] For improper rotations, we might suggest using the index finger of one hand to indicate the improper rotation axis while keeping the other hand flat and oriented perpendicular to the other hand's index finger to embody the perpendicular mirror plane as depicted in **Figure 15**.

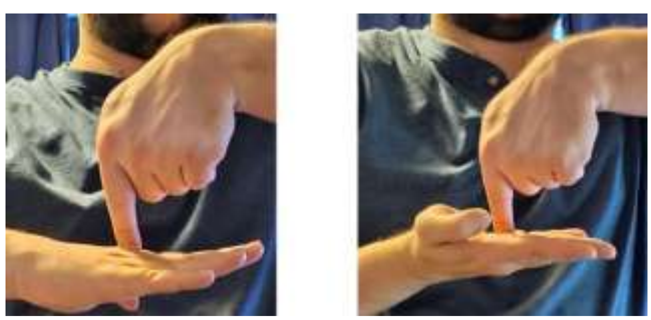


Figure 15 Proposed gestures for indicating improper rotations. On the left is {F}(2db)(Hmd) and on the right is {F}(2db)(Hmu). Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

That said, much in the same way that individuals have different speech patterns, we acknowledge that there are many plausible gestural variants that may be used to communicate any one of the notions in **Table 9**. We might offer the data presented in that table as a suggested starting point for the gestural forms instructors may wish to use in their own classrooms. For example, while we might specifically suggest {F}Hmd and {F}Hfd to communicate the "horizontal" plane notion, other plausible gestural variants might be used. As only the "H" hand shape code was consistently used by participants for this notion (excluding participants Fa1), palm-up variants could conceivably be used (e.g., {F}Hfu) as well as variants that include a motion that might emphasize the horizontal aspect of the gesture (e.g., {M}Tm(Hfd).

Regardless, this work and others[22-24] supports providing students with opportunities to explore chemistry concepts not only through words but also through bodily engagement. Though encouraging gesture was not an intentional design principle, activities like our previously published work[89] provide opportunities for students to engage with the material in this manner and we would encourage practitioners to watch for or encourage gestures in recitation periods, "dry" laboratory experiments, lectures, or anywhere else where discussion may occur.

Implications for Research

The data here show the degree to which gestural forms may vary, even in the limited context explored here. This breadth could be posed as a potential challenge for effective pedagogy. In the same way that we choose our words carefully with the intent of communicating specific notions, it is reasonable to expect that a degree of similarity in gestural form might enhance communicative efficacy. This raises the question as to how we might guide students toward the use of specific gestural forms for the productive conception of ideas (if that is feasible to begin with). While the gesture literature supports the idea that instructors use their own gestures in typical classroom environments, might we enhance the efficacy of those gestures through the investigation and development of specific principles regarding their use? Indeed, we are pursuing the purposeful development of gestures which convey the "improper rotation" and "inversion" notions considering our data show these notions as particularly undersampled. We recognize that the use of gesture in chemistry settings is of interest to the community based on various investigations that have appeared in the literature.[23,24,132] Investigating productive gestural mimicry may have been possible before the publication of this work, but we hope that our gesture coding scheme might catalyze that or other gesture-based investigations. We encourage the community to use, develop, and discuss our gesture coding scheme and welcome any collaboration or discussion that may arise. Fascinating work has been done in organic chemistry that demonstrated a signed lexicon can have an impact on summative assessments.[27] Our coding scheme can extend similar work at institutions where the resources to develop a sign language lexicon may not be available or where interesting spontaneous gestures have been observed. Relatedly, our work might be used as a framework by which concepts, such as molecular structure, are communicated across courses (VSEPR in general chemistry, absolute configuration in organic chemistry, symmetry and group theory in inorganic chemistry, etc.).

LIMITATIONS

We recognize that the claims and gestures discussed here may not be generalizable to other inorganic chemistry classrooms or classrooms of other subdisciplines of chemistry such as organic chemistry.[27] Gestures are enacted by individuals who are influenced by their culture and the local social context.[71,133] As such, we anticipate that there may be differences in gestural form across different boundaries, whether they be academic, cultural, geographic, and so on.

Though there is a literature basis in chemical education for the utility of gesture, we did not collect evidence that gesture affected student performance here. Indeed, there are demonstrable differences in gestural frequency and form between students as seen in our data, but at most we have data indicating a general perception that gesturing was useful to students. A quantitative study analyzing the relationship among student performance, gestural frequency, and gestural form might be of value and interest to the community, and we welcome collaboration in this endeavor.

Regarding the gesture coding scheme, the current iteration does have some shortcomings with respect to the immense detail it can capture. For example, we recognize that we cannot capture information on where a gesture is enacted. Assuming identical social circumstances, might a vertically aligned hand with fingers facing forward and palm facing medially (i.e., {F}Ifm) enacted in front of one's chest at the midsagittal plane express a different notion, however marginally different, compared to the same gesture enacted at the hip or in front of the face? Though our analysis did not suggest that detail as relevant, we cannot rule out the possibility. Furthermore, the orientations of the fingers and palm are currently limited to 6 descriptors, but what if the gesture was oriented between two perpendicular descriptors? For example, not forward (+x axis) or medial (−y axis) but in between them? We considered treating the gesture as existing at the origin and then describing its orientation as pointing toward an octant. This would have resulted in us adopting a scheme by which we would describe orientation with a positive or negative designation for each axis such that, as an example, a gesture with the description [+,−,+] would have an orientation in the positive x- and z-axes but negative y-axis. We elected to not further complicate the system at this time and welcome the community's feedback.

Finally, though the gesture coding scheme has been used for data across multiple semesters and instructors, it has only analyzed gestures for one specific topic in one specific course. For the gesture coding scheme to demonstrate its full power (or evolve to overcome other shortcomings not apparent in this specific context), we encourage others to consider the applicability and feasibility of this scheme when gesturing about topics in other courses.

CHAPTER IV. A GESTURE INTERVENTION IN THE INORGANIC CHEMISTRY CLASSROOM

Introduction

The work described here is a continuation of previous work on gestures in inorganic chemistry.[25] During the previous investigation, students indicated paying attention to the gestures their instructor used and indicated that some of their own gestural use may have stemmed from those observations. This was an exciting observation for several reasons, not the least of which was that students openly admitted to paying attention during lectures. Relevant to this work is the implication that instructor use of gestures can lead to student mimicry of those gestures, as was described by Vest and coworkers.[55] While gestural mimicry has been further described elsewhere,[,65] we nonetheless face an exciting question: In the same way that instructors can model appropriate use of scientific terminology and practices through the verbal and written modes (i.e., through lecture and written materials), might they also be able to model them through their gestures?

Gesture has been shown to benefit students engaging with chemistry content such as stereoisomerism,[24] and VSEPR,[23] and in science beyond chemistry such as in physics [44,49] and biology.[50] Our own students used gestures while reasoning and communicating about symmetry and group theory.[25] That our students were benefiting from gesturing is supported by student interview data gathered from Fall 2022 through Spring 2024 pursuant to this work and prior work.[25] One student from this work's data corpus who was assigned a pseudonym of Armina at one point bluntly stated that "Gestures are helpful, gestures are good."

Previously, we documented that certain gestural form components correlated with certain notions.[25] In other words, we had observed not only idiosyncratic gesticulations but also recurrent gestures.[52,73] These recurrent gestures were consistently observed for notions relating to mirror planes and rotation axes. Gestures, even idiosyncratic ones, were rarely observed for improper rotations and inversions. Given the pedagogical potential for gestures as an agrammatic, non-verbal or co-verbal communication mode, we held sustained curiosity regarding the place gesture could have in the classroom.

Owing to gesture's value in cognition[56,63] and communication,[52,71] we sought to investigate if we could encourage the use of specific gestures by students through their deliberate incorporation by instructors in lecture. There is a focus on gestures involving inversions and improper rotations as our prior work[25] revealed a comparative dearth of gesturing by students about these difficult operations.[12,89,108,119,124] Our hope was that we might enhance learning and engagement for these concepts by encouraging the students to make a connection between a physical representation (the gestural form) and the intended underlying concept (the notion).[25,67]

Research Question

This investigation pursued two goals. First, we were curious if the deliberate incorporation of specific gestures that were intended to convey notions related to the improper rotation or inversion operations would lead to students adopting these gestures; that is, could we encourage students to mimic our gestures? The hope was that the gestures students would adopt would catalyze learning and facilitate mastery of these operations. Other publications in the CER literature have remarked on the difficulty students have with improper rotations and inversions.[12,89,108,119,124] Our research plan accounted for two semesters of data collection, which included naturalistic video recordings of students using gestures during a symmetry activity,[89] one-on-one interviews, and small focus groups. Data collection occurred in the Fall 2023 and Spring 2024 semesters. The interviews and focus group conducted during the first semester would be used to inform us as to how we might adjust our approach in the second semester.

Second, we were curious if we could derive any principles regarding the use of gesture in pedagogically-relevant spaces, such as principles related to gestural mimicry as described above or the lexicalization of gestures over time. The meaning and form of gestures, like language, are subject to negotiation through continued social interaction.[134] For gesture, successful negotiation can lead to gestures becoming “entrenched”,[135] thereby moving them further along the conventionalization continuum towards full lexicalization.[52] There is literature describing the use of gesture in STEM classroom settings[23,29] and gestural mimicry,[55,65] but these investigations do not explicitly seek to develop design principles for the inclusion of gesture in educational environments. We wanted to pay attention to potential design principles in this work so that we might be able to more clearly articulate how educators and the CER community might utilize gesture beyond this specific environment. For example, we might be able to gain insight into how a new concept becomes linked to an external representation, i.e. gesture, when and why gesture might be preferentially chosen as a communicative form over other representations in specific contexts, and how a specific gestural form is selected (instead of another gestural variant) to embody a notion in a context. Because of our chosen methodology, we recognize that the strength of evidence supporting our proposed design principles might be found wanting. We instead used the substituted phrase “design suggestions” and actively encourage further inquiry to promote these evidence-based “suggestions” to more robustly supported “principles”.

With this context, we formally state our research questions as follows:

1. What, if any, gestures used by instructors to convey notions about improper rotations and inversions are students mimicking?

2. What design suggestions can we elucidate about the use of gesture in pedagogical spaces?

Data Contextualization and Collection

Environmental Context

This study was conducted at a large, federally designated Hispanic-serving urban research university in the Midwest United States. The participants were recruited from the institution's undergraduate inorganic chemistry course, with approximately 60-70 students enrolling per semester. The course has a lecture and laboratory component, with the lecture meeting thrice weekly for 50 minutes and the laboratory meeting once weekly for 3 hours.

Audio-video recordings were the primary form of collected data and were collected during the Fall 2023 and Spring 2024 semesters. All students were recorded during relevant laboratory sessions. Only recordings of students who consented to be part of the study were used; all others had their identities obfuscated through video editing and were not analyzed. Students who additionally consented to being interviewed were invited to participate in one-on-one interviews during the semester in which they were enrolled in the inorganic chemistry course. Finally, students who successfully completed the one-on-one interview were invited to participate in a group interview wherein I and four students total would discuss gestures and GT&S. These group interviews are herein referred to as "focus groups".

Though the course material between semesters is broadly similar, the Fall 2023 and Spring 2024 courses had some notable differences. These differences are summarized in **Figure**

16. The instructors of record and the lecture medium differed by semester. The Fall 2023 course had lectures conducted and recorded via Zoom while the Spring 2024 course had in-person lectures that were not recorded. I attended relevant lectures with the primary purpose of producing field observations to contextualize the environment in which students were learning GT&S. These observations are shared in the "Field Observations of Lectures" section below.

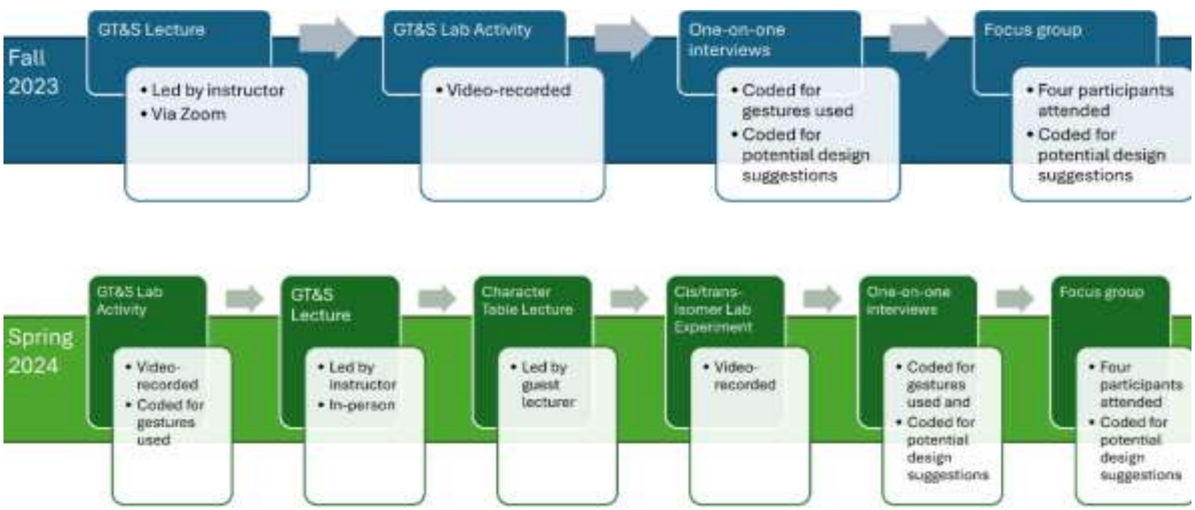


Figure 16: Data collection timeline with relevant lectures included.

The number of relevant lectures and laboratory experiments differed between semesters as well. In Fall 2023, only the GT&S laboratory activity was video-recorded. Details on this activity have been described in Chapter II and published in the *Journal of Chemical Education*.[89]

The Spring 2024 semester saw the implementation of a second relevant laboratory experiment that included a small concrete model manipulation component. Though the full details of this second experiment are beyond the scope of this investigation, the students did have to assign the point group of a cis- and trans-octahedral complex and determine the number of IR-active vibrational modes. As such, students had to utilize relevant GT&S knowledge. This second lab will be referred to herein as the “cis/trans-isomer lab”.

Consent Acquisition and Interview Protocols

Consent forms were distributed to students online through Qualtrics and with paper forms during recorded laboratory periods. Students were able to provide varying degrees of consent to the study. They could choose any combination of the following: providing access to completed laboratory reports; the use of video recordings where they are present; and to being contacted for a follow-up interview. Students were informed that the interview was compensated at a rate of $25/hour and that successful completion of the interview made them eligible for participation in the focus group. The focus group was compensated at the same rate of $25/hour.

Students who gave consent for their recordings to be used in this study were assigned pseudonyms to protect their identity. These pseudonyms were composed of a prefix indicating the semester in which the student was interviewed and a random alphanumeric identifier (e.g. F23z4 or Sp24c6). Students who also successfully attended a focus group were reassigned a more typical pseudonym to make analyzing focus groups transcripts easier. The reassigned pseudonyms were chosen after consulting with the students privately. Interview protocols for the one-on-one interview and focus groups are listed in **Appendix E**.

One-on-one interviews were conducted only after students completed the GT&S laboratory activity in their given semester. Focus groups met after all individual interviews were concluded and were comprised only of students from the same cohort. The focus group consisting of Fall 2023 interview participants met in January 2024 and the focus group consisting of Spring 2024 interview participants met in April 2024. Transcripts for the one-on-one interviews and focus group meetings were generated with Microsoft Word's transcription feature and adjusted manually as necessary. Each focus group had four participants. The pseudonyms of these participants are listed in **Table 10**.

Table 10 Focus group participants

Fall 2023 Focus Group Participants	Spring 2024 Focus Group Participants
Nina	Diara
Maryam	Banania
Aidan	Alison
Cave Johnson	Andrea Vega

Coding Gestures and Notions

To address our research question about gestural mimicry, we use our published Gestural Form Coding Scheme and the associated conception of gesture as metaphor.[25] In this view, gesture has a physical component (the gestural form) and an underlying concept that the gestural form represents (the notion). More details can be found in **Appendix G**. Furthermore, this work adopts the analytical framework developed in the previous investigation regarding the notions relevant to symmetry and group theory contexts. In that investigation, some notions covered a broad category of symmetry operator (proper rotation, inversion, etc.) or symmetry element in the case of the "axis (parent code)" notion, while other notions were more specific (horizontal plane, principal axis, etc.). From this list, only the "inversion" and "improper rotation (parent code)" notions were relevant to this study. However, we could not completely ignore all other notions if for no other reason than that improper rotations and inversions can be thought of *in terms* of those other notions. Indeed, improper rotations at this institution are taught as combinations of a rotation followed by a perpendicular mirror plane. To resolve this dilemma, all notions except for the "inversion" and "improper rotation (parent code)" notion were combined into an "Other" code. The notion code for improper rotations was also abbreviated to "improper rotation" though its definition did not change. This is summarized in **Table 11**.

Table 11 Notion coding framework adapted from Chapter III.

<table>
<tr><th>Notions from Chapter III</th><th>Notions for Present Investigation</th></tr>
<tr><td>Inversion</td><td>Inversion</td></tr>
<tr><td>Improper Rotation (Parent code)</td><td>Improper Rotation</td></tr>
<tr><td>Principal Axis</td><td rowspan="8">Other</td></tr>
<tr><td>Rotation</td></tr>
<tr><td>Dihedral</td></tr>
<tr><td>Horizontal</td></tr>
<tr><td>Vertical</td></tr>
<tr><td>Mirror plane (parent code)</td></tr>
<tr><td>Proper rotation (parent code)</td></tr>
<tr><td>Axis (parent code)</td></tr>
</table>

Only referential gestures were of interest in this study.[25,51] While instructors, TAs, and students were observed to use other kinds of gestures,[31] such as deictic and beat gestures, these were ignored in this study just as they were in Chapter III.

Field Observations of Lectures

As part of this study, the instructors were provided a document with pictures of gestures relevant to this study, as well as explanations of what notions these gestures were meant to convey. These documents are provided in **Appendix K**, with the gestures used in Fall 2023 presented in **Table 12** and the gestures used in Spring 2024 in **Table 13**. Thus, it was deemed prudent to attend the lectures to see how these gestures were utilized in the classroom environment and potential student responses to those gestures. Depictions in **Table 12** and **Table 13** are recreations by me and not photos of any instructor.

In Fall 2023, the instructor of record spent two days on the introductory GT&S lecture. Lectures during this semester were conducted over Zoom. Because of this, it was not possible to observe the number of students who mimicked gestures done by the instructor as many had their cameras turned off while others watched lectures asynchronously. Field observations confirmed that the instructor used the gestures in **Table 12**, as well as molecular models. The instructor encouraged students to gesture on their own. While another lecture about the use of GT&S in vibrational spectroscopy occurred some weeks later, this lecture was not observed.

The introductory GT&S lecture in Spring 2024 was spread across two days as well. A graduate teaching assistant led the lecture on the first day, while the instructor of record returned for the second day. Field observations confirmed that instructors used the gestures in **Table 13** when appropriate. Of the approximately 60 students in attendance, only five were observed to briefly gesture and only on the second day of instruction. Instances of gesturing appeared to mimic the instructor’s use of gesture when discussing mirror planes ({F}Ium and {F}Ifm) and axes ({F}2db).

The gestural forms depicted in **Table 12** and **Table 13**, as well as **Appendix K**, were chosen based on the results described in Chapter III, and more specifically **Table 9**. That is, the gestural forms suggested to be used by instructors were, in essence, forms used by students to convey notions relevant to GT&S. In some cases, such as using {F}2db to indicate an axis or {F}Ifm to indicate a vertical mirror plane, these gestural forms were observed as already being used by instructors. However, we did not previously observe the various inorganic chemistry instructors using consistent gestural forms to convey notions related to improper rotations or inversions. We had to choose to privilege gestural forms with certain origins, and thus *not* choose other gestural forms. That we chose gestural forms used by student participants reflects our judgement that those gestural forms reasonably mapped onto the target notions, and our hope that students might be inclined to mimic gestural forms previously used by other students.

Table 12 Gestures use by instructor in Fall 2023.

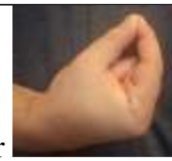
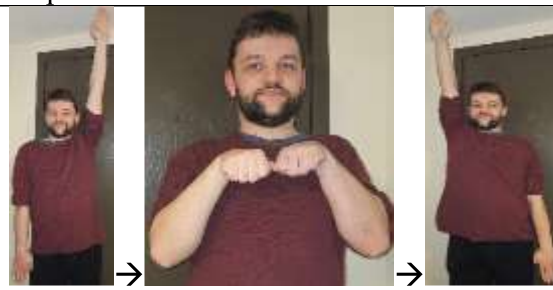
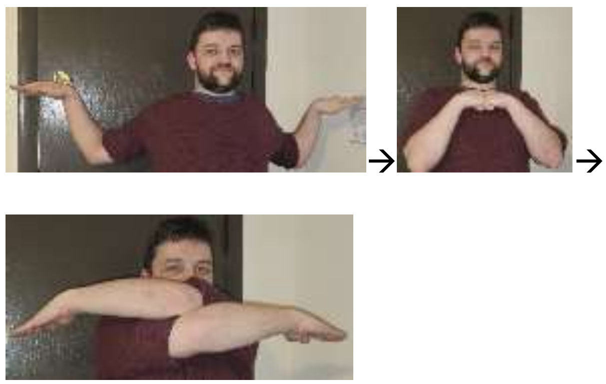
Notion	Gestural form code	Depiction
Point (in space)	{F}G2m1mm or {F} G2u1uu	 or 
Line/axis (of rotation)	{F}2mb or {F}2db	
Plane	{F}Imb or {F}Ium	 or 
Rotation (operation)	{M}R±x(Cmm) or {M}R±y(Cmm) or {M}R±z(Cmm)	 → 
Vertical plane	{F}Ifm	
Horizontal plane	{F}Hmd or {F}Hmu	 or 
Inversion (operation)	{M}Td(Pdd)Tu(Pdd)	 → 
Improper Rotation	{M}R-z(Cdd)(2db)>(Hmd)(2db)	 →  → 

Table 13 Gestures use by instructor in Spring 2024. Gestures repeated from Fall 2023 were removed from this table. These include gestures for the following notions: Point (in space); Line/axis (of rotation); Plane; Rotation (operation); Vertical plane; Horizontal plane.

Notion	Gestural form code	Depiction
Inversion (operation)	{M}Td(Iuf)Tu(Idb)> (Pmm)(Pmm)> Tu(Idb)Td(Iuf)	
	{M}Tm(Iaf)Tm(Iaf)> (Pmm)(Pmm)> Ta(Iab)Ta(Iab)	
	{M}Tb(Hfd)Tf(Hbu)> (Pmm)(Pmm) >Tb(Hbu)Tf(Hfd)	
Improper Rotation	{M}R+z(C2d3d1dd)> C2u3u1uu	

Another lecture involving relevant content occurred approximately three weeks later, again with an audience of approximately 60 students. This lecture, given by a guest lecturer, introduced character tables and established their relevance to the upcoming multi-week laboratory experiment. Field observations again confirmed the use of the gestures in **Table 12** and **Table 13** by the guest lecturer. We note that the lecture began with a prompt for "audience participation" at a future point; this may have primed students to more readily gesture in a space that has an implicitly established convention where such manual outbursts should not occur by the audience. When the guest lecturer then briefly reviewed different classes of symmetry operations, accompanied by their relevant gestures, the guest lecturer invoked the expectation of audience participation. The first gesture, a pointed finger embodying an axis, saw approximately 10 students gesture but a quick encouragement by the guest lecturer to join in saw approximately 30 additional students display the gesture. As the lecture continued, approximately 50 students mimicked a gesture used for a vertical mirror plane, though engagement fell off somewhat for the spatially-invasive inversion gestures and especially for the improper rotation gestures. The lesson continued to the generation and deconstruction of the reducible representation of a generic fac isomer for an octahedral complex. During this time, there were opportunities to gesture alongside the instructor but few students did.

The lecture conditions for the two semesters differed greatly in some respects, but these asymmetric conditions are both a necessary consequence of conducting education research in natural environments and potentially a boon to our research goals. While I cannot (and did not intend to) make any comparative claims about students and their gestures *between* semesters, the asymmetry allows us to probe if any of these differences may lend themselves to the goals behind the stated research questions. That is, students may be more likely to reveal that they found some aspect of their learning environment conducive to their education if they experience that particular aspect.

Data Analysis

Coding Student Gestures in Laboratory Settings for Potential Mimicry

To answer the first research question, which asks if students are repeating gestures that their instructors have done when talking about improper rotations and inversions, I analyzed the laboratory experiment recordings. I coded the observed gestures along two dimensions. First, I interpreted the notion associated with each of these gestures based on the surrounding context, including verbal utterances of consenting students and physical manipulations enacted by these students on nearby objects such as pens, notecards, or molecular models. Second, I determined whether the gestural form sufficiently matched gestures performed by their instructors, coding gestures that did match accordingly. This allowed me to speak not only about the kinds of symmetry elements and operations that students were gesturing (as relevant to the first research question), but also if those gestures *might* have been mimicked from their instructor. The gestural forms depicted in **Table 12** for Fall 2023 and **Table 13** for Spring 2024 are the basis by which I judged if a student gesture sufficiently matched those used by instructors. Instances where students physically interacted with the molecular models were also coded, as well as instances where students instead physically interacted with other objects such as pens or notecards. These codes are not included in this analysis.

There were instances where gestures produced by students appeared to match key gestural forms used by instructors but were *not* coded as a potentially mimicked gesture. For a student's gestural ensemble to not be coded as a potentially mimicked gesture, their gesture needed to satisfy one of two conditions. For one, gestures were not coded as potentially mimicked if the gesture greatly deviated from the instructor gesture along several gestural components, such as changing both the palm *and* finger orientation while keeping the hand shape code the same. Alternatively, they could incorporate additional gestural components such as an unexpected motion, or in the case of one-handed gestures, a second hand that is actively gesturing. Examples of both exception types are shown in **Figure 17**.

Figure 17 The gestural form on the left ({F}Idb) has the same Hand Shape code as an instructor gesture ({F}Ifm) but differ in palm and finger orientation. For the gestural form on the right, the right hand shows a similar deviation but additionally has involvement from the left hand that was not performed by the instructor.

I elected to exclude gestures produced in the focus group for several reasons. Of them, the most important is that by this point the students were exceedingly aware of the purpose of the study beyond a simple understanding of some relationship between GT&S and gestures. Gestures participants produced in the laboratory and interview settings might be more purely representative of their own knowledge and sociocultural background. However, by the end of the interview and going into the focus group, their perception of gesture and the forms they themselves embody may have been altered by their experience with me.

Extracting Design Suggestions from Interview and Focus Group Transcripts

The second research question was concerned with elucidating design suggestions for the incorporation of gesture into pedagogical spaces in higher education, such as lecture, the laboratory, or recitation sections. To address this question, I analyzed interview and focus group transcripts, engaging in open coding along three preliminary categories. These could be summarized as: ways in which gesture could be useful for students learning GT&S; ways in which gesture could be problematic for students learning GT&S; and ways in which these problems could be addressed. These categories were considered based on patterns observed during the transcription cleaning process. A fourth category was created later which addressed design suggestions while not directly addressing the ways in which gesture can be problematic.

Results

Students did not Appear to Mimic Improper Rotation or Inversion Gestures

To address our question about students potentially mimicking instructor gestures, we analyzed recordings of laboratory sessions. The Fall 2023 semester saw 28 students consent to being recorded across 4 laboratory sections. In total, there was 12 hours of laboratory footage across 7 videos. Of the 28 students who consented, 9 participated in a one-on-one interview. The Spring 2024 semester had only 18 students consent to the study, with 7 participating in the one-on-one interview. Because the Spring 2024 semester had two relevant laboratory sessions, two rounds of video data were collected. The first round of video data was collected during the

GT&S activity and resulted in 14 hours of footage across 3 laboratory sections and 4 videos. The second round of video data was collected during the cis/trans-isomer laboratory experiment and resulted in 11 hours of footage across 3 laboratory sections and 5 videos.

Pursuant to the gestural mimicry research question, the gesture codes from the Fall 2023 laboratory videos are presented in **Table 14**. The total number of gestures observed in each section are indicated in the row of that section. The row below each section titled “Mimicked gesture” is a subset of the total and indicates the number of gestures which had a gestural form used by an instructor during lecture. Gestures by Teaching Assistants were ignored. In total 244 gestures with notions relevant to **Table 11** were observed in this data set. Of those, 230 out of 244 (94.2%) gestures were associated with “Other” notions, such as mirror planes or axes. This means that only 14 gestures about improper rotations or inversions occurred in 12 hours of video recordings. In those 14 instances, not one student used a gesture associated with inversions from **Table 12** and only 2 times was the improper rotation gesture used. However, both uses of the gesture were done by the same individual, in close temporal proximity, and after extensive contact with me. This potentially renders these particular data points moot with respect to the present research question.

Table 14. Student gestures grouped by notion from Fall 2023 laboratory recordings.

Lab Section	All Gestures	Gestures with "Inversion" Notion	Gestures with "Improper Rotation" Notion	Gestures with "Other" Notion
Section 1	97	2	3	92
Mimicked gesture	55	0	0	55
Section 2	44	0	4	40
Mimicked gesture	23	0	2	21
Section 3	5	0	0	5
Mimicked gesture	0	0	0	0
Section 4	98	1	4	93
Mimicked gesture	62	0	0	62
Total	244	3	11	230
Mimicked gesture	140	0	2	138

Unfortunately, similar results were revealed from analyzing the Spring 2024 laboratory data sets. **Table 15** and **Table 16** follow the same form as **Table 14**, where **Table 15** is a tabulation of gestures observed during the Spring 2024 laboratory session involving the GT&S activity. **Table 16** instead describes gestures observed during the follow-up cis/trans-isomer laboratory experiment. While there were overall fewer gestures in the Spring 2024 semester, we cannot make comparisons *between* semesters for several reasons, including the various different lecture conditions and dearth of student demographic data. However, *within* semesters there are interestingly similar trends. For one, according to **Table 15** and **Table 16**, the overwhelming majority (90.8%) of gestures observed did not appear to convey notions of improper rotations or inversions, and instead conveyed other notions such as planes or axes. Furthermore, there was not a single instance of students using gestural forms for these notions that were similar to those used by instructors. While there were far fewer gestures observed during the cis/trans-isomer laboratory experiment, this was to be expected as this experiment was not strictly designed for this study and students spent most of their time synthesizing and characterizing the compounds.

Table 15 Student gestures grouped by notion from Spring 2024 laboratory recordings of the GT&S activity.

Lab Section	All Gestures	Gestures with “Inversion” Notion	Gestures with “Improper Rotation” Notion	Gestures with “Other” Notion
Section 1	17	2	0	15
Mimicked gesture	7	0	0	7
Section 2	35	0	2	33
Mimicked gesture	22	0	0	22
Section 3	33	1	3	29
Mimicked gesture	22	0	0	22
Section 4	2	0	0	2
Mimicked gesture	1	0	0	1
Total	87	3	5	79
Mimicked gesture	52	0	0	52

Table 16 Student gestures grouped by notion from Spring 2024 laboratory recordings of the cis/trans-isomer laboratory experiment.

Lab Section	All Gestures	Gestures with “Inversion” Notion	Gestures with “Improper Rotation” Notion	Gestures with “Other” Notion
Section 1	9	0	0	9
Mimicked gesture	4	0	0	4
Section 2	10	0	0	10
Mimicked gesture	9	0	0	9
Section 3	2	0	0	2
Mimicked gesture	2	0	0	2
Section 4	1	0	0	1
Mimicked gesture	1	0	0	1
Section 5	10	0	1	9
Mimicked gesture	8	0	0	8
Total	32	0	1	31
Mimicked gesture	24	0	0	24

In short, the data presented in **Table 14**, **Table 15**, and **Table 16** strongly suggests that students were not using gestures used by instructors when talking about improper rotations and inversions, thus answering the first research question. That said, over half of the gestures describing some "Other" notion in each of these tables did match a gestural form used by an instructor. We cannot conclusively say that every instance where the gestural forms used by students and instructors was an occurrence of gestural mimicry. After all, students who used these specific gestural forms may not have observed their instructor's gestures due to their own absence from or inattentiveness during lecture. And even if students did observe these gestures, they may have already associated similar notions with these gestural forms from prior experiences with these notions outside of a GT&S context. Regardless, it is entirely likely that *some* students did mimic *these* gestural forms and the relatively high frequency at which these gestural forms were used indicates their appropriate selection for use in this study.

We have seen previously that students appear resistant to gesturing about improper rotations and inversions,[25] and that improper rotations are difficult for students conceptually.[12,89,108,119,124] As such, while the relevant data in **Table 14, Table 15,** and **Table 16** is disappointing it is unsurprising. This lack of gestural mimicry from students highlights the importance of the second research question, which asks about design suggestions for the inclusion of gestures in educational spaces like the ones in this study. This question is addressed in the following sections.

Overview of Coding for Design Suggestions

The second research question was concerned with identifying design suggestions. To address this research question, interview and focus group transcripts were analyzed for themes related to the utility of gesture in learning environments. Four themes emerged throughout the audio transcription and coding process.

Participants often described things they liked about gesture, either about how it was used specifically in lecture or more broadly as a cognitive and communicative mode. The coding axis “Strengths of Gesture” includes all codes of this type. Conversely, participants also described ways in which gesture was lacking, with these codes being grouped in the “Shortcomings of Gesture” coding axis. When discussing a shortcoming of gesture, students would occasionally follow up with information on how they think that shortcoming could be addressed; these utterances were coded and grouped in the “Addressing Shortcomings of Gesture” axis. Finally, there were times when design suggestions would be directly discussed without a specific shortcoming in mind. These were coded and grouped into the “Gesture Design Suggestions” axis. **Table 17** lists each code, grouped within its coding axis, and the number of times that code occurred in the entire data set enclosed within parentheses. The following sections discuss each of these coding axes and specific codes in greater depth. For further information on the necessary criteria for each code and further examples, see **Appendix L**.

Table 17 Four coding axes relevant to the second research question.

Coding axis: Strengths of Gesture	**Coding axis: Shortcomings of Gesture**	**Coding axis: Addressing Shortcomings of Gesture**	**Coding axis: Gesture Design Suggestions**
Gestures can be interpreted in ways intended by the speaker (50)	Gestures can appear meaningless (21)	Tailor the size of a gesture to the size of the audience (6)	New gestures should have accompanying explanations (14)
Gestural variants can express similar notions (33)	Gestures are polysemous (29)	Closely approximate the intended notion and explain dissimilarities (8)	Gestures should closely map the intended notion (21)
Gesture can express nuance (20)	Gestures can be unpalatable (31)	Potentially confusing gestures should be explained (17)	Gestures should be comfortable for the speaker (6)
Gesture can help build understanding (40)	Mapping between gestural form and notion can seem weak (15)		To get students to gesture, instructors should encourage students to gesture (2)
Gestures are engaging (18)	Gestural forms are limited by the affordances of the human body (17)		
	Gesture is not always the optimal representation (14)		
	Small gestures cannot be seen at a distance (7)		

Participants Extolled the Strengths of Gesture

Participants often spoke about ways in which they found either specific gestures from lecture or gesture as a whole to be useful to them. The most common code and at the heart of many discussions was that *gestures can be interpreted in ways intended by the speaker*. This may seem obvious as our ability to interpret gesture is why it is a major component of human communication (e.g., showing a thumbs-up for approval, extended and separated middle and pointer fingers in the shape of a “V” to indicate peace, etc.). However, gestures in this context arguably are not lexicalized and so there is no guarantee that the viewer interprets the intended notion from a given gesture. That said, even with relatively new concepts like improper rotations, successful communication of intended notions is possible. For instance, during the first focus group, participant Nina was discussing the difficulty of properly embodying an improper rotation with a specific gesture. Participant Maryam affirmed that the gesture did not exactly match the movement of an improper rotation but also said, “If you did that as a hand gesture, I would know that that hand gesture is trying to tell me an improper rotation.”

Participants also indicated that *gestural variants can express similar notions*. In our one-on-one interview, participant Aidan expressed one example of this when discussing various planes that all shared a hypothetical principal axis. As they spoke, they produced several gestures which will be included in the following quotation within parentheses using the Gestural Form Coding Scheme syntax. They said, “σ_v would be parallel to [the principal axis]. Whether it's this way *({F}Imb)*, it's this way *({F}Ifm)*, it's this way *({F}Ifm)*, it doesn't matter *({F}Iba)*. So long as it falls within the axis.” Here, the direction in which the fingers and palm are facing is largely irrelevant. The key gestural form components are the planarity of the hand and that one of the axes which form the hand is coincident with the principle axis.

Though it was rarely explicitly stated, *gesture was also seen to express nuance*. When discussing gestures that might convey the inversion operation notion, Aidan championed a unique gesture with a gestural form code of: {F}(2db)(2ub)>(Pff)(Pbb)>(2uf)(2db), depicted in **Figure 18**. While the whole group nodded in approval of Aidan’s argued gestural form-notion mapping, Nina made a further connection; not only could the movement of the fingers express their exchange per the symmetry operation, but the initial and final orientation of the fingers could embody information about an irreducible representation. That is, this gesture would not only show a valid inversion operation because the fingers are exchanging places, but in the context of an irreducible representation it would also express a character of -1 because the individual fingers are changing "phase", e.g. the way in which they are pointing.

Figure 18 Gesture used by Aidan to convey the inversion operation notion.

Participants also consistently shared that gestures helped them learn, or that *gestures helped build their understanding of GT&S*. Diara, who was a participant in the Spring 2024 semester, demonstrated a strong understanding of GT&S in her one-on-one interview. When she was recounting her experience with the guest lecture that occurred later in the semester, she described the gestures she saw the instructor use as being only marginally useful to her at the time, but "… I feel like if it was done in the beginning of the semester, before we looked at any symmetry, [those gestures] would have been super duper helpful." She went on to say that the guest lecturer's gestures about inversion (see **Table 13**) did help her understand the characters of individual operations for an irreducible representation. Her expressed sentiment echoed that shared by Nina when discussing Aidan's inversion gesture described in the section above.

Finally, participants indicated that *gestures were an engaging part of lecture*. This sentiment was shared by several participants in the one-on-one interviews. Participant Andrea Vega said, “I specifically remember [the guest lecturer’s] gestures with the inversions. I think it was because he kind of made us all do them with him. So it helped internalize the gestures.” She later pointed to the gestures as being a reason the lecture “stood out” to her. During the second focus group, Andrea Vega and Alison both reaffirmed the engaging nature of gestures, especially when they were encouraged to actively mimic gestures during the lecture. This audience participation, to quote Andrea Vega again, “breaks up the monotony” that can accompany didactic forms of instruction.

Participants Discussed the Shortcomings of Gesture

While there was much discussion over the value gesture brings, there was also discussion about how gesture can fall short. One problematic code that appeared in the data was that *gestures can sometimes be meaningless to the one trying to interpret the gesture*. During my one-on-one interview with participant Cave Johnson, I produced a gesture with the form {F}G1u2uu. This gesture was used here and in lecture to convey the notion of an inversion center symmetry element. Despite its use in lecture, Cave Johnson said, “That one doesn’t really mean anything.”

On the other hand, gestures were sometimes found not to be meaningless but instead to have *too many* meanings. That is, *gestures were sometimes (unintentionally) polysemous*. I used this same gesture, {F}G1u2uu, to convey an inversion center symmetry element during my interview with Nina. Similar to Cave Johnson, she did not interpret the notion of an inversion center. Instead, she interpreted this gesture as, “A skewer. You’re about to turn.”, meaning that she thought I was about to rotate about an axis. When I pushed back, verbally expressing that I was going to keep the gesture static, she resolutely said, “No, you’re preparing to turn.”

But, harkening back to one of the strengths of gesture, sometimes a gesture can be interpreted by in ways intended by the speaker. Unfortunately, as was the case in the *"Gestures can be unpalatable"* code, that does not mean that the intended gestural form-notion overlap is received favorably. In other words, while the audience may understand the intended mapping between the gestural form and notion, they might find the mapping to be poor and/or prefer some other representation. In the case of the improper rotation gesture used in the Fall 2023 lectures, the gestural form {F}(Hmd)(2db) as seen in **Table 12** was often met with one of three reactions. Interview participants either interpreted the gesture as to mean a horizontal plane ("Gestures are polysemous") or to have no meaning at all ("Gestures can appear meaningless"). Other participants, including the three of the four members of the first focus group when they convened, did not approve of the gesture with respect to what it was intending to convey. Nina expressed that she "… hated this [gesture]" because of contrasts with her conception of the rotation portion of the improper rotation operation. Aidan, using softer phrasing, also spoke disapprovingly of the gesture. For Aidan, the gesture already had an established meaning based on her background in American Sign Language. The pointed finger in the gesture meant to her, "… a one-legged person", while the flat hand was the ground upon which that person stood.

Both focus groups discussed extensively *the limitations of the human body when attempting to accurately embody certain notions*. Andrea Vega, when discussing the inversion gesture in **Table 13**, admitted that, "… it's not a perfect gesture because obviously you can't actually invert your hands, but I think with a little bit of imagination it's effective enough to get the point across." Andrea implies the existence of a barrier to understanding the notion underpinning the gesture that stems from a physical limitation of the hands. While she overcomes this barrier here, there are other instances where bodily limitations are simply too great. During the first focus group, Nina and Cave Johnson are exploring a two-handed gesture that Cave Johnson proposes to possibly represent the improper rotation symmetry operation. After he performs the gesture, described in **Figure 19**, Nina remarks that Cave Johnson's second hand is, "… not the same as how it was before." After they gesture once more, both admit to a perceived inadequacy in the gesture, made apparent in Nina's modified recreation. Her gesture, seen in **Figure 20**, shows that most of the fingers will roughly align when the back of one hand rests in the palm of the other, but the thumbs will not. Nina expresses a lack of confidence that her classmates at large would accept the gesture because of the bodily limitation. In this instance, the limitation is that the left and right hands are not superimposable.

Figure 19 Cave Johnson intending to convey the "improper rotation" notion.

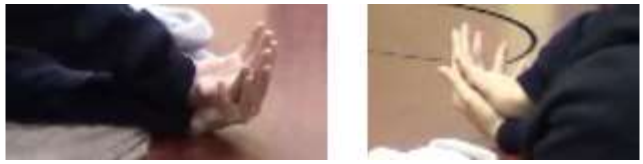


Figure 20 The end of the stroke of Nina's recreated improper rotation gesture, as seen from two different angles.

There were several instances where participants indicated that *gesture would not be an ideal representational mode*. During Nina's interview, when she was tasked with identifying the benzene's symmetry elements, she explicitly expressed that having to rely solely on gesture would have distressed her. That she solved this task in "less than a quarter of the time" because she was able to rely on a physical model strongly implies that the source of distress was because of gesture's ephemeral nature, and the compound's larger structure and symmetric complexity. In this circumstance, the provided concrete model was a better tool for her to use to solve this task if for no other reason than its quality of being a persistent representation.

Finally, though it was rarely discussed, participants did mention that *the size of a gesture can potentially be problematic*. At the start of the second focus group, I prompted participant Banania to recreate for the other participants a gesture she performed during our interview. This gesture, depicted in **Figure 21**, was meant to convey the inversion operation for square planar compounds. While participants Andrea Vega and Alison both expressed approval for the gesture, Alison cautioned that the difference in size between Banania's gesture and the gesture they had seen in lecture mattered. The guest lecturer's gestures made full use of the arms and so was more likely to be seen by people in the back of the lecture hall; Banania's gesture expressed a similar notion but was doing so with precise changes in finger orientation. While Alison was very supportive of Banania’s gesture, she though it would be more effective “… if you’re just teaching it in a small group.” Thus, while one gestural form might better convey a certain notion, the gesture may not convey that notion if it is too small to be seen. Thankfully, this potential shortcoming can be remedied. The codes in the next section correspond to suggestions to overcome shortcomings of gesture, and other suggestions related to gesture in learning spaces.

Figure 21 A recreation of Banania’s inversion gesture.

Remedying the Shortfalls of Gesture, and Design Suggestions about Gesture

There were instances in the data where suggestions to overcome problems with gesture were posed, as well as suggestions of good gestural practice more broadly. For instance, the issue of small gestures potentially not being seen in large lecture halls prompted a reasonable suggestion: *the size of a gesture should be tailored to the size of the intended audience*. This was at the heart of Allison’s conditional support for Banania’s gesture in the previous section; her small gesture would be more effective in a small group and less so in a large lecture hall.

The issue of bodily limitations to convey certain notions also had a suggested solution. When recounting Cave Johnson’s improper rotation gesture in **Figure 19**, Maryam pointedly questioned, "… It's not right entirely. But it relates the point, does it not? Are we trying to relay the point or are we trying to be correct?" Maryam more implicitly points to this dichotomy at another point during the focus group when providing conditional support for the {F}(2db)(Hmd) improper rotation gesture, depicted previously in **Table 12**. Recounting our one-on-one interview to the group, she at first interpreted this gesture as having no meaning but then accepted it as mapping on to an improper rotation after I, the gesturer, described how I intended it to be interpreted. Thus, *new gestures and gestures in which the gestural form-notion mapping might be unclear should be accompanied by an explanation to reinforce the intended mapping*.

While it may be good practice to verbally explain the underlying meaning of key gestures, convincing an audience of a specific gestural form-notion mapping may be easier if another suggestion is also followed: *Gestures should closely map the intended notion*. While discussing the inversion gesture in **Table 12** during the first focus group, Aidan supports this design suggestion when she says, "This only means inversion to me if there's something on the molecule, top and bottom to grab on to." She goes on to describe how the gesture would be meaningless in the context of a tetrahedral molecule like methane because no two atoms are diametrically opposed with molecules belonging to the T_d point group.

Finally, though it was mentioned only twice by a single participant in the span of one minute during the second focus group, Andrea Vega did provide one final design suggestion: *if we want students to gesture, we need to explicitly suggest that it is acceptable to do so*. This suggestion was mentioned during her one-on-one interview where she said she felt more comfortable gesturing during the guest lecturer's instruction because there was explicit approval from the lecturer for students to gesture. Though this design suggestion has weak evidence to support its inclusion in this analysis, its inclusion is further supported by literature.[136]

Discussion

The first research question asked what gestures, if any, were used by instructors to convey notions about improper rotations and inversions and were then used by the students. There was a risk with having the focus be specifically on improper rotations and inversions as there is evidence that these aspects of GT&S are difficult for students.[12,89,108,119,124] More specifically, prior work demonstrated that students gesture about these specific aspects less frequently than other notions.[25] It was unlikely we would collect much data in this vein and thus, while disappointing, it was unsurprising when we did not. However, the insights gained in pursuit of the second research question may address why students seem reluctant to gesture about inversions and improper rotations.

Looking at gesture as a communicative mode, work by Williams and Tang offers some insight.[137] Their review points out that modes like gesture change in the environments in which they are used. This is because these modes are being used by individuals and groups to make meaning, with the specific characteristics of the mode being constantly renegotiated. This may explain in part why we see a robust number of gestures that convey notions within our analytical scheme but do not resemble gestural forms used by instructors. It could be that students are trying out gestures they've seen their instructor or peers use and then modifying them to better resemble their own thought process or convey specific information. Students may then not be gesturing about improper rotations and inversions in part because they are unsure *how* to do so; they are unsure not only what to do with their hands but with the concepts themselves. Indeed, previous work has shown improper rotations and inversions being identified less frequently than other operations such as horizontal mirror planes and principal axes of rotation.[89]

Though the codes generated in pursuit of the second research question are all grounded in the data, some of them also have a basis in CER and gesture studies literature. That gestures may be polysemous, for example, has been widely discussed.[31,52,67] In a *Chemistry Education Research and Practice* publication, Abels emphasizes the difference between "local" gestures like those specific to this study and emblems.[138] Emblems are gestures which have been sufficiently lexicalized such that they enjoy a widespread understanding within a community, such as thumbs up to indicate approval.[52] For emblems, shared understanding can be safely assumed. As educators, we cannot make this same assumption for new or less lexicalized gestures, and so it may prudent to have novel gestures be accompanied by thorough explanation.[138] Admittedly, Kita and Emmorey note that how gesture is understood in the surrounding context is not fully understood. As such, while it may be wise to explain the meaning of novel gestures, there is room for research in how these explanations may best be conducted.[139] That said, gesture's value as a communicative mode rests on the premise that gestures *can* be understood by the audience. That we cannot always assume our gestures are understood has been emphasized by Abels, but there is evidence in the literature not only that gestures in specific STEM settings can be understood by students but that they can have a positive effect on performance.[140]

That the notion of a gesture was not properly interpreted by the audience arose often in the data, with distinctions made between the gesture appearing to be meaningless, being misinterpreted, or being correctly but unfavorably interpreted. In particular, that a gesture can be interpreted incorrectly or as meaningless has appeared elsewhere in scholarly work. Though her participants were elementary school children, Congdon's work suggested a potential link between content knowledge and interpreting the representational meaning of a gesture. Without sufficient content knowledge, participants in her study did not benefit as much from gesture training compared to other tools. Congdon suggests that this may be because these other tools are less ambiguous, thus requiring less interpretation and the allocation of fewer cognitive resources. Furthermore, the strain of interpretation might be further intensified when, "the similarity between a symbol and its referent is low or when the parallels between the two are ambiguous."[141] That is to say, a gesture may be received poorly if the gestural form-notion mapping is perceived as weak. Other work by Ovendale and coworkers has also shown not only that "… producing conceptually appropriate gestures may be important…" for supporting learning, but that producing incongruent gestures may lead to unproductive confusion.[142] We take the work of Congdon and of Ovendale and coworkers as literature support for the design suggestion promoting the use of gestures with strong gestural form-notion mapping.

And again, though the relevant code appeared only twice in this data set, there is literature support that having students themselves gesture may benefit them more than simply observing gesture.[136] Fostering environments where student gestures are encouraged thus may benefit students learning[55] and, based on the data here, their engagement while in the classroom. An environment more accepting of gesture may then facilitate gestural mimicry by students, though more research is needed.

Finally, one might frame some of these codes along conceptual, explanatory, and ergonomic axes to explain why gesture might occurs. First, gesture has a relation to inner cognitive workings, e.g. "Gesture can help build understanding". We might then speculate that gesturing about some notion is unlikely to occur *if one does not have some internal cognitive frame about that notion*. Second, gesture is but one option when considering communicative modes to share information. While this mode has several affordances ("Gestures are engaging", “Gesture can express nuance”), several participants indicated that “Gesture is not always the optimal representation” and instead might use physical models, drawings, visualizations, or simply rely on speech when attempting to explain a given notion. Third, even if gesture is chosen as a communicative mode, why is a specific gestural form selected over other potential gestural variants? We might reasonably speculate that a gestural form that is difficult or painful to enact may not be as privileged as other gestural forms. These two ergonomic considerations takes the form of the “Gestural forms are limited by the affordances of the human body” and “Gestures should be comfortable for the speaker” codes, respectively. Framing gesture along these conceptual, explanatory, and ergonomic axes might prove interesting in future investigations about when and how gestures appear.

Conclusion

Implications for Instruction

Gesture, like any pedagogical innovation, achieves its full potential when properly implemented. One of the purposes of this investigation was to probe what proper implementation might entail. While our design suggestions might be refined through further education research, they are nonetheless born from evidence and thus should affect some improvement in class performance and engagement. Specifically, we might offer educators a few suggestions. When using a gesture to communicate a specific idea, ensure that the gesture closely maps the target notion. For example, if describing an atom, a closed fist or a grasping hand might be favorably interpreted by undergraduate students. They might associate the hand’s roughly spherical shape with common depictions of s orbitals or with the balls used in molecular modeling kits, and so the mapping between gestural form and notion may seem plausible. That said, while we as educators and experts might find a particular mapping to be plausible, we cannot assume that our students will immediately understand and so new gestures should be explained, especially if they will be used repeatedly. Explanations may mitigate the likelihood that gestures perceived by students to either not have meaning, have a meaning other than the one intended, or be received poorly. Finally, like any communicative mode, gesture has its limitations and so we encourage the use of multiple modes during instruction.

Implications for Research

We have intentionally used the term “design suggestion” instead of “design principle” throughout this work. Indeed, while these design suggestions are born from evidence, each of these design suggestions might be the subject of future investigation so that they might be further specified and supported. For example, though the underlying notion of a gesture might be better understood by an audience if the gesture is explained, how might one undergo this explanation in the most efficacious way? Again, Kita and Emmorey have pointed out that how a gesture is understood in context before, during, and after the gestural event is not well understood.[139] Additionally, though gestures can be engaging and have a demonstrated cognitive and communicative function, how exactly can we leverage that during didactic teaching? That is, while it may be good for students to gesture, what kind of structure might be implemented into the design of a lecture to maximize the learning potential of gesture without unduly sacrificing the pace of instruction or the order and cohesion of the classroom?

Limitations

There are several limitations to this investigation. For one, that we did not have a stronger facsimile of a post-intervention assessment limits the degree to which we can truly address our first research question concerning the mimicry of improper rotation and inversion gestures. The Spring 2024 cis/trans-isomer lab was not designed for this purpose and the Fall 2023 semester had no proxy to the cis/trans-isomer lab whatsoever. Furthermore, with respect to the cis/trans-isomer lab, the cis isomer of an octahedral complex is C_{2v} and thus does not have *any* improper rotations (including inversion, S_2, and the horizontal mirror plane, S_1). While the trans isomer does belong to a point group with the inversion and S_4 operations, several factors interfered with capturing gestures of these operations. Some students elected to solve the reducible representation portion of the experiment *outside* of the recording environment, while others positioned themselves outside of the camera's field of view. Those few who were observed unimpeded seemed to make full use of the provided molecular model in order to generate the required reducible representations. Meanwhile, their use of gesture was generally sparse.

The fact that we did not have IRB approval to record and analyze lectures is another limitation of this study. Having this data would have allowed us to more deeply probe the social contexts surrounding student gestures, or lack thereof. We did not pursue this avenue of data as most of the class did not consent to the study and we did not want to violate their confidentiality. It may have also been valuable to record students taking exams which used GT&S concepts. Participant Nina mentioned that she gestured during one of the inorganic chemistry course's exams, which then helped her solve a problem. Other investigations have seen performance gains for students who gesture during assessments and so it may be prudent to pursue this context further.[22] Finally, it should be noted that the guest lecturer in the Spring 2024 semester was involved in this research work.

CHAPTER V. GENERAL DISCUSSION

In this dissertation, I holistically explored the topic of GT&S in the inorganic chemistry classroom. First, I developed a model-based GT&S laboratory activity based on literature-supported design principles. This activity revealed an interesting phenomenon in spontaneous student gestures. A gestural form coding scheme, inspired by Calbris,[67] was developed to systematically describe and analyze these gestures, revealing trends in association between certain gestural forms and notions, and also a relative absence of gestures conveying notions related to improper rotations and inversions. This led to an attempt to modify instruction to support student learning by promoting the use of specific gestural forms and uncover design principles related to the use of gestures in instructional settings.

Summary of Findings

Words are not our Only Communicative Form in Educational Settings

First and foremost, I have reinvented the wheel. Words, both spoken and written, are not the only form by which we as educators communicate with our students, and neither are they the only mode used by our students with their peers. Just as there is rich detail we can capture with precise word choice,[21] so too can this be done with our hands.[23] Whether this is done in a proper signed lexicon with linguistic character[52] as has been done in organic chemistry[27] or with gestures that are less lexicalized,[25] the manual mode is nonetheless important in cognition and communication. As educators, we must be aware when and how gesture occurs in pedagogical spaces because instructors and students alike are capable of both providing and receiving valuable information through gesture. Indeed, this reciprocal characteristic of gesture is evident throughout the data corpus used in this dissertation.[25] And as scholars, we must investigate the affordances and limits of this communicative mode so that it might be better utilized.[20]

The Utility Provided by the Gestural Form Coding Scheme

For systematic comparison of any phenomenon to occur, a system by which to describe and separate must first exist. The Gestural Form Coding Scheme first described in Chapter III and utilized further in Chapter IV is an attempt to do exactly that for gestural forms. While the gesture studies community has long existed without such a scheme, a call for a systematic scheme to enable systematic comparison has not gone unvoiced.[71] And while there is some interest in gesture from the CER community, it is certainly not a topic prioritized by the community.[23,24,29,30,102] One can only speculate as to why but, given the numerous ways that gesture might be broadly categorized,[31,52,54] it seems entirely possible that some scholars in our community might be dissuaded based on dissimilarities in frameworks used by the two communities. It is my hope that the Gestural Form Coding Scheme, for whatever shortcomings it may have, may embolden others in our community to tackle gesture as a topic of scholarship.

Simply Gesturing is not Enough

Though gesture has considerable literature support for its use as a cognitive and communicative tool,[22,51,55,56,65] and gesture has been reported to occur within the classroom,[23,25,37] there is much to be learned about how best to incorporate gesture effectively as a *pedagogical* tool; simply gesturing is not enough. The work discussed in Chapter IV demonstrates this well enough as students in that investigation did not adopt instructor gestures simply *because* instructors gestured. The choice to gesture for pedagogical purposes, like any deliberate move made to enhance student learning, can surely be made more efficacious by following certain principles. My work revealed some strengths and shortcomings of gesture, as well as suggestions for how these shortcomings might be overcome and how gesture might overwise be implemented in educationally-relevant spaces. Educators might use these suggestions to more thoughtfully consider how their own actions in the classroom might be affecting the learning and engagement of their students. These suggestions, however, would do well to be supported by further, more rigorous scholarly work.

Limitations of this Research

While I have done my best to produce robust research with reasonable theoretical foundations, there are several limitations that must be addressed. Some are methodological in nature, stemming from the highly exploratory and arguably pioneering nature of this work. Others instead are epistemological in nature.

Gestures are Influenced by Myriad Factors

The discussion regarding the extent to which gestural form is influenced by sociocultural factors has been going on for centuries[71] and certainly persists to the present day.[137] That these factors are important to the gesture studies community is quite evident considering the number of studies that bring to the fore ethnic or national identity,[64,66,67,87] cultural references,[49] social status,[64] and even able-bodiedness.[45] There have even been remarkable accounts of gestural form-notion overlaps where supposedly similar gestural forms had precisely *opposite* associated notions in nearby geographical areas.[143]

And yet this work did not at any point systematically collect information on students demographics such as age, socioeconomic status, ethnicity, or other potential sociocultural influences. That the work described in Chapters III and IV did not is lamentable; I hope this might be excused by the focus placed on developing the Gestural Form Coding Scheme and design suggestions for the pedagogical use of gesture, respectively. Future work should attend to this dimension of data, especially insofar as trends with certain gestural variants might reveal relationships to specific communities. In his discussion of the centuries-long debate between the universality of gesture versus the influence of local sociocultural factors, Cooperrider defines several useful terms related to the form, function, and classification of gesture. Of particular relevance is his framing of *presence* and *privilege*.[71]

Cooperrider describes a gesture as privileged "… if it is more culturally prominent or important." He uses criteria of frequency of use (preference), communally perceived strength of association (prototypicality), and the extent to which the gesture is used earlier by children than other gestures of similar function (primacy).[71] Each of these criteria are mentioned by participants in the interview data corpus, indicating the potential value of exploring this frame further in this context. Future use of this framework could benefit not only the CER or broader education community, but also the gesture studies community. Cooperrider repeatedly calls for further development of the frames by which scholars observe, characterize, and compare gestures. It seems that much work done by the gesture studies field concerns gesture as it occurs in more "natural", less professional contexts.[66,67,71,87,143] And this is reasonable considering that most people spend a considerable amount of time socializing in less formal situations as opposed to, say, in an inorganic chemistry classroom or laboratory. However, the diversity of gestural forms observed in this work which was elicited *because* of this specific choice of environment prompts an argument that how one defines a community, as used by Cooperrider, might benefit from revision. Perhaps framing this dissertation's data collection environment as a community of practice[144] might make the argument more convincing, especially if one were to consider gesture as both a form of specialized communication between its members and a skill by which the content relevant to the community might be made more easily or alternatively understood.

The Implicit Supposition that Gestures were "Helpful" or "Good"

If I am to repeatedly make comparisons between spoken language and gesture, for example as them both being communicative mediums of importance to education, it is only reasonable for me to accept the plausibility that gesture may have some of the same pitfalls as spoken language. For one, students sometimes struggle to appropriately use highly technical chemistry terminology[22] and inappropriate use of technical terms is not conducive to learning. Might I be unaware of a similar phenomenon occurring in my data corpus, where students are gesturing in a way that is detrimental to learning? Instead, there is the overarching supposition in this dissertation that gesture in and of itself is to be lauded. Or to quote participant Maryam from Chapter IV, "Gestures are helpful, gestures are good."

There is a considerable research backing for gesture to be helpful in learning and communication,[22-25,29,37,40,49,51,60] but the study in Chapter III did not specifically investigate this fundamental assertation with any quantitative backing. This may be less of a concern for molecules with typical orientations (e.g. molecular representations where principal axis commonly aligns with the z-axis like with water or PCl_5) as GT&S constructs such as the horizontal mirror plane may align with embodied preconceptions. This may instead be a larger issue for other molecules that may reasonably presented in non-standard orientations, such as ethane with the principal axis of rotation oriented along the x axis.

The Mysterious Absence of Body-Centered Gestures

The work of Geneviève Calbris has been referenced repeatedly in this dissertation, particularly as it relates to the Gestural Form Coding Scheme. Indeed, the decision to differentiate gestures based on if they do or do not have a motion component mirrors her own scheme. And yet, she describes a third category of gesture; the body-centered gesture, where a critical component of the gestures is that it is located on or at a specific part of the body.[67]

Take, for example, typical gestures and associated phrases indicating mental unwellness. In the fourth chapter of her book, Calbris cites specific gestures from French society that communicate madness, like the right hand's extended index finger ({F}2mm) or a loosely cupped hand rotating ({M}R+z(Cmm)), both pointed at the right temple.[67] One could also consider the right hand's pointed index finger rotating clockwise ({M}R+y(2mb)) aimed at the right temple, perhaps accompanied by a phrase insensitively indicating the subject of the gesture as being "coo-coo" or "loco". While the Gestural Form Coding Scheme can describe the motion of the hand during this gesture, its interpretation would be dramatically altered if instead the hand was aimed at another body part, such as the chest or other arm. That the gesture is specifically oriented at the head is a critical gestural component but cannot be described by the scheme in its current form. Across six semesters and dozens of hours of footage in laboratory, one-on-one interview and focus group settings, I have not characterized a single body-centered gesture. Why? Where are these gestures? Is this absence due to a bias in my description of gestures, somehow a consequence of the extremely narrow domain-specific data pool from which I've sampled, or is it something else entirely? I hope I have convinced the reader in the previous chapters that I have expressed sufficient caution such that my description of the observed gestural forms is adequate and beyond severe reproach. Instead, I do expect body-centered gestures to appear in the chemistry domain and that this particular context and the concept of GT&S does not lend itself well to these sorts of gestures. After all, most of the notion codes correspond either to a symmetry element (“Mirror plane”, “Axis”) or symmetry operation (“Rotation”, “Inversion”) and neither of these concepts are strictly related to specific parts of one’s body beyond the hands.

I would hypothesize that body-centered gestures may appear in contexts where the anthropomorphizing of chemical phenomena is more commonplace.[145-148] Anthropomorphizing can serve as a metaphor where the relevant human characteristics are the source domain and the unfamiliar chemical phenomenon is the target domain. Body-centered gestures may then reinforce this metaphorical connection in a deeper way than the gestures observed in Chapters III and IV by virtue of a more complex cross-domain mapping.

Future Directions

Though this dissertation contributes to the purposeful integration of gesture into the chemistry classroom and promotion of gesture as a valuable topic for scholarly investigation in chemistry education, there are many areas of exploration that may further reveal rich insights for scholars and practitioners.

Gestures as they Appear Elsewhere in the Inorganic Chemistry Curriculum

For one, the studies described in this dissertation focus specifically on GT&S in UIC’s undergraduate inorganic chemistry curriculum but the curriculum covers many other topics. While the work in Chapter IV does extend slightly further insofar as students were observed in a context where GT&S was used to extract information about the different vibrational modes of cis- and trans-octahedral systems, this only represents a fraction of the full course curriculum. Following the use of gesture in a course, particularly by both the instructor and students (and perhaps even TAs) could reveal a wealth of information. What other topics in chemistry strongly elicit gesture? What forms do those gestures take? Are there certain gestural forms that persist across time and different topics, and do they convey different notions based on context, i.e. are there polysemous gestures?[40] Furthermore, by observing the frequency and form of gestures from the beginning of the semester to the end, we may observe how gesture is "organically" used and evolves over time; this may uncover design principles for the deliberate use of gesture in instructional environments or reveal evidence of lexicalization in line with Kendon's view of gesture and the gesture-sign continuum.[52]

Gestures as they Appear Throughout all Chemistry Courses

Though chemistry-specific gesture-related research has appeared in the *Journal of Chemical Education*,[23] *Chemistry Education Research and Practice*[24,29] and elsewhere,[22,28,30,102] most of this work looks at a single course. Indeed, the work described in this entire dissertation is similarly confined. But what gestures are students utilizing to understand the various techniques in analytical chemistry? And what of the students in the common physical chemistry course sequence of Thermodynamics and Quantum Mechanics? While pointing to a gap in the literature is a poor justification for further work by itself, there is significant value in longitudinal scholarship. Furthermore, there are plenty of examples in my data corpus where students indicate that the gestures they used when conceptually handling GT&S stemmed from experiences elsewhere. To list a small few from one-on-one interviews from Chapters III and IV: F22y30 referred to his experience with planes in his undergraduate math courses; S23b1 fondly recalled interactions with her high school calculus teacher that influenced her pointing and orientation of Cartesian axes; and F23z4 repeatedly pointed to her knowledge of American Sign Language when dismissing my proposed gesture for improper rotations as it resembled “a one-legged person”. The claim that gestures have a lasting influence on cognition is supported not only by these observations but also by the literature.[51,56] That students also pointed to their instructor as a source for these gestures I argue provides sufficient justification for longitudinally investigating gesture as it appears across the broader chemistry curriculum. It may be particularly interesting to see how gesture is used as students explore specific topics in greater depth. For example, though VSEPR as covered in general chemistry does not utilize many of the terms in GT&S for inorganic chemistry, both topics are fundamentally concerned with analyzing and characterizing molecular geometry using an underlying mathematical frame. Might there be gestures which appear in both contexts, and could they be leveraged in some way to catalyze conceptual understanding? If we hope that students might build upon their chemistry knowledge and grow more sophisticated with their technical language as they progress through their degree might we then also expect to see growth in their use of gesture?

Developing Design Principles for Gesture Incorporation in Assessments and Instruction

I recognize a key interest of the CER community is practical application. Elgrishi and coworkers’ guide to cyclic voltammetry had on the community, as evidenced by view count and citations, is but one excellent example.[149] I will point specifically to Cooperative Learning, even though it is not a framework developed exclusively by and for chemists, because its positive effect on learning outcomes and articulated {design principles} make the framework exemplary and easily available for adoption or modification by practitioners. An instructor can easily develop an activity and feel confident that they are appropriately invoking the framework so long as they incorporate the 5 basic elements of Cooperative Learning.[91]

Gesture has been repeatedly demonstrated to have a positive effect on learning,[22,23,28,29] and there is some work to establish design principles for how gesture might be incorporated in instructional spaces as discussed in Chapter IV. There is some work in the embodied cognition literature addressing the issue of sparse frameworks and design principles that might be used by practitioners. Danish et al.'s reveal of the Learning in Embodied Activity Framework, or LEAF,[35] includes a detailed description of their framework, how it functions as an extension of the more established Cultural Historical Activity Theory, and design guidelines "To further illustrate the concrete value of LEAF in supporting the design and analysis of embodied learning environments…".[35] Unfortunately, their design principles focus more on the relation of the individual's actions to collective action and the relationship between collective action, collective phenomena, and specific aspects of their framework. Their focus on technology and the interaction of technology and their students is reflected in their reminder to themselves, and their audience, that they are more than "technology designers". Those who might champion gesture's place in instructional spaces need to follow the example of scholars like Danish and his colleagues, engaging in similarly iterative work beyond the scope of a single semester or academic year, or the example of Wakefield and colleagues with their clever study design to address what specific factors of gesture or action promote learning.[150]

Open questions remain about *how* gesture can be incorporated into instructional spaces. How can they be leveraged in learning activities, formative assessments, or even summative assessments? What makes a gesture "effective" in a given context? How can students be encouraged to pay attention to the gestures of others, and to use gestures themselves? Furthermore, there has been sporadic interest in oral exams and group exams in the CER community.[151] As these assessment types inherently leverage a discursive component, advocates for summative assessment types might find themselves simultaneously interested in paying closer attention to gesture and at a loss for how to process gesture in this context. This only exacerbates the need for developing frameworks around gesture, though perhaps frameworks might also be developed *from* these social, pedagogically critical contexts.

Further Developing the Gestural Form Coding Scheme

While the development of frameworks for how gesture can be effectively incorporated in learning spaces requires attention, so too does how we *describe* gesture. While the Gestural Form Coding Scheme can describe a large quantity of gestures, it certainly cannot capture the full breadth of conformational and spatial information that might be conveyed manually. This has already been partially discussed twice before, though there are even more challenges to resolve.

First, Chapter III broached the issue of gestures occurring between the bodily axes. While the Gestural Form Coding Scheme can easily describe the index finger pointing either along the x-axis (e.g., {F}2fm) or z-axis (e.g., {F}2um), there presently is not a concise way to describe the finger pointing both outward *and* upward. Either a larger or different data set may facilitate the development of this syntax, though the suggestions of utilizing either a plus-minus-dash system to describe the x, y, and z orientations or combining extent codes within another abstracted layer (e.g., {F}2[fu]m) are potential leads.

Additionally, while seemingly absent in this data corpus, if body-centered gestures were observed, their inclusion into this scheme would necessarily require the development of new syntax. The obvious identifier would be {B} for **B**ody-centered gesture but developing the syntax further without real data may be disingenuous. Taking that risk, it may be fruitful to adapt the following:

$$\{B\} < F > De(Abc)$$

Where {B} indicates this as a body-centered code, “F” indicates the part of the body at which the gesture is pointed, and the remaining letters follow the previously established syntax. Inspiration for codes for specific parts of the body might be drawn from Calbris’ work. [67]

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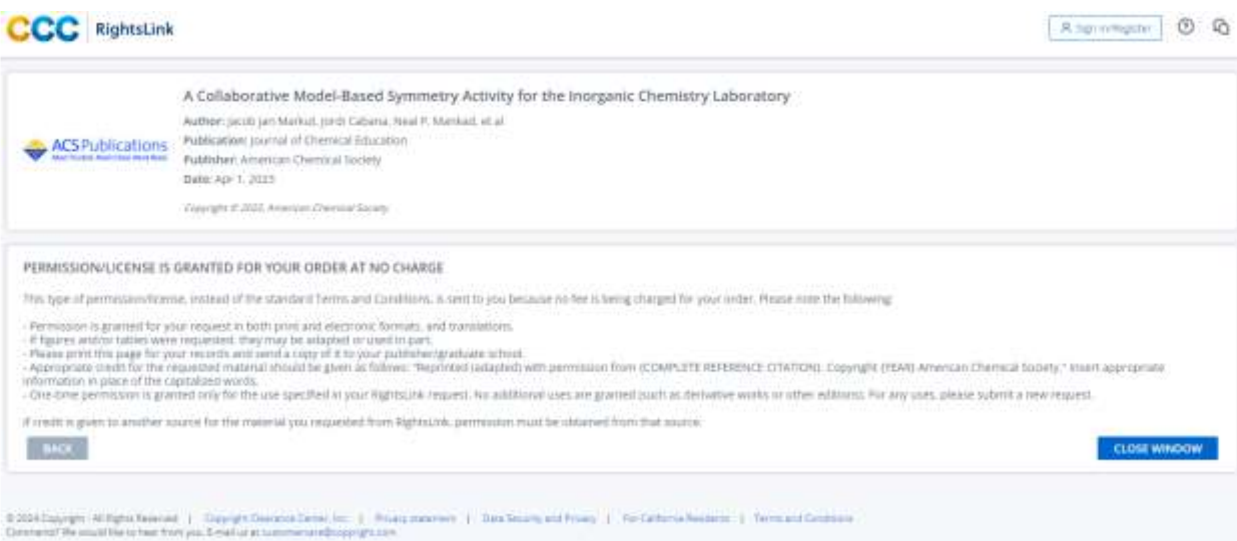

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A Collaborative Model-Based Symmetry Activity for the Inorganic Chemistry Laboratory

Author: Jacob Jan Markut, Jordi Cabana, Neal P. Mankad, et al

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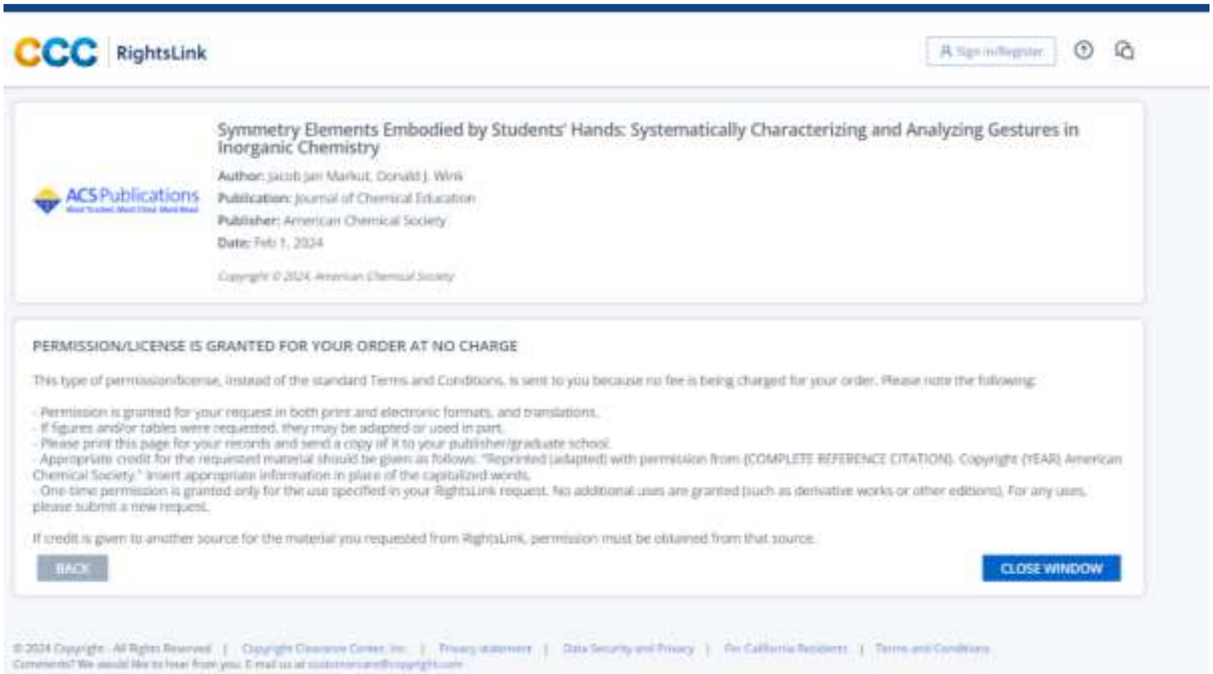
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Symmetry Elements Embodied by Students' Hands: Systematically Characterizing and Analyzing Gestures in Inorganic Chemistry

Author: Jacob Jan Markut, Donald J. Wink
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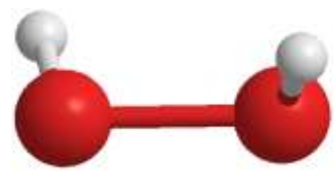
APPENDIX B. GROUP THEORY AND SYMMETRY ACTIVITY

The following appendix is the original iteration of the activity utilized in Fall 2021, followed by the corresponding TA notes and key. Line breaks provided to students as space to answer questions and for aesthetic clarity have been removed.

Original Symmetry Activity

From a young age we recognize some objects look the same as we turn them, or that they look like they can be split into two identical halves; that is, some objects have symmetry.

Both macroscopic and microscopic objects can have planar and/or axial symmetry. As seen below, objects like mugs or boomerangs, and even entire buildings, can exhibit some type

			
A ceramic mug Vertical mirror plane(σ_v)	UIC's University Hall Vertical mirror plane(σ_v)	Boomerang Axial symmetry (C_2)	Hydrogen Peroxide Axial symmetry (C_2)

of symmetry. As an example, the façade of University Hall at UIC has a vertical mirror plane; that is, the left half looks like a mirror image of the right half. Molecules such as hydrogen peroxide, water, and countless others also exhibit these same features of symmetry.

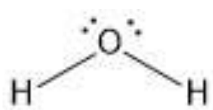
The concept of symmetry is rigorously explored in mathematics, especially in the branch of mathematics called group theory; both symmetry and group theory are significant chemistry.

There are two notations used to describe symmetry elements. Crystallographers often use Hermann-Mauguin notation, but this course will utilize the Schönflies notation. There are five types of symmetry elements described in this notation: proper rotations (C_n), mirror planes (σ), inversions (i), improper rotations (S_n), and the identity operation (E). For an overview of these operations, refer to pages 60-66 from Housecroft and Sharpe's *Inorganic Chemistry, 4th Ed*. You may find Figures 3.2 (pg. 61), 3.3 (pg. 62), and 3.5 (pg. 64) to be particularly useful.

For this activity, you will be asked to visualize and draw representations of molecules important to the discipline of inorganic chemistry and to identify the symmetry elements they contain. The symmetry tutorial on the SymOtter website may be a useful tool for you as you work through this activity (www.symotter.org/tutorial/intro).

The first problem has been done for you to serve as an example.

Compound 1: Water (H_2O)



Atoms required	Bonds required
- 2x white Hydrogens (1 hole)	- 2x short bonds
- 1x red Oxygen (2 holes)	

1) Based on the above representation, discuss with your team what symmetry elements the compound appears to have. What operations can you see that would have the compound look the same before and after the operation?

The left and right sides of water are identical, so there's a mirror plane that bisects the oxygen atom and would have the hydrogen atoms swap places; we'll call this the $\sigma_{v\ (xz)}$ **mirror plane. Also, every compound has at least E symmetry. The two operations identified so far are: E and** $\sigma_{v\ (xz)}$

2a) Construct the compound using the model kit. Take two pictures of the model you've assembled.

2b) Using your constructed model, see if there are any symmetry elements present in the compound that your team didn't see in question #1. If you did find any new operations, try to describe where they are and how they relate to the representation above.

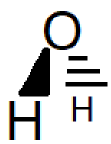
There exists a different mirror plane than the first one. Instead of the plane just bisecting the oxygen, this other plane bisects all three atoms. So instead of having a left and right half of the molecule, it splits the molecule into "front" and "back" halves. This should be called the $\sigma_{v\ (yz)}$ mirror plane because this new plane still uses the z axis ("up" and "down" from the picture given) but doesn't use the x axis ("left" and "right" from the picture given); instead, it uses the y axis ("in" and "out").

3a) See if your team can come up with ways to draw the compound that better shows some of the symmetry elements you may have identified in question #2 or any other symmetry element you find particularly difficult to see.

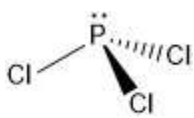
So this is a different view of the molecule, as if we were looking right down the z axis. If we draw a line straight through the O-H bonds, we can see the two identical halves as described above.

3b) Check in with your TA to make sure you haven't missed any operations. If there are any you missed, try to draw and describe them here. If necessary, you can always come back to this step later.

Of course, water can be rotated 180° and still look like water! Our TA had us look at water from the side and then rotated it and yeah, water has a C_2 axis. The drawing from that side view, which is almost from the view of the y-axis, is below. Water has in total 4 unique operations: E, C_2, $\sigma_{v\,(xz)}$, $\sigma_{v\,(yz)}$



Compound 2: Phosphorus Trichloride (PCl_3)



Atoms required	Bonds required
- 1x purple Phosphorus (4 holes)	- 3 short bonds
- 3x green Halogens	

1) Based on the above representation, discuss with your team what symmetry elements the compound appears to have. What operations can you see that would have the compound look the same before and after the operation?

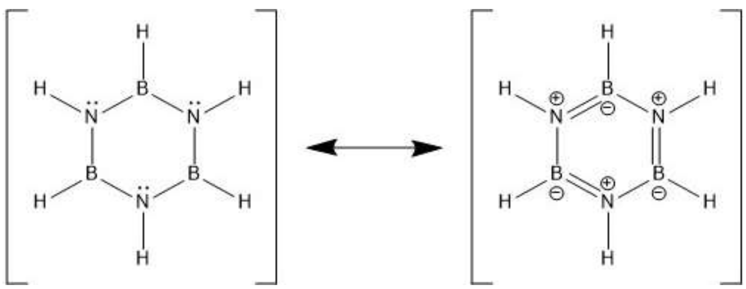
2a) Construct the compound using the model kit. Take two pictures of the model you've assembled; one of the pictures should show the principal axis of rotation.

2b) Using your constructed model, see if there are any symmetry elements present in the compound that your team didn't see in question #1. If you did find any new operations, try to describe where they are and how they relate to the representation above.

3a) See if your team can come up with ways to draw the compound that better shows some of the symmetry elements you may have identified in question #2 or any other symmetry element you find particularly difficult to see.

3b) Check in with your TA to make sure you haven't missed any operations. If there are any you missed, try to draw and describe them here. If necessary, you can always come back to this step later.

Compound 3: Borazine ($B_3N_3H_6$) (planar)



Atoms required	Bonds required
- 3x blue Nitrogens (4 holes)	- 6 long bonds
- 3x silver Metals (4 holes)	- 9 short bonds
- 6x white Hydrogens (1 hole)	

Model construction notes: Your constructed model should resemble the zwitterionic representation

(i.e. each N atom should have a single bond to one B atom and a double bond to the other B atom).

1) Based on the above representation, discuss with your team what symmetry elements the compound appears to have. What operations can you see that would have the compound look the same before and after the operation?

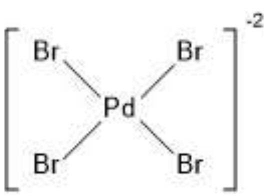
2a) Construct the compound using the model kit. Take two pictures of the model you've assembled; one of the pictures should show the principal axis of rotation.

2b) Using your constructed model, see if there are any symmetry elements present in the compound that your team didn't see in question #1. If you did find any new operations, try to describe where they are and how they relate to the representation above.

3a) See if your team can come up with ways to draw the compound that better shows some of the symmetry elements you may have identified in question #2 or any other symmetry element you find particularly difficult to see.

3b) Check in with your TA to make sure you haven't missed any operations. If there are any you missed, try to draw and describe them here. If necessary, you can always come back to this step later.

Compound 4: Tetrabromopalladinate ($PdBr_4^{2-}$) (planar)



Atoms required	Bonds required
- 1x silver Metal (6 holes)	- 4x short bonds
- 4x green Halogens	

1) Based on the above representation, discuss with your team what symmetry elements the compound appears to have. What operations can you see that would have the compound look the same before and after the operation?

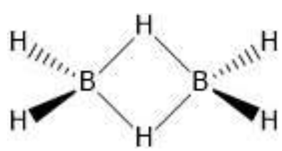
2a) Construct the compound using the model kit. Take two pictures of the model you've assembled.

2b) Using your constructed model, see if there are any symmetry elements present in the compound that your team didn't see in question #1. If you did find any new operations, try to describe where they are and how they relate to the representation above.

3a) See if your team can come up with ways to draw the compound that better shows some of the symmetry elements you may have identified in question #2 or any other symmetry element you find particularly difficult to see.

3b) Check in with your TA to make sure you haven't missed any operations. If there are any you missed, try to draw and describe them here. If necessary, you can always come back to this step later.

Compound 5: Diborane



Atoms required	Bonds required
- 2x silver Metals (4 holes)	- 4 long bonds
- 4x white Hydrogens (1 hole)	- 4 short bonds
- 2x white Hydrogens (2 holes)	

1) Based on the above representation, discuss with your team what symmetry elements the compound appears to have. What operations can you see that would have the compound look the same before and after the operation?

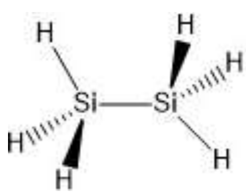
2a) Construct the compound using the model kit. Take two pictures of the model you've assembled.

2b) Using your constructed model, see if there are any symmetry elements present in the compound that your team didn't see in question #1. If you did find any new operations, try to describe where they are and how they relate to the representation above.

3a) See if your team can come up with ways to draw the compound that better shows some of the symmetry elements you may have identified in question #2 or any other symmetry element you find particularly difficult to see.

3b) Check in with your TA to make sure you haven't missed any operations. If there are any you missed, try to draw and describe them here. If necessary, you can always come back to this step later.

Compound 6: Disilane (staggered)



Atoms required	Bonds required
- 2x silver Metals (4 holes)	- 7 short bonds
- 6x white Hydrogens (1 hole)	

1) Based on the above representation, discuss with your team what symmetry elements the compound appears to have. What operations can you see that would have the compound look the same before and after the operation?

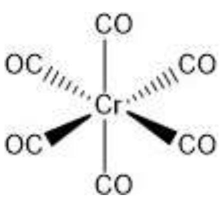
2a) Construct the compound using the model kit. Take two pictures of the model you've assembled.

2b) Using your constructed model, see if there are any symmetry elements present in the compound that your team didn't see in question #1. If you did find any new operations, try to describe where they are and how they relate to the representation above.

3a) See if your team can come up with ways to draw the compound that better shows some of the symmetry elements you may have identified in question #2 or any other symmetry element you find particularly difficult to see.

3b) Check in with your TA to make sure you haven't missed any operations. If there are any you missed, try to draw and describe them here. If necessary, you can always come back to this step later.

Compound 7: Hexacarbonylchromium ($Cr(CO)_6$)



Atoms required	Bonds required
- 1x silver Metal (6 holes)	- 12 short bonds
- 4x black Carbons (5 holes)	
- 2x black Carbons (6 holes)	
- 6x red Oxygens (2 holes)	

Model construction notes: Make sure to orient the carbon atoms such that the oxygen atom, carbon atom, and metal center are all colinear (in a straight line). For ease, simply use a single short bond between the carbon and oxygen atoms (note that the CO bond, in reality, is greater than a single bond).

1) Based on the above representation, discuss with your team what symmetry elements the compound appears to have. What operations can you see that would have the compound look the same before and after the operation? Do note that the CO ligands are all identical and linear!

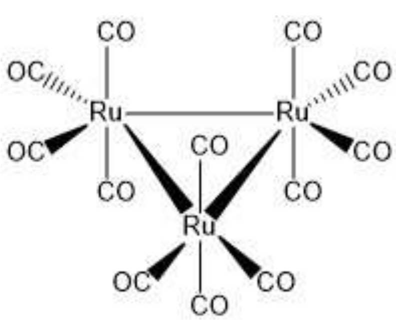
2a) Construct the compound using the model kit. Take two pictures of the model you've assembled; one picture should include an odd-numbered rotational axis (eg. C_n where n = an odd number).

2b) Using your constructed model, see if there are any symmetry elements present in the compound that your team didn't see in question #1. If you did find any new operations, try to describe where they are and how they relate to the representation above.

3a) See if your team can come up with ways to draw the compound that better shows some of the symmetry elements you may have identified in question #2 or any other symmetry element you find particularly difficult to see.

3b) Check in with your TA to make sure you haven't missed any operations. If there are any you missed, try to draw and describe them here. If necessary, you can always come back to this step later.

Compound 8: Triruthenium dodecarbonyl ($Ru_3(CO)_{12}$)



Atoms required

- 3x silver Metals (6 holes)

Bonds required

- 12 short bonds

- 12x carbon atoms (4 holes)
- 3 long bonds

Model construction notes: Due to limitations with the kit, treat the CO ligand as if it were a single carbon atom; this approximation will have no effect on the apparent symmetry of the compound. Use the long bonds between the metal centers and the short bonds for the Ru-C bonds.

1) Based on the above representation, discuss with your team what symmetry elements the compound appears to have. What operations can you see that would have the compound look the same before and after the operation?

2a) Construct the compound using the model kit. Take two pictures of the model you've assembled.

2b) Using your constructed model, see if there are any symmetry elements present in the compound that your team didn't see in question #1. If you did find any new operations, try to describe where they are and how they relate to the representation above.

3a) See if your team can come up with ways to draw the compound that better shows some of the symmetry elements you may have identified in question #2 or any other symmetry element you find particularly difficult to see.

3b) Check in with your TA to make sure you haven't missed any operations. If there are any you missed, try to draw and describe them here. If necessary, you can always come back to this step later.

Original Symmetry Activity TA Notes

Some good resources if you need a refresher on symmetry and point groups, most of which are referenced throughout the notes for you below:

Housecroft, Catherine; Sharpe, Alan. *Inorganic Chemistry*, 4th ed.; Pearson, 2012.

Class textbook, solid intro to symmetry/group theory, lots of good pictures.

Can be found in Daley Library (as of 8/1/2021)

https://www.chemtube3d.com/sym-elementsplanes/

Symmetry@Otterbein. https://symotter.org/

Fantastic collection of interactive animations organized into tutorial, gallery, and "challenge" sections. Students can reference this during the activity if needed.

Carter, Robert. *Molecular Symmetry and Group Theory*; John Wiley & Sons, 1998.

Solid text, discusses group theory in inorganic chemistry context (MO theory, vibrational modes, JT distortions, etc.). Can be found in Daley Library (as of 8/1/2021)

Levine, Ira. *Molecular Spectroscopy*; John Wiley & Sons, 1975.

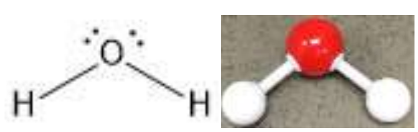
A more advanced text, heavy emphasis on calculus and matrix algebra.

Can be found in Daley Library (as of 8/1/2021)

Miessler, Gary; Fischer, Paul J.; Tarr, Donald A. *Inorganic Chemistry*, 5th ed.; Pearson, 2014.

Alternative textbook, shorter intro but it's an option. Some good pictures with labelled atoms after operations like S_4, i, etc.

<u>Compound 1: Water (H_2O)</u>



<u>Atoms required</u>

- 2x white Hydrogens (1 hole)
- 1x red Oxygen (2 holes)

<u>Bonds required</u>

- 2x short bonds

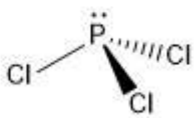
Point group: C_{2v} Full list of symmetry operations: E, C_2, σ_{xz}, σ_{yz}

Notes: Problem is done for students. Simple point group, but some things to note:

1) labeling of x- and y-axes are arbitrary but y-axis perpendicular to the plane containing all three atoms is typical.

2) labeling principal rotation as z-axis is not arbitrary; this is the widely accepted convention [See: Miessler & Tarr, 5th ed., pg. 77].

<u>Compound 2: Phosphorus Trichloride (PCl_3)</u>



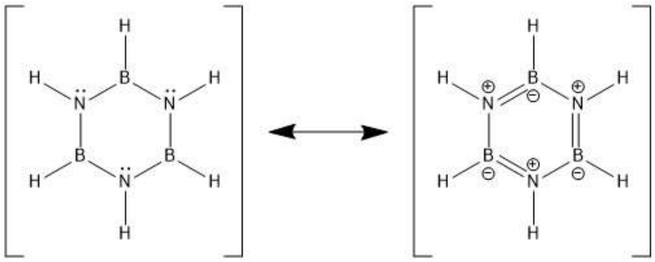
Atoms required	Bonds required
- 1x purple Phosphorus (4 holes)	- 3 short bonds
- 3x green Halogens	

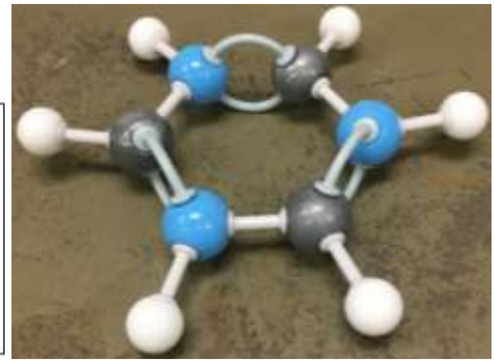
Point group: C_{3v} Full list of symmetry operations: E, $2C_3$, $3\sigma_v$

New feature introduced: (technically) multiple proper rotations

Notes: Simple point group. Could be good to stress to students that both C_3 operations (C_3^1 vs. $C_3^{-1} = C_3^2$) have identical character but are technically unique operations. [See: Housecroft & Sharpe, 5th ed., Ch. 3.3; Miessler & Tarr, 5th ed., pg. 76]

<u>Compound 3: Borazine ($B_3N_3H_6$) (planar)</u>





<u>Atoms required</u>

- 3x blue Nitrogens (4 holes)
- 3x silver Metals (4 holes)
- 6x white Hydrogens (1 hole)

<u>Bonds required</u>

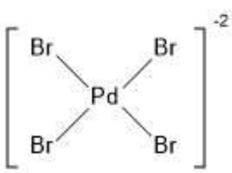
- 6 long bonds
- 9 short bonds

Point group: D_{3h} Full list of symmetry operations: E, $2C_3$, $3C'_2$, σ_h, $2S_3$, $3\sigma_v$

New feature introduced: Principal axis of rotation doesn't pass through an atomic center (or a bond). Also, rotational axes perpendicular to principal axis.

Notes: Might not see S_3 operation ($S_3 = C_3 + \sigma_h$), model a p orbital to show this, contrast with C_3.

<u>Compound 4: Tetrabromopalladinate ($PdBr_4^{2-}$) (planar)</u>



<u>Atoms required</u>

- 1x silver Metal (6 holes)
- 4x green Halogens

<u>Bonds required</u>

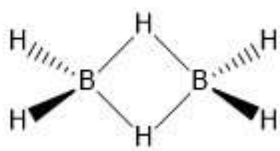
- 4x short bonds

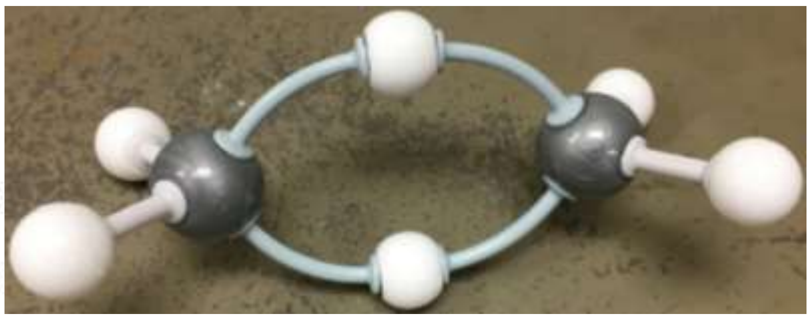
Point group: D_{4h} Full list of symmetry operations: E, $2C_{4(z)}$, C_2, $2C'_2$ $2C''_2$, i, σ_h, $2\sigma_v$, $2\sigma_d$

New feature introduced: Inversion center. Also, distinction with σ_v vs. σ_d

Notes: Similar to PCl_3, see if students recognize $C_4^2 = C_2$, because here it actually matters in the character table. Students may struggle separating σ_v, from σ_d but they ARE distinct operations. Vertical mirror planes will utilize the principal rotation axis and the atomic axis (Br-Pd-Br, same as C_2') while dihedral mirror planes will utilize principal rotation axis and the C_2 axis in between the C_2' axes (read: C_2'') [See: Levine, pg. 407; Carter, pg. 5-8].

<u>Compound 5: Diborane</u>





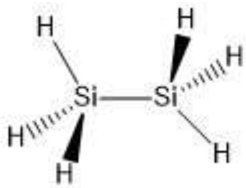
Atoms required	Bonds required
- 2x silver Metals (4 holes)	- 4 long bonds
- 4x white Hydrogens (1 hole)	- 4 short bonds
- 2x white Hydrogens (2 holes)	

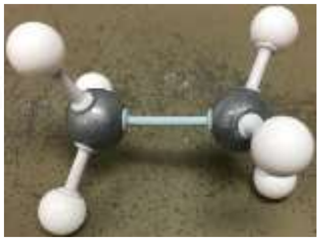
Point group: D_{2h} Full list of symmetry operations: E, $C_{2(z)}$, $C_{2(y)}$, $C_{2(x)}$, i, $\sigma_{(xy)}$, $\sigma_{(xz)}$, $\sigma_{(yz)}$

New feature introduced: Inversion center *not* at an atomic center.

Notes: $C_{2(y)}$ axis doesn't go through an atom or bond, watch for students to miss this and the inversion center. May be first experience with 3c-2e bonds for some.

<u>Compound 6: Disilane (staggered)</u>





Atoms required

- 2x silver Metals (4 holes)
- 6x white Hydrogens (1 hole)

Bonds required

- 7 short bonds

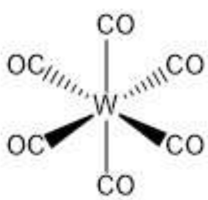
Point group: D_{3d} Full list of symmetry operations: E, $2C_3$, $3C'_2$, i, $2S_6$, $3\sigma_d$

New feature introduced: Improper rotation *without* σ_h

Notes: Tricky because there is an S_6 but no C_6 or σ_h (instead, $C_3^1 * i = S_6^1$ and $C_3^2 * i = S_6^5$).

Note inversion center isn't at an atom, could be missed by students.

Compound 7: Hexacarbonylchromium ($Cr(CO)_6$)



Atoms required

- 1x silver Metal (6 holes)
- 4x black Carbons (5 holes)
- 2x black Carbons (6 holes)
- 6x red Oxygens (2 holes)

Bonds required

- 12 short bonds

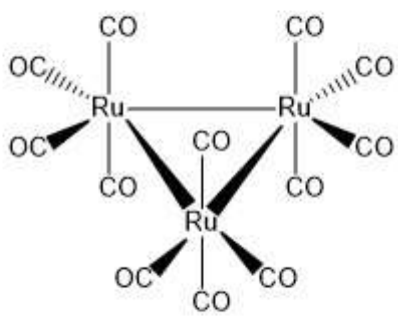
Model construction notes: Make sure to orient the carbon atoms such that the oxygen atom, carbon atom, and metal center are all colinear (in a straight line). For ease, simply use a single short bond between the carbon and oxygen atoms (note that the CO bond, in reality, is greater than a single bond).

Point group: O_h Full list of symm. ops.: E, $8C_3$, $6C_2$, $6C_4$, $3C_2=(C_4)^2$, i, $6S_4$, $8S_6$, $3\sigma_h$, $6\sigma_d$

New feature introduced: None

Notes: Tough because high symmetry, lots of symmetry elements. The $6C_2$ axes are between the ligands, while the C_4 and $C_2=C_4^2$ axes are, of course, through atomic centers. C_3 axes are in the middle of the triangle that can be drawn between each 3 ligands on the same face (imagine fac isomer of ML_3X_3). Also, make sure students know CO ligand is linear.

<u>Compound 8: Triruthenium dodecarbonyl ($Ru_3(CO)_{12}$)</u>



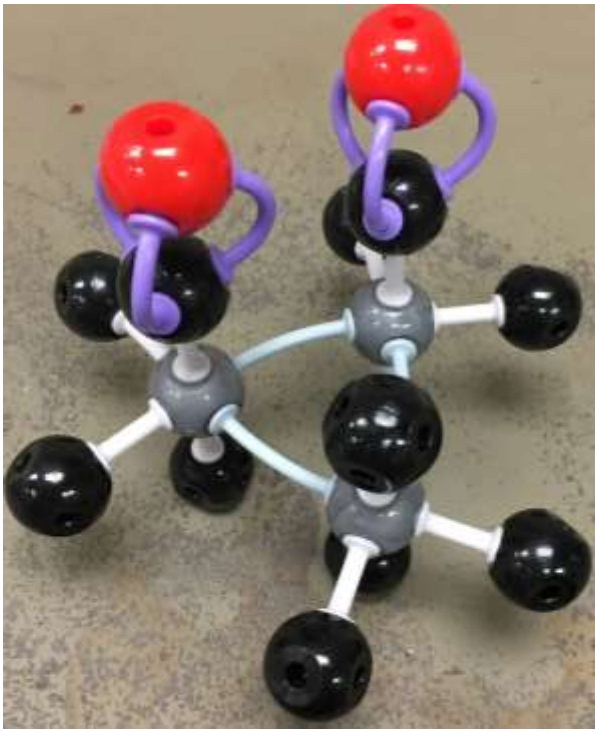
Atoms required	Bonds required
- 3x silver Metals (6 holes)	- 12 short bonds
- 12x carbon atoms (4 holes)	- 3 long bonds

Model construction notes: Due to limitations with the kit, treat the CO ligand as if it were a single carbon atom; this approximation will have no effect on the apparent symmetry of the compound. Use the long bonds between the metal centers and the short bonds for the Ru-C bonds.

Point group: D_{3h} Full list of symmetry operations: E, $2C_3$, $3C'_2$, i, $2S_6$, $3\sigma_d$

New feature introduced: None

Notes: This is a test for how students handle many, many atoms at once. Same point group as Compound 3, just bigger and bulkier. If anyone is having difficulty, maybe try breaking down this compound into small chunks (ex. Just the metal centers, apical CO ligands, etc.).



Sample Grading Schemes

Because the eight problems have the same components, we could use the same general point outline across all compounds. Below is a possible point distribution with some things we could dock points for.

- Question 1: 2 points
  - -1, Only listing E for identified operations (unless they indicate serious struggle and really can only see E; some students aren't good at this stuff!)
  - -0.5, Identifying operations without using (semi-)proper notation
- Question 2a: 1.5 points
  - -0.75, Missing a picture
  - -0.5, For compounds #2, 3, and 7, if neither of their pictures have the indicated operation
- Question 2b: 4 points
  - -1, No attempt at describing location of newly discovered operations (either at all or relative to previously identified operations).

  - -0.5, Identifying operations without using (semi-)proper notation
- Question 3a: 3 points
  - -1.5, Simply repeating the given representation without modifying it in <u>any</u> way
  - -3, No drawings present
- Question 3b: 2 points
  - -1, Operations were missed but are not accompanied by drawings

  Total: 12.5 points * 8 compounds = 100 points

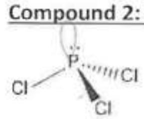
APPENDIX C. CODED LABORATORY REPORT SAMPLE

S5

Name: ____________________ CHEM 314 - Inorganic Chemistry

Representations of Symmetry Elements

Compound 2: Phosphorus Trichloride (PCl_3)



Atoms required	Bonds required
- 1x purple Phosphorus - 3x green Halogens	- 3 medium bonds

1a) Based on the above representation, discuss with your team what symmetry elements the compound appears to have and record them here.

Looking at the above diagram, we were able to identify a C_3 axis running through the P atom and the unpaired electron orbital (z-axis). We can also see mirror planes cutting along each of the P-Cl bonds, bisecting the other two Cl atoms. Symmetry elements: $E, C_3, 3\sigma_v$

Found in Question 1 (2D only)

1b) According to VSEPR theory, what electronic geometry should this compound have? What molecular geometry?

According to VSEPR theory, the electronic geometry should be tetrahedral and the molecular geometry should be trigonal pyramidal.

1c) Consider that the model kit comes with two different "kinds" of phosphorus atoms; a 4-hole and a 5-hole phosphorous atom. Using what you wrote for Q1b, which should you use? Why?

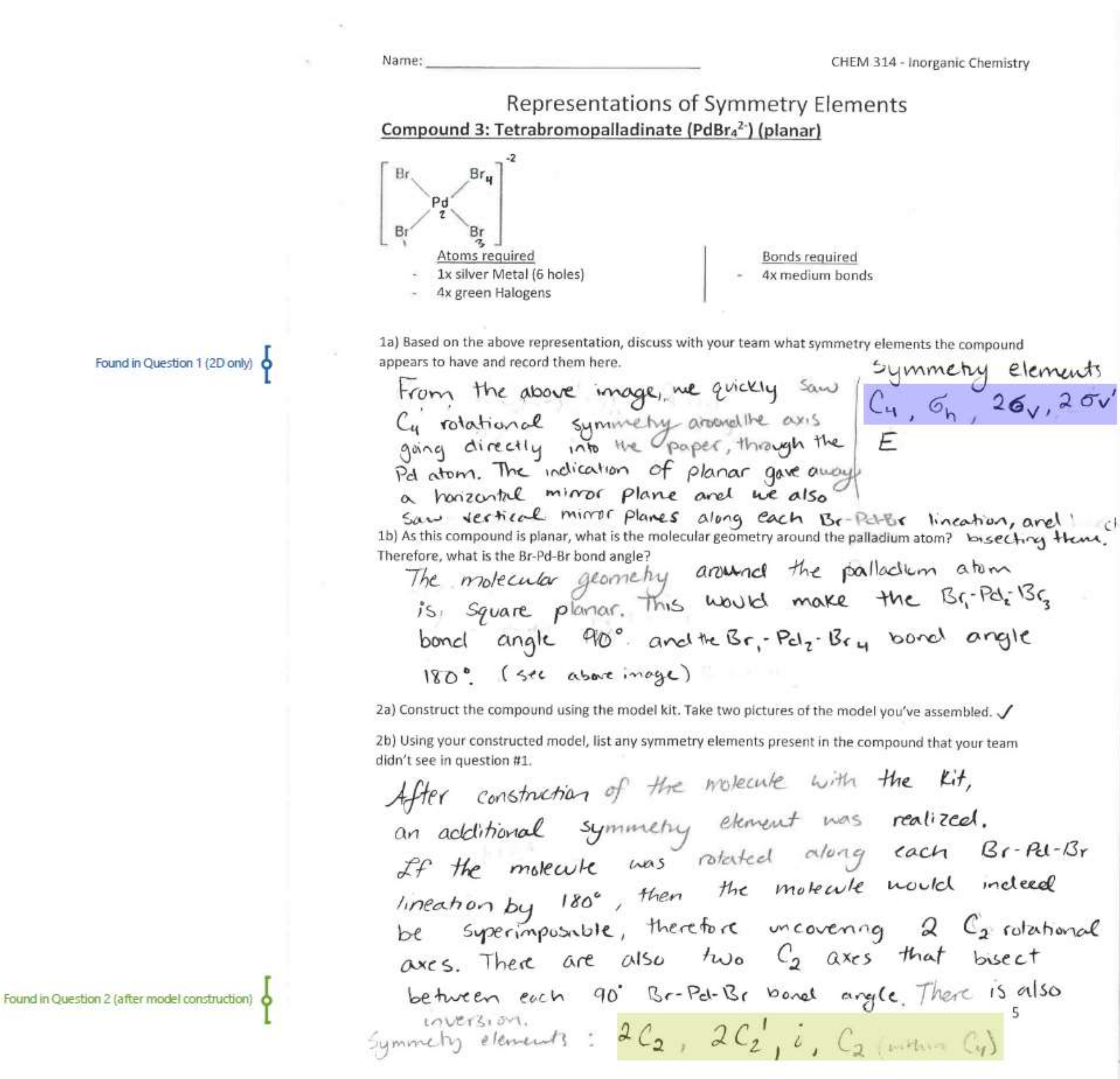
Based on the VSEPR analysis, the 4-hole should be used to generate the correct bond angles to yield a trigonal pyramidal geometry. Also, the electron geometry is tetrahedral, which can be made using the 4-hole only; the 5-hole would be able to yield trigonal bipyramamidal bond angles of 120° and 90° but not tetrahedral bond angles of <109°.

2a) Construct the compound using the model kit. Take two pictures of the model you've assembled.

✓

3

Figure 22 Coded activity page submitted by participant S5. This page of the activity is for phosphorus trichloride.



S5

Name: ______________________________ CHEM 314 - Inorganic Chemistry

Representations of Symmetry Elements

Compound 3: Tetrabromopalladinate ($PdBr_4^{2-}$) (planar)

Atoms required	Bonds required
- 1x silver Metal (6 holes) - 4x green Halogens	- 4x medium bonds

Found in Question 1 (2D only)

1a) Based on the above representation, discuss with your team what symmetry elements the compound appears to have and record them here.

From the above image, we quickly saw C_4 rotational symmetry around the axis going directly into the paper, through the Pd atom. The indication of planar gave away a horizontal mirror plane and we also saw vertical mirror planes along each Br-Pd-Br lineation, and bisecting them.

Symmetry elements: C_4, σ_h, $2\sigma_v$, $2\sigma_v'$, E

1b) As this compound is planar, what is the molecular geometry around the palladium atom? Therefore, what is the Br-Pd-Br bond angle?

The molecular geometry around the palladium atom is square planar. This would make the Br_1-Pd_2-Br_3 bond angle 90° and the Br_1-Pd_2-Br_4 bond angle 180°. (see above image)

2a) Construct the compound using the model kit. Take two pictures of the model you've assembled. ✓

2b) Using your constructed model, list any symmetry elements present in the compound that your team didn't see in question #1.

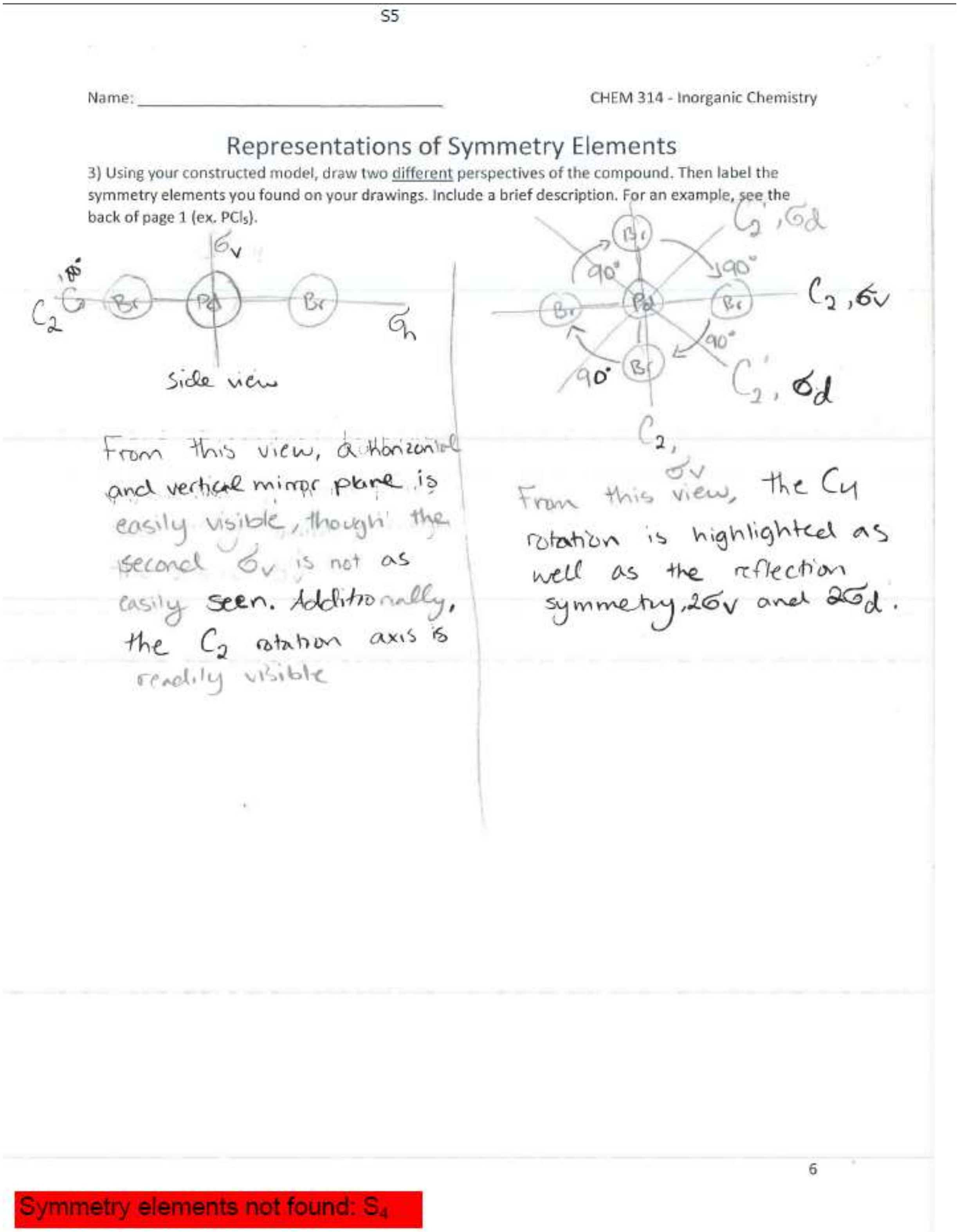
After construction of the molecule with the kit, an additional symmetry element was realized. If the molecule was rotated along each Br-Pd-Br lineation by 180°, then the molecule would indeed be superimposable, therefore uncovering 2 C_2 rotational axes. There are also two C_2 axes that bisect between each 90° Br-Pd-Br bond angle. There is also inversion.

Found in Question 2 (after model construction)

Symmetry elements: $2C_2$, $2C_2'$, i, C_2 (within C_4)

5

Figure 23 Coded activity page submitted by participant S5. This page of the activity is for tetrabromopalladate.


S5

Name: ____________________ CHEM 314 - Inorganic Chemistry

Representations of Symmetry Elements

3) Using your constructed model, draw two different perspectives of the compound. Then label the symmetry elements you found on your drawings. Include a brief description. For an example, see the back of page 1 (ex. PCl_5).

From this view, a horizontal and vertical mirror plane is easily visible, though the second σv is not as easily seen. Additionally, the C_2 rotation axis is readily visible

From this view, the C_4 rotation is highlighted as well as the reflection symmetry, 2σv and 2σd.

6

Symmetry elements not found: S_4

Figure 24 Coded activity page submitted by participant S5. This is another page of the activity is for tetrabromopalladate.

APPENDIX D. TABULATED LAB REPORT CODING DATA

	Lab report	F1	F2	F4	F5	F6	F7	F9	F10	F11	F12	F13	F16
Comp #2	2C3	1	1	1	1	1	1	1	1	1	1	1	1
PCl3	3σv	1	1	2	2	1	1	2	1	1	1	1	1
Comp #3	2C3	1	1	1	1	1	1	1	1	1	1	1	1
Borazine	3C'2	4	1	2	2	1	1	2	4	2	1	1	1
	σh	1	1	2	2	1	1	1	4	4	1	3	1
	2S3	1	1	2	2	1	2	2	2	3	2	3	3
	3σv	1	1	4	2	1	1	1	1	1	4	3	1
Comp #4	2C4	1	1	1	1	1	1	1	1	1	1	2	1
PdBr4	C2	1	3	2	1	2	1	2	4	4	1	1	1
	2C'2	1	3	2	2	2	3	2	1	4	4	1	3
	2C''2	1	3	2	2	2	4	2	2	3	4	4	3
	i	1	1	2	1	2	3	2	1	1	4	2	1
	σh	1	1	1	1	1	1	1	2	1	1	2	1
	2σv	1	1	1	1	2	1	1	1	1	2	4	1
	2σd	1	1	2	1	2	3	4	2	4	2	1	1
	2S4	1	1	4	4	2	2	1	4	4	4	4	1
Comp #5	C2z	1	1	1	1	1	1	2	1	1	1	1	1
Diborane	C2x	1	1	1	1	1	1	4	4	4	1	1	1
	C2y	1	1	1	1	1	1	4	4	4	1	1	1
	i	1	1	1	1	1	1	2	4	2	1	2	1
	σxy	1	1	1	1	1	1	1	1	1	1	1	1
	σxz	1	1	1	1	1	1	1	1	1	1	1	1
	σyz	1	1	1	1	1	1	4	2	1	2	1	1
Comp #6	2C3	1	1	1	1	1	1	2	1	1	2	1	1
Disilane	3C'2	4	4	1	1	1	1	2	4	2	1	1	2
	i	4	1	1	1	1	2	2	1	1	4	1	1
	2S6	1	3	2	1	2	4	2	1	1	4	3	2
	3σd	1	1	1	1	1	1	2	1	1	4	3	1
Comp #7	8C3	1	1	2	1	4	1	2	1	1	2	2	1
CrCO6	6C2	1	3	1	1	1	1	1	1	1	2	3	2
	6C4	1	1	1	1	1	1	1	1	1	1	1	2
	3C2=C4^2	1	3	4	1	4	4	2	4	4	4	2	1
	i	1	1	1	1	1	4	1	4	1	1	3	1
	6S4	1	1	1	1	1	1	1	1	1	4	1	2
	8S6	1	3	2	4	1	2	2	1	1	1	2	1
	3σh	1	1	1	1	1	1	1	1	1	1	3	1
	6σd	1	1	1	1	1	1	1	1	1	2	1	1
Comp #8	2C3	1	1	1	1	1	1	1	1	1	1	1	1
	3C'2	1	1	1	1	1	2	2	1	1	1	3	1
	σh	1	1	1	1	1	1	2	1	1	1	4	1
	2S3	1	1	2	1	1	4	2	1	1	2	4	1
	3σv	1	1	1	1	1	1	1	1	1	2	2	1

Figure 25 Image of lab report coding from Fall 2021 lab reports. Reprinted with permission from J. Chem. Educ. 2023, 100, 1633-1640. Copyright 2023 American Chemical Society.

	Lab report	S1	S2	S3	S5	S6
Comp #2	2C3	1	1	1	1	1
PCl3	3σv	1	2	1	1	1
Comp #3	2C3	1	1	1	1	1
Borazine	3C'2	1	1	4	2	2
	σh	1	1	1	1	4
	2S3	1	4	2	4	4
	3σv	1	4	1	1	1
Comp #4	2C4	1	1	1	1	1
PdBr4	C2	1	1	1	2	4
	2C'2	1	1	4	2	4
	2C''2	1	1	4	2	1
	i	1	2	1	2	1
	σh	1	4	1	1	1
	2σv	1	4	1	1	1
	2σd	1	4	1	1	2
	2S4	1	4	1	4	2
Comp #5	C2z	1	1	1	1	1
Diborane	C2x	1	1	4	1	1
	C2y	1	4	4	2	2
	i	1	1	1	1	1
	σxy	1	1	1	1	1
	σxz	1	1	1	1	1
	σyz	1	1	4	1	4
Comp #6	2C3	1	1	1	1	1
Disilane	3C'2	1	4	2	2	2
	i	1	2	2	1	1
	2S6	1	4	2	2	4
	3σd	1	1	1	2	2
Comp #7	8C3	1	1	1	3	2
CrCO6	6C2	1	3	4	3	4
	6C4	1	1	1	1	1
	3C2=C4^2	1	3	1	3	2
	i	1	3	1	2	1
	6S4	1	4	2	2	4
	8S6	1	4	4	4	4
	3σh	1	1	1	1	1
	6σd	1	1	1	2	1
Comp #8	2C3	1	2	1	1	1
	3C'2	1	4	1	1	4
	σh	1	1	1	1	1
	2S3	1	4	2	2	4
	3σv	1	1	1	1	4

Figure 26 Image of lab report coding from Spring 2022 lab reports. Reprinted with permission from *J. Chem. Educ.* **2023**, 100, 1633-1640. Copyright 2023 American Chemical Society.

APPENDIX E. INTERVIEW PROTOCOLS

Fall 2022 Interview Protocol

Phase 0 – Introduction

- Hello <name>, thank you for agreeing to do this interview. Before we begin in earnest, I'd like to remind you that you can withdraw your consent to participate in this research at any time, including during the interview. Do you have any questions before we begin?

Phase 1 – Symmetry Element Review

- To begin, you've been covering symmetry and group theory in CHEM 314; my questions will be about this topic and the related lab activity you completed. For the first question, could you please list all of the main types of symmetry elements?

- You may have seen a notation like the following; C_2 C_2' C_2''. What can you tell me about these 3 symmetry operators?

- You may have also seen: σ_h σ_v σ_d . What can you tell me about these symmetry operators?

- The inversion operator, i, is a little uncommon. What can you tell me about it?

- And the final question for this part, improper rotations; what can you tell me about them? For example, how do they differ from proper rotations?

Phase 2 – Symmetry element ID with benzene

- For the next part of the interview, I want to take about 10 minutes and ask you to identify any symmetry elements you can using this model of trans-tetracarbonyldichloroosmium(II). Feel free to gesture using your hands, pen, what have you. Do you have any questions?

- I would ask you to do the same task but with this new model. <Swap one carbonyl ligand with a chloro to make the fac- isomer>

Phase 3 – Interpretation of common gestures

- I am now going to produce a few gestures with this model of benzene. After each gesture, please tell me what, if any, meaning you understand from the gesture. Please note there are NO wrong answers here.

<Gestures: {F}Hmu, {M}Tm(Hmu), {F}Ifm, {F}2db, {F}2mb>

<Additional actions: rotate model, rotate and flip model>

Phase 4 – Activity questions

- I'd like to take a few minutes talking about the activity itself.

- The activity mentioned working in groups, with your peers. What purpose do you think that served?

    - Do you think this aspect of the activity served its purpose?

- The activity also had a prompt to build the molecules with model kits. What did you think about this part of the activity?

    - Do you think this aspect of the activity served its purpose?

- Finally, each compound ended with a question asking you to draw the compound and its symmetry elements. Could you tell me about your experience with this question?

Phase 6 – Concluding Remarks

- Those are all the questions I had. Do you have anything else you'd like to share?

- Well, thank you so much for doing this interview with me!

Spring 2023 - Spring 2024 Interview Protocol

Phase 0 – Introduction

- Hello <name>, thank you for agreeing to do this interview. I'll be asking you some questions about symmetry and group theory as you know it in inorganic chemistry, as well as the gestures you might have seen or performed related to this topic. Before we begin, I would remind you that you can withdraw your consent to participate in this research at any time. Do you still consent to this interview?

- Very good! Do you have any questions before we start?

- Alright, so symmetry and group theory as you've experienced it in class is a very spatial concept: you're rotating molecules, seeing if they look the same before and after a transformation. It can really force you to do a lot of imagining if you don't have a picture present. My first question is: How would you describe your ability to picture and manipulate things in your mind?

Phase 2 – Symmetry element review

- Next, I'll be asking you questions about symmetry operators, things like mirror planes, improper rotations. Please do share any strategies or hand movements, anything that you personally do or find useful during these questions. Feel free to talk through your thoughts out loud. What's important to me is learning how you think about this stuff, not that you get "the right answer". Sound good?

- Alright, here we go: You may have seen a notation like the following. <show notecard displaying C_2 C_2' C_2''> What can you tell me about these 3 symmetry operators?

[If more prompting is necessary] Could you show me or tell me more about that?

- Next, these: <show notecard displaying σ_h σ_v σ_d> What can you tell me about these symmetry operators?

- The inversion operator, i, is a little uncommon. What can you tell me about it?

- And the final question for this part, improper rotations. What can you tell me about them? For example, how do they differ from proper rotations?

Phase 3 – Symmetry element ID with/out models

- For the next part of the interview, I'll ask you to identify as many symmetry elements as you can for a number of molecules. Feel free to gesture using your hands, any nearby objects, anything you want. Any questions?

- I imagine you're familiar with water, H_2O. What symmetry elements does it have?

- I'm going to make things a little harder now: Phosphorus pentachloride, or PCl_5. Are you familiar with this compound?

[No] It's a trigonal bipyramidal compound with two apical chlorine atoms and three equatorial chlorine atoms; the phosphorus atom is in the center.

[Yes] What symmetry elements does this compound have?

- For the next compound, I have a model of trans-tetracarbonyldichloroosmium(II). What symmetry elements can you identify in this compound?

- Last one, this is a model of benzene. What symmetry elements can you find?

Phase 4 – Interpretation of their gestures

- Now I'd like to ask about the gestures you've employed. Were you aware that you were gesturing or did they sometimes happen without you thinking about it?

- I'm going to try to recreate some of the gestures I saw you do. After each gesture, could you tell me what that gesture meant to you(and, if possible, why you did it?

- I know this might be a difficult question but these gestures, do you know where they came from? That is, how did you come to associate gesture X with meaning Y?

Did you see <professor's name> use them? Perhaps your peers were doing that during the lab activity on symmetry? Or were these just kind of your own?

Phase 5 – Interpretation of common gestures

- I am now going to produce some gestures. After each gesture, please tell me what, if any, meaning you interpret from the gesture. There are NO wrong answers.

Gesture list: {F}2mb, {F}2db, {F}2fm, {F}Ifm, {F}Imb, {M}O+y(2mb), {M}R+z(2mb), {F}Hfd, {F}Hmd, {M}R+z(Cdd), {M}R+x(Hfd)

Phase 6 – Concluding Remarks

- Those are all the questions I had. Do you have anything else you'd like to share?

Fall 2023 and Spring 2024 Focus Group Protocol

Phase 0 – Introduction

Hello everyone, thank you for agreeing to be in this focus group. Before we begin in earnest, I'd like to remind you that you can withdraw your consent to participate in this research at any time, including during this meeting. Does anyone have any questions before we begin?

Very good. Before we continue, we should introduce ourselves. I am Jacob Markut, graduate researcher in the chemistry department, thank you again for being here. <Prompt others to introduce themselves>

Phase 1 – Symmetry Element Review

I understand it's been some time since some of you have thought about symmetry and group theory so allow me to briefly refresh some of the basics. When we talk about symmetry operations, we are referring to transformations that we can do on an entity, like a molecule, such that the appearance of the molecule after the transformation is identical to it before the transformation. The entity about which we do these operations is called a symmetry element. There are N types of symmetry operations: proper rotations, reflections, inversions, and improper rotations. The identity operator also exists, but that's the "do nothing" or "multiply everything by 1" operator so we won't talk about it much today.

Proper rotations are exactly what they sound like. The operation is a rotation about an axis, where the axis is the symmetry element. We use the following notation to describe these rotations: C_n C_n' C_n'', where n is equal to 360 divided by the degree of rotation. So a C_2 is a 180 degree rotation, C_3 is 120, and so on. A given molecule may have several unique axes of rotation. The principal axis of rotation is the axis by which one can do the smallest degree rotation, or would have the largest value of n.

Reflections are the translation of points across a 2-dimensional mirror plane. They use the notation: σ_h σ_v σ_d, where the h, v, and d stand for horizontal, vertical, and dihedral respectively. Remember that we define the horizontal mirror plane very specifically; that is the plane that is perpendicular to the principal axis of rotation.

The inversion operator, i, is the operation by which all points are translated to, and then through, the origin.

Finally, improper rotations are often described as a compound operation. We often think of them as a rotation followed by a mirror in the plane perpendicular to the axis of rotation.

Are there any questions?

Phase 2 – Previously Established Gestures

To expand on what we discussed via email, the primary purpose of this focus group is to discuss how gestures can be used to show symmetry elements and operations, especially when it comes to improper rotations and inversions. I will do a series of gestures that we used in CHEM 314 last semester and I'd like us to talk about what symmetry elements or operations you think they show. <<Go through list>>

Phase 3 – New Gesture Development

<<If discussion doesn't naturally move this direction>> Now, there was some dissatisfaction with some of these gestures last semester, especially these gestures that were intended to refer to improper rotations and inversions. I'd like us to throw around some ideas for what gestures could be better than what was attempted before.

Phase 4 – Concluding Remarks

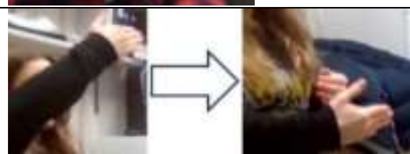
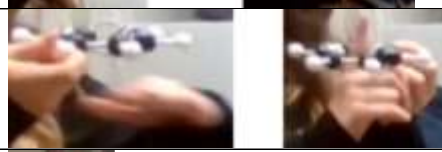
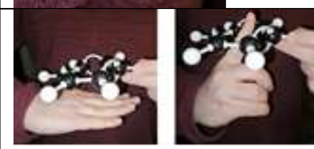
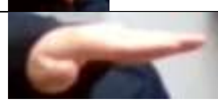
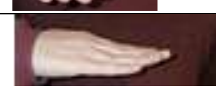
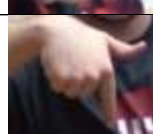
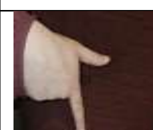
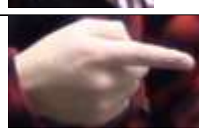
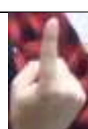
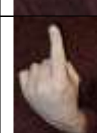
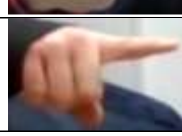
Alright, I think that's everything from me. Does anyone have anything else they'd like to share?

Very good, thank you all for coming!

APPENDIX F. ORIGINAL AND RECREATED GESTURE DEPICTIONS

The images of gestures in Chapter III are attempts by me to recreate gestures produced by students during interviews. The following table includes the original images of student gestures alongside my recreations for data transparency.

Table 18 Original and recreated images of student gestures

Gestural Form code	*Original image*	*Recreated image*
{F}Ifm		
{M}Td(Imb)		
{M}Tf(Hmd) {F}2um		
{F}Ium		
{M}Td(Ifm)		
{F}Hfd		
{F}Hmd		
{F}Imb		
{F}2db		
{F}2fm		
{F}2ub		
{F}2mb		
{F}2fd		

APPENDIX G. GESTURAL FORM CODING SCHEME SYNTAX

Form-Dependent Gesture Syntax

Form-dependent gestures use the following four-letter code as a base to describe gestures:

$$\{F\}Abc$$

Where "{F}" classifies the gesture as form-dependent, "A" indicates the dominant hand shape using the Hand Shape Codes, "b" describes the orientation of the fingers with respect to the planes and axes of the body using the Orientation Modifier Codes, and "c" describes the orientation of the palm also using the Orientation Modifier Codes.

Motion-Dependent Gesture Syntax

Gestures that include a motion component are classified as motion-dependent gestures and utilize a base five-letter syntax:

$$\{M\}De(Abc)$$

Where "{M}" classifies the gesture as motion-dependent, "D" indicates the type of motion involved using the Motion Description Codes, and "e" further specifies the direction of the motion. In the case that the motion is translational, "e" simply uses Orientation Modifier Codes to specify the direction of motion. If instead the motion is rotational or circular, either the "+" or "-" orientation modifier code is used in conjunction with the axis by which the motion occurs.

Expanding the Syntax for Complex Gestures

The above syntaxes may be expanded to describe more complex gestures. There are three situations which may necessitate such an expansion: 1) the gesture is two-handed; 2) the gesture utilizes more than one Hand Shape Code; 3) the gesture changes shape over time.

If the gesture is two-handed, another term is added such that each hand is described separately. For clarity, both terms are contained within parentheticals with the left parenthetical describing the left hand and the right parenthetical describing the right hand. The hierarchical classifier is only used once at the start of the code; the {F} classifier is only used in the circumstance where *neither* hand moves. The following is an example of a code describing a two-handed gesture:

$$\{M\}(Hfd)R + x(Hfd)$$

Here, both hands start in the Hfd position (flat and parallel with the transverse body plane, fingers faced forward, palm faced down) but the right hand then rotates along the x-axis such that the thumb would move up and away from the midsagittal plane.

Instances where a gesture utilizes more than one Hand Shape Code are often instances where multiple fingers having different orientations. In this case, an Orientation Modifier Code is used in conjunction with each Hand Shape Code as necessary. Because of the deictic significance of the index finger in American culture (and others), gestures utilizing multiple Hand Shape Codes involving fingers have the index finger ("2") listed first, followed by fingers 3-5, and ending with the thumb ("1"). The following code is an example a gesture utilizing multiple fingers:

$$\{F\}2f3m1um$$

Here, the index finger is pointed forward ("2f"), the middle finger is pointed medially ("3m"), the thumb is pointed upward ("1u") and the palm is faced medially (the final "m"). Recall that all syntaxes should end with a code describing the orientation of the palm. One may recognize this gesture as taking the form of the “right hand rule” gesture often employed in physics classrooms.

When a gesture changes over time, most notably when the Hand Shape Code changes entirely, the initial and final forms of the stroke are separated by a greater-than symbol (“>”). The following code is an example of such a gesture:

$$\{\mathrm{F}\}\mathrm{Hfd} > 2\mathrm{fm}$$

Here, the hand started flat and parallel with the transverse body plane, fingers faced forward, palm faced down (“Hfd”) and changed such that the index finger alone was now pointed forward with the palm faced medially (“2fm”).

Full Table of Gesture Syntax Codes

The following table contains all of the abbreviations used in the gesture coding scheme syntax, separated into categories. Motion Codes are used to specify the type of motion enacted in a motion-dependent gesture. Hand Shape Codes correspond to the “A” term in the syntaxes above and describe the dominant physical form of the hand in the gesture. Orientation Modifier Codes are used to describe the orientation of parts of the hand, whether they be a specific finger identified with a Hand Shape Code, the direction of the fingers for a flattened hand with the “I” and “H” Hand Shape Codes, or the orientation of the palm.

Table 19. Gesture syntax codes.

Shorthand	Full Code Name	Description
Motion Codes		
T	Translational motion	The motion of the gesture is linear
R	Rotational motion	The motion of the gesture is rotational
O	Circular motion	The motion of the gesture is rotational, with *specific emphasis* on the gesture making a full 360° rotation
Hand Shape Codes		
I	Vertical flat hand	Hand is flat and parallel to the coronal *or* the sagittal plane
H	Horizontal flat hand	Hand is flat and parallel to the transverse plane
1	Thumb extended	The thumb is extended and is no longer at rest
2	Index finger extended	The index finger is extended and is no longer at rest
3	Middle finger extended	The middle finger is extended and is no longer at rest
4	Ring finger extended	The ring finger is extended and is no longer at rest
5	Little finger extended	The little finger is extended and is no longer at rest
G	*Grappolo* (finger bunch)	The fingers are pressed together at a single point. David McNeill, a prominent gesture scholar, refers to this gesture as "*grappolo"*
C	Cupped	The fingers are spread and bent, as if grasping a ball
P	Closed fist	The fingers are closed together to form a balled fist
Orientation Modifier Codes		
f	Forward	Oriented such that it would proceed in an anterior direction (*e.g.*, in the +x direction)
b	Backward	Oriented such that it would proceed in a posterior direction (*e.g.*, in the -x direction)
u	Upward	Oriented facing upward (*e.g.,* in the +z direction)
d	Downward	Oriented facing downward (*e.g.,* in -z direction)
m	Medial	Oriented facing toward the midsagittal plane (*e.g.,* in the -y direction)
a	Lateral	Oriented facing away from the midsagittal plane (*e.g.,* in the +y direction)
+	Clockwise	Motion or orientation evolved in a clockwise fashion
-	Anticlockwise	Motion or orientation evolved in an anticlockwise fashion
>	Gesture form change	The gesture moves from the form specified on the left to the form specified on the right

APPENDIX H. FULL GESTURAL FORM-NOTION CORRELATION TABLE

Table 20 Correlation table between gestural forms used by a participant and the notion conveyed by the gestural form. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Inversion	Principal axis	Rotation	Dihedral	Horizontal	Vertical
Sp1	{F}Hfd	0	0	0	0	2	0
Sp1	{F}Hmd	0	0	0	0	7	0
Sp1	{F}(Hmd)(Hmd)	0	0	0	0	1	0
Sp1	{F}Gmm	1	0	0	0	0	0
Sp1	{F}(Gmm)(Gmm)	1	0	0	0	0	0
Sp1	{F}Iaf	0	0	0	0	0	0
Sp1	{F}Ida	0	0	0	0	0	1
Sp1	{F}Idb	0	0	0	1	0	1
Sp1	{F}Idm	0	0	0	0	0	1
Sp1	{F}Ifm	0	0	0	0	0	5
Sp1	{F}Imb	0	0	0	1	0	2
Sp1	{F}Iua	0	0	0	0	0	1
Sp1	{F}Iuf	0	0	0	0	0	1
Sp1	{F}Ium	0	3	0	0	0	5
Sp1	{F}2da	0	2	1	0	0	0
Sp1	{F}2db	0	0	0	0	0	0
Sp1	{F}2fa	0	0	0	0	0	0
Sp1	{F}2fd	0	0	0	0	1	0
Sp1	{F}2fm	0	0	1	0	0	0
Sp1	{F}2fu	0	0	0	0	0	0
Sp1	{F}2f1um	0	0	1	0	0	0
Sp1	{F}2f1md	0	0	0	0	0	0
Sp1	{F}2mb	0	0	0	0	0	0
Sp1	{F}2md	0	0	0	0	0	0
Sp1	{F}2m1df	0	1	0	0	0	0
Sp1	{F}2um	0	3	0	0	0	0
Sp1	{F}(2um)(1d2mf)	0	1	0	0	0	0
Sp1	{F}2d3db	0	0	0	0	0	2
Sp1	{M}Ta(2fd)	0	0	0	0	0	1
Sp1	{M}Ta(2mb)	0	1	0	0	0	1
Sp1	{M}(Guu)Ta(Guu)	0	0	0	0	0	0
Sp1	{M}Tb(2fm)	0	0	0	1	0	0
Sp1	{M}Td(Ifm)	0	0	0	0	0	0
Sp1	{M}Td(Imb)	1	1	0	0	0	0
Sp1	{M}Td(Ium)	0	0	0	0	0	0
Sp1	{M}Td(2ub)	0	0	0	0	0	0
Sp1	{M}Tf(Gmm)	1	0	0	0	0	0

Sp1	{M}Tf(G12mm)	0	0	0	0	0	0
Sp1	{M}Tf(Ium)(Ium)>Tb (Ium)(Ium)	0	0	0	0	0	0
Sp1	{M}Tf(2fm)	0	0	0	1	0	0
Sp1	{M}Tm(Cmm>Gmm) Tm(Cmm>Gmm)	1	0	0	0	0	0
Sp1	{M}Tm(Gmm)Tm(G mm)>Ta(Gaa)Ta(Ga a)	1	0	0	0	0	0
Sp1	{M}Tm(G12uu)(Ium)	0	0	0	0	0	0
Sp1	{M}Tm(Iub)	0	0	0	0	0	1
Sp1	{M}Tm(2mb)	0	0	0	0	0	0
Sp1	{M}Tu(Ium)	0	1	0	0	0	0
Sp1	{M}Tu(Ium)(Ium)>T d(Ium)Ium)	0	0	0	0	0	0
Sp1	{M}Tu(2um)	0	2	0	0	0	0
Sp1	{M}R+x(Cmm)	0	0	0	0	0	0
Sp1	{M}R+x(Hfd)	0	0	2	0	0	0
Sp1	{M}R+x(Hmd)	0	0	0	0	0	0
Sp1	{M}R+x(2bb)	0	0	1	0	0	0
Sp1	{M}R+x(2db)(Ifm)	0	0	0	0	0	0
Sp1	{M}R+x(2fd)	0	0	0	0	0	0
Sp1	{M}R+x(2f1md)	0	0	1	0	0	0
Sp1	{M}R+x(2mb)	0	0	0	0	0	0
Sp1	{M}R-x(Hfd)	0	0	0	0	1	0
Sp1	{M}R+z(Cff)	0	0	1	0	0	0
Sp1	{M}R+z(Cuu)	0	0	1	0	0	0
Sp1	{M}R+z(Cdd)	0	0	1	0	0	0
Sp1	{M}R+z(Had)	0	0	0	0	1	0
Sp1	{M}R+z(Ifm)	0	0	0	0	0	0
Sp1	{M}R+z(2ub)(2da)	0	2	2	0	0	0
Sp1	{M}R+z(2um)	0	0	1	0	0	0
Sp1	{M}R-z(Cdd)	0	0	1	0	0	0
Sp1	{M}R-z(Cub)	0	0	1	0	0	0
Sp1	{M}R-z(Had)	0	0	0	0	1	0
Sp1	{M}R-z(Iuf)	0	0	1	0	0	0
Sp1	{M}R-z(2d3db)	0	0	0	0	0	0
Sp1	{M}R-z(2uCmm)	0	0	1	0	0	0
Sp1	{M}R-z(2um)	0	0	1	0	0	0
Sp1	{M}(Cmm)R-z(Cff)	0	0	1	0	0	0
Sp1	{M}(Cmm)R-z(Cmm)	0	0	4	0	0	0
Sp1	{M}(Ifm)R-z(Ifm)	0	0	0	1	0	1
Sp1	{M}O+y(2mb)	0	0	1	0	0	0
Sp2	{F}Hau	0	0	0	0	1	0
Sp2	{F}Hfu	0	0	0	0	3	0

Sp2	{F}Idb	0	0	0	0	0	1
Sp2	{F}Ifm	0	0	0	0	0	0
Sp2	{F}Iub	0	0	0	0	0	1
Sp2	{F}Ium	0	0	0	0	0	0
Sp2	{F}2db	0	0	0	0	0	0
Sp2	{M}Ta(Hfd)	0	0	0	0	0	0
Sp2	{M}Ta(Hmd)	0	0	0	0	1	0
Sp2	{M}Td(Iaf)	0	0	0	0	0	0
Sp2	{M}Ta(Imb)Tu(Iuf)	0	0	0	0	0	0
Sp2	{M}Tb(Ibm)	0	0	0	0	0	0
Sp2	{M}Tb(2fd)	0	0	0	0	1	0
Sp2	{M}Tb(2md)	0	0	0	0	1	0
Sp2	{M}Td(Hfu)	0	0	0	1	0	0
Sp2	{M}Td(Ifm)	0	0	0	0	0	2
Sp2	{M}Td(Imb)	0	0	0	0	0	1
Sp2	{M}Td(Iub)	0	0	0	0	0	1
Sp2	{M}Td(Ium)	0	0	0	0	0	2
Sp2	{M}Td(2m1ub)	0	0	0	0	0	1
Sp2	{M}Td(2uf)	0	0	0	0	0	1
Sp2	{M}Tf(Hfu)	0	0	0	0	0	0
Sp2	{M}Tf(2dd)Tb(2dd)	1	0	0	0	0	0
Sp2	{M}Tf(2fd)	0	0	0	0	1	0
Sp2	{M}Tm(Hmd)	0	0	0	0	1	0
Sp2	{M}Tu(Ium)	0	0	0	0	0	1
Sp2	{M}Tu(2m1ub)	0	0	0	0	0	1
Sp2	{M}R-x(Cdd)R-x(Cuu)	0	0	1	0	0	0
Sp2	{M}R-x(2f3fd)	2	0	1	0	0	0
Sp2	{M}R+z(Cdd)	0	0	1	0	0	0
Sp2	{M}R+z(Hmd)	0	0	0	0	0	1
Sp2	{M}R-z(Cuu)	0	0	1	0	0	0
Sp2	{M}R-z(Iuf)	0	0	0	0	0	0
Sp2	{M}O+y(2mb)	0	0	1	0	0	0
Sp3	{F}Hfd	0	0	0	0	1	0
Sp3	{F}Hfu	0	0	0	0	0	0
Sp3	{F}Hmd	0	0	0	0	1	0
Sp3	{F}(Gfu)(Gmd)	0	0	0	0	0	0
Sp3	{F}Ifm	0	0	0	2	1	2
Sp3	{F}(Ifm)(Imb)	0	0	0	0	0	0
Sp3	{F}(Ifm)(Ifm)	0	0	0	1	1	0
Sp3	{F}Imb	0	0	0	1	0	1
Sp3	{F}Ium	0	0	0	0	0	1
Sp3	{F}2db	0	1	0	0	1	0
Sp3	{F}2fd	0	0	0	0	0	0

Sp3	{F}2fm	0	0	0	0	0	0
Sp3	{F}2mb	0	0	0	0	0	0
Sp3	{F}(2md)(2um)	0	0	0	0	0	0
Sp3	{F}2ub	0	2	0	0	1	0
Sp3	{F}(2uf)(1d2df)	0	0	0	0	0	0
Sp3	{F}2u3mm	0	0	0	0	0	0
Sp3	{M}Ta(Hfd)	0	0	0	0	2	0
Sp3	{M}Tb(Imb)(Imb)>Tf(Imb)(Imb)>(Imb)Tf(Imb)	0	0	0	0	0	0
Sp3	{M}Tb(2fd)	0	0	0	0	0	0
Sp3	{M}Td(Ifm)	0	0	0	0	0	0
Sp3	{M}Td(2fm)	0	0	0	0	0	0
Sp3	{M}Td(2mb)	0	0	0	0	0	0
Sp3	{M}Td(2m1ub)	0	0	0	0	0	0
Sp3	{M}Tf(Hmd)	0	0	0	0	1	0
Sp3	{M}Tf(Ium)	0	0	0	0	0	1
Sp3	{M}Tf(2fm)	0	0	0	0	0	0
Sp3	{M}Tf(2md)	0	0	0	0	1	0
Sp3	{M}Tm(Iub)	0	0	0	0	0	0
Sp3	{M}Tm(2mb)	0	0	0	0	0	0
Sp3	{M}(Ium)Tm(2um)>(Ium)Ta(2um)	2	0	0	0	0	0
Sp3	{M}Tu(Hfd)	0	0	0	0	1	0
Sp3	{M}Tu(2fm)	0	0	0	0	0	0
Sp3	{M}Tu(2um)	0	0	0	0	0	0
Sp3	{M}R+x(Hfd)	0	0	1	0	0	0
Sp3	{M}R+x(2fd)	0	0	0	0	0	0
Sp3	{M}R+x(2fm)	0	0	0	0	0	0
Sp3	{M}R-x(2f1um)	0	0	1	0	0	0
Sp3	{M}R-x(2u1bm)	0	0	0	0	1	0
Sp3	{M}R+z(Cdd)	0	0	1	0	0	0
Sp3	{M}R+z(1d2df)	0	0	0	0	0	0
Sp3	{M}R+z(2dd)	0	0	1	0	0	0
Sp3	{M}R+z(2mb)	0	0	2	0	0	0
Sp3	{M}R-z(2u1uu)	0	0	1	0	0	0
Sp3	{M}O+y(2mb)	0	0	1	0	0	0
Sp4	{F}Hfd	0	0	0	0	1	0
Sp4	{F}Hfu	0	0	0	0	1	0
Sp4	{F}Hmd	0	0	0	0	3	0
Sp4	{F}Ifm	0	0	0	0	0	0
Sp4	{F}Imb	0	0	0	0	0	1
Sp4	{F}Iub	0	0	0	0	0	1
Sp4	{F}Iuf	0	0	0	0	0	1
Sp4	{F}Ium	0	0	0	0	0	5

Sp4	{F}2db	0	0	0	0	0	0
Sp4	{F}2fd	0	3	0	0	0	0
Sp4	{F}2fm	0	1	0	0	0	0
Sp4	{F}2mb	0	0	1	0	0	0
Sp4	{F}2md	0	0	0	0	0	0
Sp4	{F}2ub	0	1	0	0	0	0
Sp4	{F}2um	0	0	0	0	0	0
Sp4	{F}(2um)(2md)	0	0	0	0	0	0
Sp4	{M}Ta(Pfd)Ta(Pfd)	0	1	0	0	0	0
Sp4	{M}Ta(2fd)	0	0	0	0	0	0
Sp4	{M}Tb(Gdd)Tf(Gdd)	1	0	0	0	0	0
Sp4	{M}Td(Gmm)>Tu(Gmm)	0	0	0	0	0	0
Sp4	{M}Td(Ifm)	0	0	0	0	0	0
Sp4	{M}Td(Imb)	0	0	0	1	0	2
Sp4	{M}Td(Pfd)Tu(Pfd)	1	0	0	0	0	0
Sp4	{M}Td(Pfu)Tu(Pfd)>(Pfd)(Pfu)	1	0	0	0	0	0
Sp4	{M}Td(2db)	0	0	0	0	0	0
Sp4	{M}Tf(Gdd)Tb(Gdd)	2	0	0	0	0	0
Sp4	{M}Tf(Hmd)	0	0	0	0	1	0
Sp4	{M}(Imb)R+x(Imb)	0	0	0	0	0	0
Sp4	{M}(Ium)R+x(2fd)	0	0	1	0	0	0
Sp4	{M}R-x(Hfd)	0	0	0	0	0	0
Sp4	{M}R+y(Cmm)	0	0	0	0	0	0
Sp4	{M}(Ium)R+y(Cmm)	0	0	2	0	0	0
Sp4	{M}(Imb)R+y(Imf)	0	0	0	0	0	0
Sp4	{M}R+z(Cdd)	0	0	2	0	0	0
Sp4	{M}R+z(Gda)	0	0	3	0	0	0
Sp4	{M}R-z(Gdd)R-z(Gdd)	1	0	0	0	0	0
Sp4	{M}R-z(Gmm)R-z(Gmm)	0	0	0	0	0	0
Sp4	{M}R-z(2md)	0	0	0	0	0	0
Sp4	{M}(Cmm)R-z(Cmm)	0	0	1	0	0	0
Sp4	{M}(Gmm)R+z(2mb)	0	0	1	0	0	0
Sp4	{M}O-y(2mb)	0	0	0	0	0	0
Sp5	{F}Hfd	0	0	0	1	3	0
Sp5	{F}Hmd	0	0	0	0	1	0
Sp5	{F}Ifm	0	0	0	0	0	3
Sp5	{F}Imb	0	0	0	0	0	1
Sp5	{F}(Imb)(Hfd)	0	0	0	0	1	0
Sp5	{F}Ium	0	0	0	0	0	0
Sp5	{F}2db	0	1	1	0	0	1
Sp5	{F}2fd	0	0	1	0	0	0

Sp5	{F}2mb	0	0	0	0	0	0
Sp5	{F}2md	0	0	0	0	0	0
Sp5	{M}Ta(Hfd)	0	0	0	0	1	0
Sp5	{M}Ta(Hmd)	0	0	0	0	1	0
Sp5	{M}Td(Gmm)	0	0	0	0	0	0
Sp5	{M}Td(Ifm)	1	0	0	0	0	5
Sp5	{M}Td(Imb)	0	0	0	0	0	1
Sp5	{M}Td(2db)	0	0	2	0	0	0
Sp5	{M}Td(2db)>Td(Tub)	0	0	0	0	0	0
Sp5	{M}Td(2fd)	0	1	0	0	0	0
Sp5	{M}Td(2fm)	0	0	0	0	0	0
Sp5	{M}Td(2md)	0	1	0	0	0	0
Sp5	{M}Td(2um)	0	2	0	0	0	0
Sp5	{M}Tf(2fd)	0	0	0	0	0	0
Sp5	{M}Tm(Gmm)Tm(Gmm)>Ta(Gaa)Ta(Gaa)	3	0	0	0	0	0
Sp5	{M}Tm(Hfd)	0	0	0	0	0	0
Sp5	{M}Tm(Hfu)	0	0	0	0	1	0
Sp5	{M}Tm(Hmd)	0	0	0	0	0	0
Sp5	{M}Tu(Gmm)Td(Gmm)	1	0	0	0	0	0
Sp5	{M}Tu(2fd)	0	1	0	0	0	0
Sp5	{M}R+x(Cff)	0	0	1	0	0	0
Sp5	{M}R+x(Hfd)	0	0	0	0	0	0
Sp5	{M}R+z(2da)	0	0	1	0	0	0
Sp5	{M}R-z(Cdd)	0	0	1	0	0	0
Sp5	{M}R-z(Gdd)	0	1	0	0	0	0
Sp5	{M}R-z(Gmm)R-z(Gmm)	0	0	1	0	0	0
Sp5	{M}O+y(2mb)	0	0	1	0	0	0
Sp5	{M}O+z(2db)	0	0	2	0	0	0
Fa1	{F}Ifm	0	0	0	0	0	0
Fa1	{F}(Ifm)(Ifm)	0	0	0	0	0	0
Fa1	{F}Imb	0	0	0	0	0	0
Fa1	{F}Ium	0	0	0	0	0	0
Fa1	{F}2fm	0	0	0	0	0	0
Fa1	{M}Ta(Hfu)	0	0	0	0	0	0
Fa1	{M}Ta(Hmd)	0	0	0	0	1	0
Fa1	{M}Ta(2dd)	0	0	0	0	0	0
Fa1	{M}Tb(2dd)	0	0	0	0	0	0
Fa1	{M}Tb(2fm)	0	0	0	0	0	0
Fa1	{M}Td(Ifm)	0	0	0	0	0	0
Fa1	{M}Td(2db)	0	0	0	0	0	0

Fa1	{M}Tf(G12mm)	1	0	0	0	0	0
Fa1	{M}Tf(Hmd)	0	0	0	0	1	0
Fa1	{M}Tf(2md)	1	0	0	0	1	0
Fa1	{M}Tm(Hfu)	0	0	0	0	0	0
Fa1	{M}R-x(Ifm)R-x(Ifm)	0	0	0	0	0	0
Fa1	{M}(2u1uu)R+y(2m1mm)	0	0	1	0	0	0
Fa1	{M}(Pfm)R-z(2mm>2bb)	0	0	1	0	0	0
Fa2	{F}Hmd	0	0	0	0	1	0
Fa2	{F}Gdd	0	1	1	0	0	0
Fa2	{F}Iba	0	0	0	1	0	0
Fa2	{F}Ifm	0	0	0	1	0	1
Fa2	{F}Imb	0	0	0	0	0	1
Fa2	{F}Ium	0	0	0	0	0	0
Fa2	{F}2db	0	1	0	0	0	0
Fa2	{F}2dd	0	0	0	0	0	0
Fa2	{F}2d1mb	0	1	0	0	0	0
Fa2	{F}2d1md	0	0	0	0	0	0
Fa2	{F}2f1ff	0	1	0	0	0	0
Fa2	{F}2u1fu	0	1	0	0	0	0
Fa2	{M}Ta(Hfd)	0	0	0	0	0	0
Fa2	{M}Tb(2f1um)	0	0	0	0	0	0
Fa2	{M}Tb(2dd)	0	0	0	0	0	1
Fa2	{M}Td(Iba)	0	0	0	1	0	0
Fa2	{M}Td(Ifm)	0	0	0	0	0	1
Fa2	{M}Td(Imb)	0	0	0	0	0	2
Fa2	{M}Td(2dd)	0	0	0	0	0	0
Fa2	{M}Td(2mm)	0	0	0	0	1	0
Fa2	{M}Tf(Hmd)	0	0	0	0	1	0
Fa2	{M}Tf(Ifm)	0	0	0	1	0	1
Fa2	{M}Tm(Gbb)Tm(Gbb)>Ta(Gbb)Ta(Gbb)	1	0	0	0	0	0
Fa2	{M}Tu(Gff)	0	0	0	0	1	0
Fa2	{M}Tu(2mm)	0	0	0	0	1	0
Fa2	{M}R-y(2mm)	0	0	0	0	0	0
Fa2	{M}R+z(1d2dd)	0	0	1	0	0	0
Fa2	{M}R+z(Cdd)	0	0	2	0	0	0
Fa2	{M}R+z(Hmd)	0	0	0	0	1	0
Fa2	{M}R+z(2um)	0	0	1	0	0	0
Fa2	{M}R-z(2dd)	0	0	1	0	0	0
Fa2	{M}R-z(Cdd)	0	0	1	0	0	0
Fa2	{M}R-z(Cmm>Cbb)	0	0	3	0	0	0
Fa2	{M}R-z(Gdd)	0	0	1	0	0	0
Fa2	{M}R-z(2um)	0	0	1	0	0	0

APPENDIX I. GESTURAL FORM-NOTION HEAT MAPS

To accommodate the guidelines for page dimensions, the heat maps originally published elsewhere have been modified.[25] Heat maps for each participant have now been split into separate tables, with one table showing overlap between gestural forms and notions and the other showing overlap between gestural forms and *parent* notions.

Table 21 Gestural form-notion overlap heatmap for participant Sp1. Parent notions excluded. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Inversion	Principal axis	Rotation	Dihedral	Horizontal	Vertical
Sp1	{F}Hfd	0	0	0	0	2	0
Sp1	{F}Hmd	0	0	0	0	7	0
Sp1	{F}(Hmd)(Hmd)	0	0	0	0	1	0
Sp1	{F}Gmm	1	0	0	0	0	0
Sp1	{F}(Gmm)(Gmm)	1	0	0	0	0	0
Sp1	{F}Iaf	0	0	0	0	0	0
Sp1	{F}Ida	0	0	0	0	0	1
Sp1	{F}Idb	0	0	0	1	0	1
Sp1	{F}Idm	0	0	0	0	0	1
Sp1	{F}Ifm	0	0	0	0	0	5
Sp1	{F}Imb	0	0	0	1	0	2
Sp1	{F}Iua	0	0	0	0	0	1
Sp1	{F}Iuf	0	0	0	0	0	1
Sp1	{F}Ium	0	3	0	0	0	5
Sp1	{F}2da	0	2	1	0	0	0
Sp1	{F}2db	0	0	0	0	0	0
Sp1	{F}2fa	0	0	0	0	0	0
Sp1	{F}2fd	0	0	0	0	1	0
Sp1	{F}2fm	0	0	1	0	0	0
Sp1	{F}2fu	0	0	0	0	0	0
Sp1	{F}2f1um	0	0	1	0	0	0
Sp1	{F}2f1md	0	0	0	0	0	0
Sp1	{F}2mb	0	0	0	0	0	0
Sp1	{F}2md	0	0	0	0	0	0
Sp1	{F}2m1df	0	1	0	0	0	0
Sp1	{F}2um	0	3	0	0	0	0
Sp1	{F}(2um)(1d2mf)	0	1	0	0	0	0
Sp1	{F}2d3db	0	0	0	0	0	2
Sp1	{M}Ta(2fd)	0	0	0	0	0	1
Sp1	{M}Ta(2mb)	0	1	0	0	0	1
Sp1	{M}(Guu)Ta(Guu)	0	0	0	0	0	0
Sp1	{M}Tb(2fm)	0	0	0	1	0	0
Sp1	{M}Td(Ifm)	0	0	0	0	0	0
Sp1	{M}Td(Imb)	1	1	0	0	0	0
Sp1	{M}Td(Ium)	0	0	0	0	0	0
Sp1	{M}Td(2ub)	0	0	0	0	0	0
Sp1	{M}Tf(Gmm)	1	0	0	0	0	0

Sp1	{M}Tf(G12mm)	0	0	0	0	0	0
Sp1	{M}Tf(Ium)(Ium)>Tb(Ium)(Ium)	0	0	0	0	0	0
Sp1	{M}Tf(2fm)	0	0	0	1	0	0
Sp1	{M}Tm(Cmm>Gmm)Tm(Cmm>Gmm)	1	0	0	0	0	0
Sp1	{M}Tm(Gmm)Tm(Gmm)>Ta(Gaa)Ta(Gaa)	1	0	0	0	0	0
Sp1	{M}Tm(G12uu)(Ium)	0	0	0	0	0	0
Sp1	{M}Tm(Iub)	0	0	0	0	0	1
Sp1	{M}Tm(2mb)	0	0	0	0	0	0
Sp1	{M}Tu(Ium)	0	1	0	0	0	0
Sp1	{M}Tu(Ium)(Ium)>Td(Ium)Ium)	0	0	0	0	0	0
Sp1	{M}Tu(2um)	0	2	0	0	0	0
Sp1	{M}R+x(Cmm)	0	0	0	0	0	0
Sp1	{M}R+x(Hfd)	0	0	2	0	0	0
Sp1	{M}R+x(Hmd)	0	0	0	0	0	0
Sp1	{M}R+x(2bb)	0	0	1	0	0	0
Sp1	{M}R+x(2db)(Ifm)	0	0	0	0	0	0
Sp1	{M}R+x(2fd)	0	0	0	0	0	0
Sp1	{M}R+x(2f1md)	0	0	1	0	0	0
Sp1	{M}R+x(2mb)	0	0	0	0	0	0
Sp1	{M}R-x(Hfd)	0	0	0	0	1	0
Sp1	{M}R+z(Cff)	0	0	1	0	0	0
Sp1	{M}R+z(Cuu)	0	0	1	0	0	0
Sp1	{M}R+z(Cdd)	0	0	1	0	0	0
Sp1	{M}R+z(Had)	0	0	0	0	1	0
Sp1	{M}R+z(Ifm)	0	0	0	0	0	0
Sp1	{M}R+z(2ub)(2da)	0	2	2	0	0	0
Sp1	{M}R+z(2um)	0	0	1	0	0	0
Sp1	{M}R-z(Cdd)	0	0	1	0	0	0
Sp1	{M}R-z(Cub)	0	0	1	0	0	0
Sp1	{M}R-z(Had)	0	0	0	0	1	0
Sp1	{M}R-z(Iuf)	0	0	1	0	0	0
Sp1	{M}R-z(2d3db)	0	0	0	0	0	0
Sp1	{M}R-z(2uCmm)	0	0	1	0	0	0
Sp1	{M}R-z(2um)	0	0	1	0	0	0
Sp1	{M}(Cmm)R-z(Cff)	0	0	1	0	0	0
Sp1	{M}(Cmm)R-z(Cmm)	0	0	4	0	0	0
Sp1	{M}(Ifm)R-z(Ifm)	0	0	0	1	0	1
Sp1	{M}O+y(2mb)	0	0	1	0	0	0

Table 22 Gestural form-notion overlap heatmap for participant Sp1. Parent notions only. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Mirror plane (Parent)	Proper Rotation (Parent)	Improper Rotation (Parent)	Axis (Parent)
Sp1	{F}Hfd	2	0	0	0
Sp1	{F}Hmd	2	1	0	0
Sp1	{F}(Hmd)(Hmd)	0	0	0	0
Sp1	{F}Gmm	0	0	0	0
Sp1	{F}(Gmm)(Gmm)	0	0	0	0
Sp1	{F}Iaf	2	0	0	0
Sp1	{F}Ida	0	0	0	0
Sp1	{F}Idb	2	0	0	0
Sp1	{F}Idm	0	0	0	0
Sp1	{F}Ifm	14	0	0	0
Sp1	{F}Imb	7	0	0	0
Sp1	{F}Iua	0	0	0	0
Sp1	{F}Iuf	0	0	0	0
Sp1	{F}Ium	4	0	0	1
Sp1	{F}2da	0	1	0	1
Sp1	{F}2db	0	0	0	2
Sp1	{F}2fa	0	1	0	0
Sp1	{F}2fd	0	2	0	0
Sp1	{F}2fm	0	0	0	2
Sp1	{F}2fu	0	0	0	1
Sp1	{F}2f1um	0	0	0	3
Sp1	{F}2f1md	0	0	0	1
Sp1	{F}2mb	0	0	0	4
Sp1	{F}2md	0	1	0	0
Sp1	{F}2m1df	0	0	0	1
Sp1	{F}2um	0	0	0	4
Sp1	{F}(2um)(1d2mf)	0	0	0	1
Sp1	{F}2d3db	0	0	0	0
Sp1	{M}Ta(2fd)	0	0	0	0
Sp1	{M}Ta(2mb)	0	0	0	0
Sp1	{M}(Guu)Ta(Guu)	1	0	0	0
Sp1	{M}Tb(2fm)	0	0	0	0
Sp1	{M}Td(Ifm)	3	0	0	0
Sp1	{M}Td(Imb)	0	0	0	0
Sp1	{M}Td(Ium)	0	0	0	1
Sp1	{M}Td(2ub)	0	0	0	1

Sp1	{M}Tf(Gmm)	0	0	0	0
Sp1	{M}Tf(G12mm)	0	0	0	1
Sp1	{M}Tf(Ium)(Ium)>Tb(Ium)(Ium)	1	0	0	0
Sp1	{M}Tf(2fm)	0	0	0	0
Sp1	{M}Tm(Cmm>Gmm)Tm(Cmm>Gmm)	0	0	0	0
Sp1	{M}Tm(Gmm)Tm(Gmm)>Ta(Gaa)Ta(Gaa)	0	0	0	0
Sp1	{M}Tm(G12uu)(Ium)	1	0	0	0
Sp1	{M}Tm(Iub)	0	0	0	0
Sp1	{M}Tm(2mb)	0	0	0	1
Sp1	{M}Tu(Ium)	0	0	0	1
Sp1	{M}Tu(Ium)(Ium)>Td(Ium)Ium)	1	0	0	0
Sp1	{M}Tu(2um)	0	0	0	2
Sp1	{M}R+x(Cmm)	0	1	0	0
Sp1	{M}R+x(Hfd)	0	0	0	0
Sp1	{M}R+x(Hmd)	0	1	0	0
Sp1	{M}R+x(2bb)	0	0	0	0
Sp1	{M}R+x(2db)(Ifm)	1	0	0	0
Sp1	{M}R+x(2fd)	0	1	0	0
Sp1	{M}R+x(2f1md)	0	0	0	0
Sp1	{M}R+x(2mb)	0	0	0	1
Sp1	{M}R-x(Hfd)	1	1	0	0
Sp1	{M}R+z(Cff)	0	0	0	0
Sp1	{M}R+z(Cuu)	0	0	0	0
Sp1	{M}R+z(Cdd)	0	1	0	0
Sp1	{M}R+z(Had)	0	0	0	0
Sp1	{M}R+z(Ifm)	2	0	0	0
Sp1	{M}R+z(2ub)(2da)	0	0	0	0
Sp1	{M}R+z(2um)	0	0	0	0
Sp1	{M}R-z(Cdd)	0	0	0	0
Sp1	{M}R-z(Cub)	0	0	0	0
Sp1	{M}R-z(Had)	0	0	0	0
Sp1	{M}R-z(Iuf)	0	0	0	0
Sp1	{M}R-z(2d3db)	0	2	0	0
Sp1	{M}R-z(2uCmm)	0	0	0	0
Sp1	{M}R-z(2um)	0	0	0	0
Sp1	{M}(Cmm)R-z(Cff)	0	1	0	0
Sp1	{M}(Cmm)R-z(Cmm)	0	2	0	0
Sp1	{M}(Ifm)R-z(Ifm)	0	0	0	0
Sp1	{M}O+y(2mb)	0	0	0	0

Table 23 Gestural form-notion overlap heatmap for participant Sp2. Parent notions excluded. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Inversion	Principal axis	Rotation	Dihedral	Horizontal	Vertical
Sp2	{F}Hau	0	0	0	0	1	0
Sp2	{F}Hfu	0	0	0	0	3	0
Sp2	{F}Idb	0	0	0	0	0	1
Sp2	{F}Ifm	0	0	0	0	0	0
Sp2	{F}Iub	0	0	0	0	0	1
Sp2	{F}Ium	0	0	0	0	0	0
Sp2	{F}2db	0	0	0	0	0	0
Sp2	{M}Ta(Hfd)	0	0	0	0	0	0
Sp2	{M}Ta(Hmd)	0	0	0	0	1	0
Sp2	{M}Td(Iaf)	0	0	0	0	0	0
Sp2	{M}Ta(Imb)Tu(Iuf)	0	0	0	0	0	0
Sp2	{M}Tb(Ibm)	0	0	0	0	0	0
Sp2	{M}Tb(2fd)	0	0	0	0	1	0
Sp2	{M}Tb(2md)	0	0	0	0	1	0
Sp2	{M}Td(Hfu)	0	0	0	1	0	0
Sp2	{M}Td(Ifm)	0	0	0	0	0	2
Sp2	{M}Td(Imb)	0	0	0	0	0	1
Sp2	{M}Td(Iub)	0	0	0	0	0	1
Sp2	{M}Td(Ium)	0	0	0	0	0	2
Sp2	{M}Td(2m1ub)	0	0	0	0	0	1
Sp2	{M}Td(2uf)	0	0	0	0	0	1
Sp2	{M}Tf(Hfu)	0	0	0	0	0	0
Sp2	{M}Tf(2dd)Tb(2dd)	1	0	0	0	0	0
Sp2	{M}Tf(2fd)	0	0	0	0	1	0
Sp2	{M}Tm(Hmd)	0	0	0	0	1	0
Sp2	{M}Tu(Ium)	0	0	0	0	0	1
Sp2	{M}Tu(2m1ub)	0	0	0	0	0	1
Sp2	{M}R-x(Cdd)R-x(Cuu)	0	0	1	0	0	0
Sp2	{M}R-x(2f3fd)	2	0	1	0	0	0
Sp2	{M}R+z(Cdd)	0	0	1	0	0	0
Sp2	{M}R+z(Hmd)	0	0	0	0	0	1
Sp2	{M}R-z(Cuu)	0	0	1	0	0	0
Sp2	{M}R-z(Iuf)	0	0	0	0	0	0
Sp2	{M}O+y(2mb)	0	0	1	0	0	0

Table 24 Gestural form-notion overlap heatmap for participant Sp2. Parent notions only. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Mirror plane (Parent)	Proper Rotation (Parent)	Improper Rotation (Parent)	Axis (Parent)
Sp2	{F}Hau	0	0	0	0
Sp2	{F}Hfu	0	0	0	0
Sp2	{F}Idb	0	0	0	0
Sp2	{F}Ifm	2	0	0	0
Sp2	{F}Iub	2	0	0	0
Sp2	{F}Ium	1	0	0	1
Sp2	{F}2db	0	0	0	2
Sp2	{M}Ta(Hfd)	1	0	0	0
Sp2	{M}Ta(Hmd)	0	0	0	0
Sp2	{M}Td(Iaf)	1	0	0	0
Sp2	{M}Ta(Imb)Tu(Iuf)	1	0	0	0
Sp2	{M}Tb(Ibm)	0	0	0	1
Sp2	{M}Tb(2fd)	0	0	0	0
Sp2	{M}Tb(2md)	0	0	0	0
Sp2	{M}Td(Hfu)	0	0	0	0
Sp2	{M}Td(Ifm)	1	0	0	1
Sp2	{M}Td(Imb)	0	0	0	0
Sp2	{M}Td(Iub)	0	0	0	0
Sp2	{M}Td(Ium)	0	0	0	0
Sp2	{M}Td(2m1ub)	0	0	0	0
Sp2	{M}Td(2uf)	0	0	0	0
Sp2	{M}Tf(Hfu)	0	0	0	1
Sp2	{M}Tf(2dd)Tb(2dd)	0	0	0	0
Sp2	{M}Tf(2fd)	0	0	0	0
Sp2	{M}Tm(Hmd)	0	0	0	1
Sp2	{M}Tu(Ium)	1	0	0	2
Sp2	{M}Tu(2m1ub)	0	0	0	0
Sp2	{M}R-x(Cdd)R-x(Cuu)	0	0	0	0
Sp2	{M}R-x(2f3fd)	0	0	0	0
Sp2	{M}R+z(Cdd)	0	0	0	0
Sp2	{M}R+z(Hmd)	0	0	0	0
Sp2	{M}R-z(Cuu)	0	0	0	0
Sp2	{M}R-z(Iuf)	1	0	0	0
Sp2	{M}O+y(2mb)	0	0	0	0

Table 25 Gestural form-notion overlap heatmap for participant Sp3. Parent notions excluded. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Inversion	Principal axis	Rotation	Dihedral	Horizontal	Vertical
Sp3	{F}Hfu	0	0	0	0	0	0
Sp3	{F}Hmd	0	0	0	0	1	0
Sp3	{F}(Gfu)(Gmd)	0	0	0	0	0	0
Sp3	{F}Ifm	0	0	0	2	1	2
Sp3	{F}(Ifm)(Imb)	0	0	0	0	0	0
Sp3	{F}(Ifm)(Ifm)	0	0	0	1	1	0
Sp3	{F}Imb	0	0	0	1	0	1
Sp3	{F}Ium	0	0	0	0	0	1
Sp3	{F}2db	0	1	0	0	1	0
Sp3	{F}2fd	0	0	0	0	0	0
Sp3	{F}2fm	0	0	0	0	0	0
Sp3	{F}2mb	0	0	0	0	0	0
Sp3	{F}(2md)(2um)	0	0	0	0	0	0
Sp3	{F}2ub	0	2	0	0	1	0
Sp3	{F}(2uf)(1d2df)	0	0	0	0	0	0
Sp3	{F}2u3mm	0	0	0	0	0	0
Sp3	{M}Ta(Hfd)	0	0	0	0	2	0
Sp3	{M}Td(2m1ub)	0	0	0	0	0	0
Sp3	{M}Tf(Hmd)	0	0	0	0	1	0
Sp3	{M}Tf(Ium)	0	0	0	0	0	1
Sp3	{M}Tf(2fm)	0	0	0	0	0	0
Sp3	{M}Tf(2md)	0	0	0	0	1	0
Sp3	{M}(Ium)Tm(2um)>(Ium)Ta(2um)	2	0	0	0	0	0
Sp3	{M}Tu(Hfd)	0	0	0	0	1	0
Sp3	{M}Tu(2fm)	0	0	0	0	0	0
Sp3	{M}Tu(2um)	0	0	0	0	0	0
Sp3	{M}R+x(Hfd)	0	0	1	0	0	0
Sp3	{M}R+x(2fd)	0	0	0	0	0	0
Sp3	{M}R+x(2fm)	0	0	0	0	0	0
Sp3	{M}R-x(2f1um)	0	0	1	0	0	0
Sp3	{M}R-x(2u1bm)	0	0	0	0	1	0
Sp3	{M}R+z(Cdd)	0	0	1	0	0	0
Sp3	{M}R+z(2dd)	0	0	1	0	0	0
Sp3	{M}R+z(2mb)	0	0	2	0	0	0
Sp3	{M}R-z(2u1uu)	0	0	1	0	0	0
Sp3	{M}O+y(2mb)	0	0	1	0	0	0

Table 26 Gestural form-notion overlap heatmap for participant Sp3. Parent notions only. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Mirror plane (Parent)	Proper Rotation (Parent)	Improper Rotation (Parent)	Axis (Parent)
Sp3	{F}Hfu	1	0	0	0
Sp3	{F}Hmd	2	0	0	0
Sp3	{F}(Gfu)(Gmd)	0	0	0	1
Sp3	{F}Ifm	4	0	0	0
Sp3	{F}(Ifm)(Imb)	2	0	0	0
Sp3	{F}(Ifm)(Ifm)	0	0	0	0
Sp3	{F}Imb	3	0	0	0
Sp3	{F}2db	0	0	0	1
Sp3	{F}2fd	0	0	0	1
Sp3	{F}2fm	0	0	0	5
Sp3	{F}2mb	0	0	0	2
Sp3	{F}(2md)(2um)	0	0	0	1
Sp3	{F}2ub	0	1	0	8
Sp3	{F}(2uf)(1d2df)	0	0	0	1
Sp3	{F}2u3mm	0	0	0	1
Sp3	{M}Ta(Hfd)	1	0	0	0
Sp3	{M}Tb(Imb)(Imb)>Tf(Imb)(Imb)>(Imb)Tf(Imb)	2	0	0	0
Sp3	{M}Tb(2fd)	0	0	0	1
Sp3	{M}Td(Ifm)	1	0	0	0
Sp3	{M}Td(2fm)	1	0	0	1
Sp3	{M}Td(2mb)	0	1	0	1
Sp3	{M}Td(2m1ub)	1	0	0	0
Sp3	{M}Tf(Hmd)	1	0	0	0
Sp3	{M}Tf(2fm)	0	0	0	2
Sp3	{M}Tm(Iub)	1	0	0	0
Sp3	{M}Tm(2mb)	1	0	0	0
Sp3	{M}Tu(Hfd)	1	0	0	0
Sp3	{M}Tu(2fm)	1	0	0	0
Sp3	{M}Tu(2um)	0	0	0	1
Sp3	{M}R+x(2fd)	0	0	0	1
Sp3	{M}R+x(2fm)	0	0	0	2
Sp3	{M}R-x(2f1um)	0	1	0	0
Sp3	{M}R+z(Cdd)	0	0	0	1
Sp3	{M}R+z(1d2df)	0	1	0	0

Table 27 Gestural form-notion overlap heatmap for participant Sp4. Parent notions excluded. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Inversion	Principal axis	Rotation	Dihedral	Horizontal	Vertical
Sp4	{F}Hfd	0	0	0	0	1	0
Sp4	{F}Hfu	0	0	0	0	1	0
Sp4	{F}Hmd	0	0	0	0	3	0
Sp4	{F}Ifm	0	0	0	0	0	0
Sp4	{F}Imb	0	0	0	0	0	1
Sp4	{F}Iub	0	0	0	0	0	1
Sp4	{F}Iuf	0	0	0	0	0	1
Sp4	{F}Ium	0	0	0	0	0	5
Sp4	{F}2db	0	0	0	0	0	0
Sp4	{F}2fd	0	3	0	0	0	0
Sp4	{F}2fm	0	1	0	0	0	0
Sp4	{F}2mb	0	0	1	0	0	0
Sp4	{F}2md	0	0	0	0	0	0
Sp4	{F}2ub	0	1	0	0	0	0
Sp4	{F}2um	0	0	0	0	0	0
Sp4	{F}(2um)(2md)	0	0	0	0	0	0
Sp4	{M}Ta(Pfd)Ta(Pfd)	0	1	0	0	0	0
Sp4	{M}Ta(2fd)	0	0	0	0	0	0
Sp4	{M}Tb(Gdd)Tf(Gdd)	1	0	0	0	0	0
Sp4	{M}Td(Gmm)>Tu(Gmm)	0	0	0	0	0	0
Sp4	{M}Td(Ifm)	0	0	0	0	0	0
Sp4	{M}Td(Imb)	0	0	0	1	0	2
Sp4	{M}Td(Pfd)Tu(Pfd)	1	0	0	0	0	0
Sp4	{M}Td(Pfu)Tu(Pfd)>(Pfd)(Pfu)	1	0	0	0	0	0
Sp4	{M}Td(2db)	0	0	0	0	0	0
Sp4	{M}Tf(Gdd)Tb(Gdd)	2	0	0	0	0	0
Sp4	{M}Tf(Hmd)	0	0	0	0	1	0
Sp4	{M}(Imb)R+x(Imb)	0	0	0	0	0	0
Sp4	{M}(Ium)R+x(2fd)	0	0	1	0	0	0
Sp4	{M}(Ium)R+y(Cmm)	0	0	2	0	0	0
Sp4	{M}R+z(Cdd)	0	0	2	0	0	0
Sp4	{M}R+z(Gda)	0	0	3	0	0	0
Sp4	{M}R-z(Gdd)R-z(Gdd)	1	0	0	0	0	0
Sp4	{M}(Cmm)R-z(Cmm)	0	0	1	0	0	0
Sp4	{M}(Gmm)R+z(2mb)	0	0	1	0	0	0
Sp4	{M}O-y(2mb)	0	0	0	0	0	0

Table 28 Gestural form-notion overlap heatmap for participant Sp4. Parent notions only. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Mirror plane (Parent)	Proper Rotation (Parent)	Improper Rotation (Parent)	Axis (Parent)
Sp4	{F}Hfd	0	0	0	0
Sp4	{F}Hfu	0	0	0	0
Sp4	{F}Hmd	3	0	1	1
Sp4	{F}Ifm	1	0	0	0
Sp4	{F}Imb	3	0	0	0
Sp4	{F}Iub	0	0	0	0
Sp4	{F}Iuf	0	0	0	0
Sp4	{F}Ium	3	0	0	2
Sp4	{F}2db	0	0	0	2
Sp4	{F}2fd	0	0	1	1
Sp4	{F}2fm	0	1	0	2
Sp4	{F}2mb	0	0	0	3
Sp4	{F}2md	0	0	0	1
Sp4	{F}2ub	0	0	0	0
Sp4	{F}2um	0	0	0	1
Sp4	{F}(2um)(2md)	0	0	0	1
Sp4	{M}Ta(Pfd)Ta(Pfd)	0	0	0	0
Sp4	{M}Ta(2fd)	0	0	0	1
Sp4	{M}Tb(Gdd)Tf(Gdd)	0	0	0	0
Sp4	{M}Td(Gmm)>Tu(Gmm)	0	0	1	0
Sp4	{M}Td(Ifm)	2	0	0	0
Sp4	{M}Td(Imb)	0	0	0	0
Sp4	{M}Td(Pfd)Tu(Pfd)	0	0	2	0
Sp4	{M}Td(Pfu)Tu(Pfd)>(Pfd)(Pfu)	0	0	0	0
Sp4	{M}Td(2db)	1	0	0	0
Sp4	{M}Tf(Gdd)Tb(Gdd)	0	0	0	0
Sp4	{M}(Imb)R+x(Imb)	0	0	1	0
Sp4	{M}(Ium)R+x(2fd)	0	0	0	0
Sp4	{M}R-x(Hfd)	0	1	0	0
Sp4	{M}R+y(Cmm)	0	0	1	0
Sp4	{M}(Imb)R+y(Imf)	0	0	1	0
Sp4	{M}R-z(Gmm)R-z(Gmm)	0	0	1	0
Sp4	{M}R-z(2md)	1	0	0	0
Sp4	{M}(Cmm)R-z(Cmm)	0	0	0	0
Sp4	{M}(Gmm)R+z(2mb)	0	0	0	0
Sp4	{M}O-y(2mb)	0	0	0	1

Table 29 Gestural form-notion overlap heatmap for participant Sp5. Parent notions excluded. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Inversion	Principal axis	Rotation	Dihedral	Horizontal	Vertical
Sp5	{F}Hmd	0	0	0	0	1	0
Sp5	{F}Ifm	0	0	0	0	0	3
Sp5	{F}Imb	0	0	0	0	0	1
Sp5	{F}(Imb)(Hfd)	0	0	0	0	1	0
Sp5	{F}Ium	0	0	0	0	0	0
Sp5	{F}2db	0	1	1	0	0	1
Sp5	{F}2fd	0	0	1	0	0	0
Sp5	{M}Ta(Hfd)	0	0	0	0	1	0
Sp5	{M}Ta(Hmd)	0	0	0	0	1	0
Sp5	{M}Td(Gmm)	0	0	0	0	0	0
Sp5	{M}Td(Ifm)	1	0	0	0	0	5
Sp5	{M}Td(Imb)	0	0	0	0	0	1
Sp5	{M}Td(2db)	0	0	2	0	0	0
Sp5	{M}Td(2db)>Td(Tub)	0	0	0	0	0	0
Sp5	{M}Td(2fd)	0	1	0	0	0	0
Sp5	{M}Td(2fm)	0	0	0	0	0	0
Sp5	{M}Td(2md)	0	1	0	0	0	0
Sp5	{M}Td(2um)	0	2	0	0	0	0
Sp5	{M}Tf(2fd)	0	0	0	0	0	0
Sp5	{M}Tm(Gmm)Tm(Gmm)>Ta(Gaa)Ta(Gaa)	3	0	0	0	0	0
Sp5	{M}Tm(Hfd)	0	0	0	0	0	0
Sp5	{M}Tm(Hfu)	0	0	0	0	1	0
Sp5	{M}Tm(Hmd)	0	0	0	0	0	0
Sp5	{M}Tu(Gmm)Td(Gmm)	1	0	0	0	0	0
Sp5	{M}Tu(2fd)	0	1	0	0	0	0
Sp5	{M}R+x(Cff)	0	0	1	0	0	0
Sp5	{M}R+x(Hfd)	0	0	0	0	0	0
Sp5	{M}R+z(2da)	0	0	1	0	0	0
Sp5	{M}R-z(Cdd)	0	0	1	0	0	0
Sp5	{M}R-z(Gdd)	0	1	0	0	0	0
Sp5	{M}R-z(Gmm)R-z(Gmm)	0	0	1	0	0	0
Sp5	{M}O+y(2mb)	0	0	1	0	0	0
Sp5	{M}O+z(2db)	0	0	2	0	0	0

Table 30 Gestural form-notion overlap heatmap for participant Sp5. Parent notions only. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Mirror plane (Parent)	Proper Rotation (Parent)	Improper Rotation (Parent)	Axis (Parent)
Sp5	{F}Hmd	3	0	0	0
Sp5	{F}Ifm	2	0	0	0
Sp5	{F}Imb	2	0	0	0
Sp5	{F}Ium	4	0	0	0
Sp5	{F}2db	0	0	0	2
Sp5	{F}2fd	0	0	0	1
Sp5	{F}2mb	0	0	0	2
Sp5	{F}2md	1	0	0	0
Sp5	{M}Ta(Hfd)	1	0	0	1
Sp5	{M}Ta(Hmd)	0	0	0	0
Sp5	{M}Td(Gmm)	0	0	0	1
Sp5	{M}Td(Ifm)	6	0	0	0
Sp5	{M}Td(Imb)	1	0	0	0
Sp5	{M}Td(2db)	0	0	0	4
Sp5	{M}Td(2db)>Td(Tub)	1	0	0	0
Sp5	{M}Td(2fd)	1	0	0	0
Sp5	{M}Td(2fm)	1	0	0	0
Sp5	{M}Td(2md)	0	0	0	0
Sp5	{M}Td(2um)	0	0	0	0
Sp5	{M}Tf(2fd)	0	0	0	1
Sp5	{M}Tm(Gmm)Tm(Gmm)>Ta(Gaa)Ta(Gaa)	0	0	0	0
Sp5	{M}Tm(Hfd)	1	0	0	0
Sp5	{M}Tm(Hfu)	0	0	0	0
Sp5	{M}Tm(Hmd)	1	0	0	0
Sp5	{M}Tu(Gmm)Td(Gmm)	0	0	0	0
Sp5	{M}R+x(Cff)	0	0	0	0
Sp5	{M}R+x(Hfd)	1	0	0	0
Sp5	{M}R+z(2da)	0	0	0	0
Sp5	{M}R-z(Cdd)	0	0	0	0
Sp5	{M}R-z(Gdd)	0	1	0	0
Sp5	{M}R-z(Gmm)R-z(Gmm)	0	0	0	0
Sp5	{M}O+y(2mb)	0	0	0	0
Sp5	{M}O+z(2db)	0	0	0	0

Table 31 Gestural form-notion overlap heatmap for participant Fa1. Parent notions excluded. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Inversion	Principal axis	Rotation	Dihedral	Horizontal	Vertical
Fa1	{F}Ifm	0	0	0	0	0	0
Fa1	{F}(Ifm)(Ifm)	0	0	0	0	0	0
Fa1	{F}Imb	0	0	0	0	0	0
Fa1	{F}Ium	0	0	0	0	0	0
Fa1	{F}2fm	0	0	0	0	0	0
Fa1	{M}Ta(Hfu)	0	0	0	0	0	0
Fa1	{M}Ta(Hmd)	0	0	0	0	1	0
Fa1	{M}Ta(2dd)	d	0	0	0	0	0
Fa1	{M}Tb(2dd)	0	0	0	0	0	0
Fa1	{M}Tb(2fm)	0	0	0	0	0	0
Fa1	{M}Td(Ifm)	0	0	0	0	0	0
Fa1	{M}Td(2db)	0	0	0	0	0	0
Fa1	{M}Td(2dd)	0	0	0	0	0	0
Fa1	{M}Td(2fd)	0	0	0	0	0	0
Fa1	{M}Td(2fm)	0	0	0	0	0	0
Fa1	{M}Tf(G12mm)	1	0	0	0	0	0
Fa1	{M}Tf(Hmd)	0	0	0	0	1	0
Fa1	{M}Tf(2md)	1	0	0	0	1	0
Fa1	{M}Tm(Hfu)	0	0	0	0	0	0
Fa1	{M}Tm(Iuf)	0	0	0	0	0	0
Fa1	{M}R-x(Ifm)R-x(Ifm)	0	0	0	0	0	0
Fa1	{M}(2u1uu)R+y(2m1mm)	0	0	1	0	0	0
Fa1	{M}(Pfm)R-z(2mm>2bb)	0	0	1	0	0	0

Table 32 Gestural form-notion overlap heatmap for participant Fa1. Parent notions only. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Mirror plane (Parent)	Proper Rotation (Parent)	Improper Rotation (Parent)	Axis (Parent)
Fa1	{F}Ifm	1	1	0	0
Fa1	{F}(Ifm)(Ifm)	0	2	0	0
Fa1	{F}Imb	1	0	0	0
Fa1	{F}Ium	1	0	0	0
Fa1	{F}2fm	0	0	0	1
Fa1	{M}Ta(Hfu)	1	0	0	0
Fa1	{M}Ta(Hmd)	0	0	0	0
Fa1	{M}Ta(2dd)	0	0	0	1
Fa1	{M}Tb(2dd)	0	0	0	1
Fa1	{M}Tb(2fm)	0	0	0	1
Fa1	{M}Td(Ifm)	1	1	0	1
Fa1	{M}Td(2db)	0	0	0	1
Fa1	{M}Td(2dd)	0	2	0	3
Fa1	{M}Td(2fd)	0	0	0	2
Fa1	{M}Td(2fm)	0	0	0	1
Fa1	{M}Tf(G12mm)	0	0	0	0
Fa1	{M}Tf(Hmd)	0	0	0	0
Fa1	{M}Tf(2md)	0	0	0	0
Fa1	{M}Tm(Hfu)	1	0	0	0
Fa1	{M}Tm(Iuf)	0	0	0	1
Fa1	{M}R-x(Ifm)R-x(Ifm)	0	1	0	0
Fa1	{M}(2u1uu)R+y(2m1mm)	0	0	0	0
Fa1	{M}(Pfm)R-z(2mm>2bb)	0	0	0	0

Table 33 Gestural form-notion overlap heatmap for participant Fa2. Parent notions excluded. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Inversion	Principal axis	Rotation	Dihedral	Horizontal	Vertical
Fa2	{F}Gdd	0	1	1	0	0	0
Fa2	{F}Iba	0	0	0	1	0	0
Fa2	{F}Ifm	0	0	0	1	0	1
Fa2	{F}Imb	0	0	0	0	0	1
Fa2	{F}Ium	0	0	0	0	0	0
Fa2	{F}2db	0	1	0	0	0	0
Fa2	{F}2dd	0	0	0	0	0	0
Fa2	{F}2d1mb	0	1	0	0	0	0
Fa2	{F}2d1md	0	0	0	0	0	0
Fa2	{F}2f1ff	0	1	0	0	0	0
Fa2	{F}2u1fu	0	1	0	0	0	0
Fa2	{M}Ta(Hfd)	0	0	0	0	0	0
Fa2	{M}Tb(2f1um)	0	0	0	0	0	0
Fa2	{M}Tb(2dd)	0	0	0	0	0	1
Fa2	{M}Td(Iba)	0	0	0	1	0	0
Fa2	{M}Td(Ifm)	0	0	0	0	0	1
Fa2	{M}Td(Imb)	0	0	0	0	0	2
Fa2	{M}Td(2dd)	0	0	0	0	0	0
Fa2	{M}Td(2mm)	0	0	0	0	1	0
Fa2	{M}Tf(Hmd)	0	0	0	0	1	0
Fa2	{M}Tf(Ifm)	0	0	0	1	0	1
Fa2	{M}Tm(Gbb)Tm(Gbb) >Ta(Gbb)Ta(Gbb)	1	0	0	0	0	0
Fa2	{M}Tu(Gff)	0	0	0	0	1	0
Fa2	{M}Tu(2mm)	0	0	0	0	1	0
Fa2	{M}R-y(2mm)	0	0	0	0	0	0
Fa2	{M}R+z(1d2dd)	0	0	1	0	0	0
Fa2	{M}R+z(Cdd)	0	0	2	0	0	0
Fa2	{M}R+z(Hmd)	0	0	0	0	1	0
Fa2	{M}R+z(2um)	0	0	1	0	0	0
Fa2	{M}R-z(2dd)	0	0	1	0	0	0
Fa2	{M}R-z(Cdd)	0	0	1	0	0	0
Fa2	{M}R-z(Cmm>Cbb)	0	0	3	0	0	0
Fa2	{M}R-z(Gdd)	0	0	1	0	0	0
Fa2	{M}R-z(2um)	0	0	1	0	0	0

Table 34 Gestural form-notion overlap heatmap for participant Fa2. Parent notions only. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

	Code System	Mirror plane (Parent)	Proper Rotation (Parent)	Improper Rotation (Parent)	Axis (Parent)
Fa2	{F}Gdd	0	1	0	0
Fa2	{F}Iba	0	0	0	0
Fa2	{F}Ifm	3	0	0	0
Fa2	{F}Imb	0	0	0	0
Fa2	{F}Ium	1	0	0	0
Fa2	{F}2db	0	1	0	1
Fa2	{F}2dd	0	0	0	2
Fa2	{F}2d1mb	0	1	0	0
Fa2	{F}2d1md	0	1	0	1
Fa2	{F}2f1ff	0	1	0	0
Fa2	{F}2u1fu	0	1	0	0
Fa2	{M}Ta(Hfd)	1	0	0	0
Fa2	{M}Tb(2f1um)	0	1	0	1
Fa2	{M}Tb(2dd)	1	1	0	1
Fa2	{M}Td(Iba)	0	0	0	0
Fa2	{M}Td(Ifm)	0	0	0	0
Fa2	{M}Td(Imb)	1	0	0	0
Fa2	{M}Td(2dd)	0	0	0	4
Fa2	{M}Td(2mm)	0	0	1	0
Fa2	{M}Tf(Hmd)	0	0	0	0
Fa2	{M}Tf(Ifm)	0	0	0	0
Fa2	{M}Tm(Gbb)Tm(Gbb)>Ta(Gbb)Ta(Gbb)	0	0	0	0
Fa2	{M}Tu(Gff)	0	0	0	0
Fa2	{M}Tu(2mm)	0	0	1	0
Fa2	{M}R-y(2mm)	0	0	1	0
Fa2	{M}R+z(1d2dd)	0	1	0	0
Fa2	{M}R+z(Cdd)	0	0	0	0
Fa2	{M}R+z(Hmd)	0	0	0	0
Fa2	{M}R+z(2um)	0	0	0	0
Fa2	{M}R-z(2dd)	0	0	0	0
Fa2	{M}R-z(Cdd)	0	0	0	0
Fa2	{M}R-z(Cmm>Cbb)	0	0	2	0
Fa2	{M}R-z(Gdd)	0	0	0	0
Fa2	{M}R-z(2um)	0	0	0	0

APPENDIX J. ZIPFIAN DISTRIBUTION DATA

The following table has been reorganized with abbreviated values to fit the page dimensions as required by the University of Illinois' Graduate College. For the full table in its original format and unabbreviated data, see the Supporting Information of the associated publication.[25]

Table 35 Gestural forms ranked in descending order of frequency of appearance, with number of times gestural form used also listed. Reprinted with permission from *J. Chem. Educ.* **2024**, 101, 819-830. Copyright 2024 American Chemical Society.

Code System	#	Rank	Code System	#	Rank
{F}Ifm	43	1	{M}Tf(2fm)	3	37
{F}Ium	32	2	{M}Tf(2md)	3	37
{F}Hmd	27	3	{M}Tm(Hmd)	3	37
{M}Td(Ifm)	26	4	{M}R-x(2f3fd)	3	37
{F}Imb	24	5	{M}R+z(Gda)	3	37
{F}2db	17	6	{M}R-z(Cdd)	3	37
{F}Hfd	16	7	{M}R-z(Gdd)	3	37
{F}2fm	13	8	{F}Iaf	2	49
{F}2ub	13	8	{F}(Ifm)(Imb)	2	49
{F}2mb	12	10	{F}Iuf	2	49
{F}2fd	11	11	{F}2dd	2	49
{M}Td(Imb)	11	11	{F}2d1mb	2	49
{M}Td(2dd)	9	13	{F}2d1md	2	49
{M}R+z(Cdd)	9	13	{F}2f1ff	2	49
{F}2um	8	15	{F}2m1df	2	49
{M}Ta(Hfd)	8	15	{F}2u1fu	2	49
{M}Td(2db)	8	15	{F}(2um)(1d2mf)	2	49
{M}(Cmm)R-z(Cmm)	7	18	{F}2d3db	2	49
{M}Tu(Ium)	6	19	{M}Ta(2fd)	2	49
{F}Hfu	5	20	{M}Ta(2mb)	2	49
{F}Idb	5	20	{M}Tb(2f1um)	2	49
{F}2da	5	20	{M}Tb(Imb)(Imb)>Tf(Imb)(Imb)>(Imb)Tf(Imb)	2	49
{M}Tb(2dd)	5	20	{M}Tb(2fd)	2	49
{M}Tf(Hmd)	5	20	{M}Tb(2fm)	2	49
{M}Tu(2um)	5	20	{M}Td(2mb)	2	49
{M}R-z(Cmm>Cbb)	5	20	{M}Td(2mm)	2	49
{F}(Ifm)(Ifm)	4	27	{M}Td(2m1ub)	2	49
{F}Iub	4	27	{M}Td(2um)	2	49
{F}2f1um	4	27	{M}Tf(Gdd)Tb(Gdd)	2	49
{M}Td(2fd)	4	27	{M}Tf(G12mm)	2	49
{M}Td(2fm)	4	27	{M}Tf(Ifm)	2	49
{M}Tm(Gmm)Tm(Gmm)>Ta(Gaa)Ta(Gaa)	4	27	{M}Tf(2fd)	2	49
{M}R+x(Hfd)	4	27	{M}Tm(Hfu)	2	49
{M}R-x(Hfd)	4	27	{M}Tm(Iub)	2	49
{M}R+z(2ub)(2da)	4	27	{M}Tm(2mb)	2	49
{M}O+y(2mb)	4	27	{M}(Ium)Tm(2um)>(Ium)Ta(2um)	2	49

{F}Gdd	3	37	{M}Tu(Hfd)	2	49
{F}2md	3	37	{M}Tu(2mm)	2	49
{M}Ta(Hmd)	3	37	{M}R+x(2fd)	2	49
{M}Td(Ium)	3	37	{M}R+x(2fm)	2	49
{M}Td(Pfd)Tu(Pfd)	3	37	{M}R-x(2f1um)	2	49
{M}(Ium)R+y(Cmm)	2	49	{M}Td(Hfu)	1	96
{M}R+z(1d2dd)	2	49	{M}Td(Iba)	1	96
{M}R+z(Hmd)	2	49	{M}Td(Iub)	1	96
{M}R+z(Ifm)	2	49	{M}Td(Pfu)Tu(Pfd)>(Pfd)(Pfu)	1	96
{M}R+z(2mb)	2	49	{M}Td(2db)>Td(Tub)	1	96
{M}R+z(2um)	2	49	{M}Td(2md)	1	96
{M}R-z(Gmm)R-z(Gmm)	2	49	{M}Td(2ub)	1	96
{M}R-z(Iuf)	2	49	{M}Td(2uf)	1	96
{M}R-z(2d3db)	2	49	{M}Tf(Gmm)	1	96
{M}R-z(2um)	2	49	{M}Tf(Hfu)	1	96
{M}(Cmm)R-z(Cff)	2	49	{M}Tf(Ium)	1	96
{M}(Ifm)R-z(Ifm)	2	49	{M}Tf(Ium)(Ium)>Tb(Ium)(Ium)	1	96
{M}O+z(2db)	2	49	{M}Tf(2dd)Tb(2dd)	1	96
{F}Hau	1	96	{M}Tm(Cmm>Gmm)Tm(Cmm>Gmm)	1	96
{F}(Hmd)(Hmd)	1	96	{M}Tm(Gbb)Tm(Gbb)>Ta(Gbb)Ta(Gbb	1	96
{F}(Gfu)(Gmd)	1	96	{M}Tm(G12uu)(Ium)	1	96
{F}Gmm	1	96	{M}Tm(Hfd)	1	96
{F}(Gmm)(Gmm)	1	96	{M}Tm(Iuf)	1	96
{F}Iba	1	96	{M}Tu(Gff)	1	96
{F}Ida	1	96	{M}Tu(Gmm)Td(Gmm)	1	96
{F}Idm	1	96	{M}Tu(Ium)(Ium)>Td(Ium)Ium)	1	96
{F}(Imb)(Hfd)	1	96	{M}Tu(2fd)	1	96
{F}Iua	1	96	{M}Tu(2fm)	1	96
{F}2fa	1	96	{M}Tu(2m1ub)	1	96
{F}2fu	1	96	{M}R+x(Cff)	1	96
{F}2f1md	1	96	{M}R+x(Cmm)	1	96
{F}(2md)(2um)	1	96	{M}R+x(Hmd)	1	96
{F}(2um)(2md)	1	96	{M}R+x(2bb)	1	96
{F}(2uf)(1d2df)	1	96	{M}R+x(2db)(Ifm)	1	96
{F}2u3mm	1	96	{M}R+x(2f1md)	1	96
{M}Ta(Hfu)	1	96	{M}R+x(2mb)	1	96
{M}Td(Iaf)	1	96	{M}(Imb)R+x(Imb)	1	96
{M}Ta(Imb)Tu(Iuf)	1	96	{M}(Ium)R+x(2fd)	1	96
{M}Ta(Pfd)Ta(Pfd)	1	96	{M}R-x(Cdd)R-x(Cuu)	1	96
{M}Ta(2dd)	1	96	{M}R-x(Ifm)R-x(Ifm)	1	96
{M}(Guu)Ta(Guu)	1	96	{M}R-x(2u1bm)	1	96
{M}Tb(Gdd)Tf(Gdd)	1	96	{M}R+y(Cmm)	1	96
{M}Tb(Ibm)	1	96	{M}(Imb)R+y(Imf)	1	96

{M}Tb(2md)	1	96	{M}(2u1uu)R+y(2m1mm)	1	96
{M}Td(Gmm)	1	96	{M}R-y(2mm)	1	96
{M}Td(Gmm)>Tu(Gmm)	1	96	{M}R+z(Cff)	1	96
{M}R+z(Cuu)	1	96	{M}R-z(Gdd)R-z(Gdd)	1	96
{M}R+z(Had)	1	96	{M}R-z(Had)	1	96
{M}R+z(1d2df)	1	96	{M}R-z(2u1uu)	1	96
{M}R+z(2da)	1	96	{M}R-z(2md)	1	96
{M}R+z(2dd)	1	96	{M}R-z(2uCmm)	1	96
{M}R-z(2dd)	1	96	{M}(Gmm)R+z(2mb)	1	96
{M}R-z(Cub)	1	96	{M}(Pfm)R-z(2mm>2bb)	1	96
{M}R-z(Cuu)	1	96	{M}O-y(2mb)	1	96

The tabulated data above, when plotted with the logarithm of the gesture frequency by the logarithm of that gesture's rank (determined by frequency), generates the following figure.

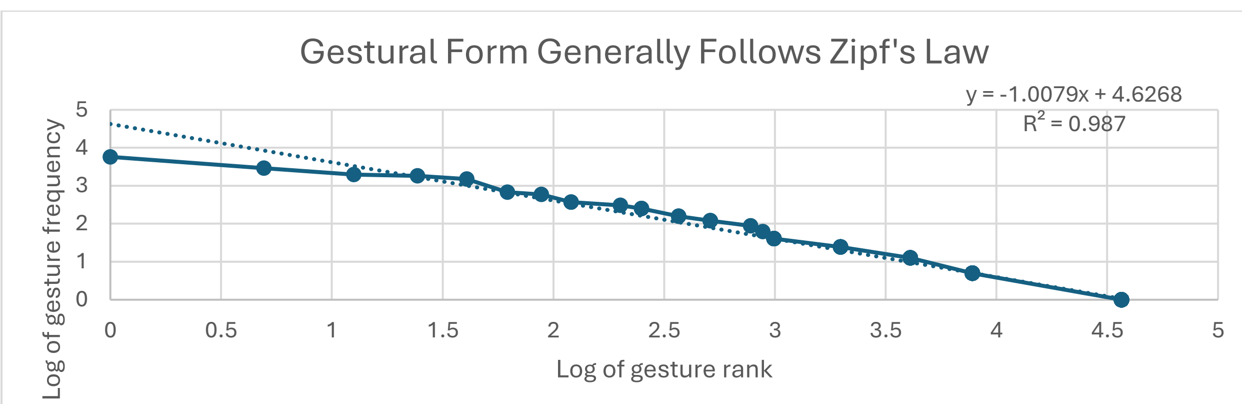


Figure 27 Plot of the logarithm of gesture frequency against the logarithm of gesture rank.

APPENDIX K. INSTRUCTOR GESTURE DOCUMENTS

The following are documents given to the instructors of CHEM 314 in the Fall 2023 and Spring 2024 semesters, respectively. These documents were meant to provide suggestions on what gestures to use during lectures to convey specific meanings.

Fall 2023 Instructor Gesture Document

Symmetry Gesture List

1. Point (in space) – Pinching the thumb and forefinger together (orientation irrelevant)


2. Line/axis (of rotation) - Pointer finger extended (direction irrelevant)

3. Plane - Fingers extended together a la karate chop (direction irrelevant)


4. Rotation (operation) - Loose, clawed hand with all fingers extended (as if you were gripping a tennis ball), then rotate hand about the wrist. Have direction fingers are pointed match the described axis


→


5. Right-hand rule - Explicitly defining each finger with an axis, especially the thumb as Z, is crucial.

6. Vertical plane - Flat hand, fingers pointed forward, palm faced towards the medial plane of the body AND flat hand with fingers faced medially and palm facing back towards the body

 AND 

7. Horizontal plane - Flat hand, fingers forward (or sideways) but with palm faced DOWNWARD (or upward, whichever is comfier to you.).

 and/or 

8. Inversion operation - Two closed fists moving past each other, either in the X, Y, or Z direction (or repeat along multiple axes for emphasis).

 → 

9. Improper rotation – This is a two-handed gesture
    a. With one hand: point index finger along rotation axis.

b. With the other hand: First, do the rotation gesture (cupped hand faced along rotation axis, then rotate wrist). Second, place flat hand perpendicular to the finger of the other hand to show the plane perpendicular to the specified axis

 →  →  OR 

Spring 2024 Instructor Gesture Document

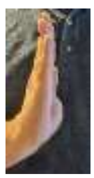
Symmetry Gesture List

1. Single point – Pinch the thumb and forefinger together (orientation irrelevant)

2. Line/axis (of rotation) - Pointer finger extended (direction irrelevant)

3. Plane - Fingers extended together a la karate chop (direction irrelevant)

4. Rotation (operation) - Loose, clawed hand with all fingers extended (as if you were gripping a tennis ball), then rotate hand about the wrist. Have direction fingers are pointed match the described axis

 → 

5. Right-hand rule - Explicitly defining each finger with an axis, especially the thumb as Z, is crucial.

6. Vertical plane - Flat hand, fingers pointed forward, palm faced towards the medial plane of the body AND flat hand with fingers faced medially and palm facing back towards the body

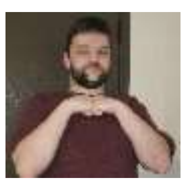
 AND 

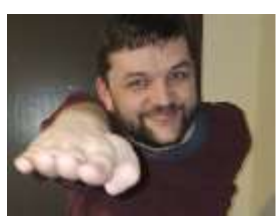
7. Horizontal plane - Flat hand, fingers forward (or sideways) but with palm faced DOWNWARD (or upward, whichever is comfier to you.).

 and/or 

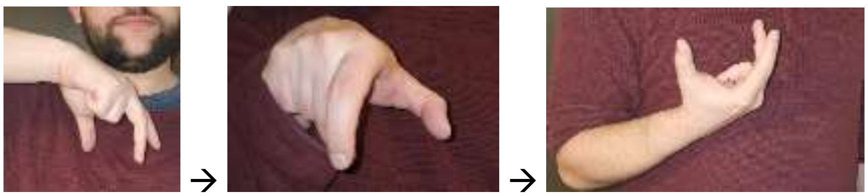
8. Inversion operation - Two flat hands moving past each other (repeat along multiple axes for emphasis). Hands should become closed at the origin.

 →  →  OR

 →  →  OR

 →  → 

9. Improper rotation operation – First, cup the hand downward and point the thumb, index, and middle fingers downward (ring and pinky fingers are withdrawn into the palm). Then, rotate the hand 180 degrees such that the hand is still faced downward (e.g. along the z axis, moving the arm as needed). Finally, flip the hand so that the direction of the fingers is reflection through the transverse plane (fingers now facing upward).



The symmetry elements are to be done as a sequential combination of an axis and plane (gestures 2 and 3).

APPENDIX L. GESTURE DESIGN SUGGESTION CODING CRITERIA

The following tables provide information on the coding scheme used to address the second research question in Chapter IV. Each table is reserved for a single coding axis, with the individual codes within that axis presented in the leftmost column. The middle column describes the criteria used to apply that code to an utterance(s). The rightmost column provide limited examples from the data of those codes. Each quote is attributed to a participant and where they expressed that utterance, either in the one-on-one interview or focus group. Some quotes may be accompanied by additional context shared within parentheses. **Table 36** describes the "Strengths of Gesture" coding axis. **Table 37** describes the "Shortcomings of Gesture" coding axis. **Table 38** describes the "Addressing Shortcomings of Gesture" coding axis. And **Table 39** describes the "Gesture Design Suggestions" coding axis.

Table 36 Criteria and coded examples in the "Strengths of Gesture" coding axis.

Coding axis: Strengths of Gesture	**Coding Criteria**	**Examples from Data Corpus**
Gestures can be interpreted in ways intended by the speaker (50)	Context indicates that a hypothetical or performed gesture successfully communicated a notion intended by the gesturer	• "I feel like that makes sense for improper rotation because you do have two sequential symmetry elements. So it's like you're showing both of them." – Cave Johnson, Fall '23 focus group • (After I performed a gesture intended to convey "Inversion") "For me this is inversion." – Maryam, Fall '23 Focus group
Gestural variants can express similar notions (33)	Participant indicates that several different gestural forms correlate to a single notion	• (After I performed {F}Hfd and {F}Hmd) " Still a plane, just the differences-, instead of, I don't know, XZ, it's XY." – Aidan, interview • (After Nina and I demonstrated different gestural forms while talking about the "Rotation" notion) "Yeah, that's the same as this." – Nina, interview
Gesture can express nuance (20)	Participant discusses the meaning of a gesture beyond a simple gestural form-notion correlation.	• "And that's what I'd do if I was thinking of a specific molecule. But if I'm talking about the [symmetry] elements outside of any specific molecule, I'm like, you got the axis and you have a plane that cuts through the axis." – Aidan, Fall '23 focus group
Gesture can help build understanding (40)	Participant indicates that gestures provided some utility in learning content.	• "Gestures are helpful and gestures are good." – Maryam, Fall '23 focus group • (When discussing the guest lecturer prompting students to gesture during lecture) "I think it was because he kind of made us all do them with him. So it helped I guess internalize the gestures." – Andrea Vega, interview
Gestures are engaging (18)	Participant indicates that gestures promote engagement or preserve student attention during lecture.	"You would catch a lot of students' attention. Like, they would focus back in on the lecture when they see that." – Aidan, Fall '23 focus group

Table 37 Criteria and coded examples in the "Shortcomings of Gesture" coding axis.

<u>**Coding axis:**</u> **Shortcomings of Gesture**	**Coding Criteria**	**Examples from Data Corpus**
Gestures can appear meaningless (21)	Participant indicates they did not interpret meaning from a gesture.	"I feel like if you just did it like that and expected me to know what it was, I wouldn't." – Maryam, Fall '23 focus group "I don't know. That one doesn't really mean anything." – Cave Johnson, interview
Gestures are polysemous (29)	Participant indicates they interpreted a different or additional meaning from a gesture than intended by the gesturer.	• "I feel like this is not inversion to me. I feel like this is a plane." – Aidan, Fall '23 focus group • "I genuinely thought he was just putting an axis and a plane together. I didn't realize that he was actually talking about improper rotation." – Nina, Fall '23 focus group
Gestures can be unpalatable (31)	Participant may successfully interpret meaning from a gesture but they dislike the associated gestural form.	• "I remember dislike that one [gesture] too." – Aidan, Fall '23 focus group • "I mean, it also makes sense, but I think that gets confusing for me." – Diara, interview
Mapping between gestural form and notion can seem weak (15)	Participant specifically indicates that there is a degree of mismatch between a gestural form and the discussed notion.	• (After I produced {F}(2db)(Hfd)) "It kind of feels like the principal axis is not quite in the middle. It's kind of off to the side and that feels kind of weird." – Andrea Vega, Spring '24 focus group
Gestural forms are limited by the affordances of the human body (17)	A gestural form is indicated as problematic because a more accurate contortion of the human body is difficult or impossible.	• "It's physically impossible." – Cave Johnson, Fall '23 focus group •"It's not a perfect gesture because obviously you can't actually invert your hands…" – Andrea Vega, interview
Gesture is not always the optimal representation (14)	Participant indicates that a different representation would be better suited to communicate a notion.	• "… When learning that concept specifically, that kind of model would be easiest to visualize [an S_6]." – Andrea Vega, Spring '24 focus group
Small gestures cannot be seen at a distance (7)	Participant indicates that the small size of a gesture is problematic.	• "This is too small to see." – Nina, interview

Table 38 Criteria and coded examples in the "Addressing Shortcomings of Gesture" coding axis.

Coding axis: Addressing Shortcomings of Gesture	**Coding Criteria**	**Examples from Data Corpus**
Tailor the size of a gesture to the size of the audience (6)	Relevant to the *"Small gestures cannot be seen at a distance"* Shortcoming code, participant indicates the size of a gesture should correlate to the size of the audience	• "When [the gesture lecturer] did it with his arms, we were talking about, I feel for the classroom settings, that was better to do it with his arm so anybody in the back all the way can see it. But I like yours if you're just teaching it in a small group." – Alison, Spring '24 focus group
Closely approximate the intended notion and explain dissimilarities (8)	Relevant to the Shortcoming codes related to limitations of the human body, polysemous gestures, or gestures being unpalatable, participant indicates that a gesture is imperfect but in some way justifies the shortcomings.	• "Your hand is not actually doing it an improper rotation, but like if you were to hold a molecule in your hand and then do that that had like an improper rotation symmetry element, then it would work." – Cave Johnson, Fall '23 focus group
Potentially confusing gestures should be explained (17)	Relevant to the Shortcoming codes of gestures being unpalatable or meaningless, participant indicates that these undesirable aspects are addressed by explanation.	• "It made sense when you sat there and you did it for me like 8 times, and then you brought out the molecular kit. That was fine because then when I saw the molecule I was like, oh, I see where your fingers are. But at first, like, I couldn't understand that these were like the little guys [hydrogen atoms]." – Nina, Fall '23 focus group

Table 39 Criteria and coded examples in the "Gesture Design Suggestions" coding axis.

Coding axis: Gesture Design Suggestions	**Coding Criteria**	**Examples from Data Corpus**
New gestures should have accompanying explanations (14)	Participant indicates that explanations help gestures to be understood.	• "I think what happened was you were like, 'Oh, like, what's this?' I was like, 'I don't know.' And then you were like, 'This is supposed to be an improper rotation.' I was like, 'Oh, yeah, ok, I get it.'" – Cave Johnson, Fall '23 focus group
Gestures should closely map the intended notion (21)	Participant indicates that the gestural form should have a strong mapping to its intended notion.	• " I always think of them sequential, and I feel like the clearest way to do a hand gesture for improper rotation is to do a sequence of two hand gestures, one of which is the axis and the other ones is the plane." – Cave Johnson, Fall '23 focus group
Gestures should be comfortable for the speaker (6)	Context indicates that a gestural variant should be chosen to communicate a notion that is physically reasonable for the gesturer to produce.	• (When trying out several related gestural forms to express an improper rotation) "Put these fingers down. And that's an easy position because if you try to put your thumb down, that's still kind of hard." – Nina, Fall '23 focus group
To get students to gesture, instructors should encourage students to gesture (2)	Context indicates that students found utility from being told to gesture during class.	• (When discussing the guest lecturer's prompts for students to gesture during class) "Yeah, in the moment it feels silly. But then you go home. You look back at your notes and you realize, like, oh, actually it helped me visualize it better." – Andrea Vega, interview

VITA

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PUBLICATIONS: **Markut, J. J.**, & Wink, D. J. (2023). Symmetry Elements Embodied by Students' Hands: Systematically Characterizing and Analyzing Gestures in Inorganic Chemistry. *Journal of chemical Education*, *101*(3), 819-830.

Markut, J. J.; Cabana, J.; Mankad, N. P.; Wink, D. J. (2023). A Collaborative Model-Based Symmetry Activity for the Inorganic Chemistry Laboratory. *Journal of Chemical Education*, *100*(4), 1633-1640.

ORAL PRESENTATIONS:

Markut, J. J. (2023) How the hands speak louder than words: Gestures embodying symmetry elements in inorganic chemistry. X-DBER 2023 Conference, Virtual (hosted by the University of Nebraska-Lincoln).

Markut, J. J. (2023) Gestures embodying symmetry elements: Interviews from undergraduates in the inorganic chemistry laboratory. Spring 2023 ACS National Meeting, Indianapolis, Indiana.

Markut, J. J. & Wink, D. J. (2022) Socially-Collaborative Model-Based Inorganic Symmetry Activity. Fall 2022 ACS National Meeting, Chicago, Illinois.

Markut, J. J. & Wink, D. J. (2022) Unprompted Student Gestures in a Model-Based Inorganic Symmetry Activity. 27th Biennial Conference on Chemical Education, West Lafayette, Indiana.

POSTER PRESENTATIONS:

Markut, J. J. (2023; poster) Symmetry Elements as Gestures: Towards Establishing Conventionalized Gestures in the Inorganic Chemistry Classroom. Gordon Research Conference: Chemistry Education Research and Practice, Bates College, Maine.

Markut, J. J. & Wink, D. J. (2022; poster) Unprompted Student Gestures in a Model-Based Symmetry Activity for Inorganic Chemistry. Fall 2022 ACS National Meeting, Chicago, Illinois.

Markut, J. J. & Wink, D. J. (2022; poster) A Socially-Collaborative Model-Based Symmetry Activity for Inorganic Chemistry. 27th Biennial Conference on Chemical Education, West Lafayette, Indiana.

Markut, J. J. (2022; poster) Unprompted Student Gestures in a Model-Based Inorganic Symmetry Activity: Initial Coding and Classification. The Chemistry Laboratory: Evaluation, Assessment & Research Conference, Virtual.

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Fall 2020 – Fall 2023
University of Illinois Chicago, Department of Chemistry
CHEM 101 Preparatory Chemistry
CHEM 116 Honors and majors general and analytical chemistry I
CHEM 122 General Chemistry 1 Lecture
CHEM 123 General Chemistry 1 Laboratory
CHEM 314 Inorganic Chemistry

Spring 2022 – Spring 2023
University of Illinois at Chicago, Department of Biology
NATS 106 Chemical and Biological Systems
CHEM 124 General Chemistry 2 Lecture

Fall 2017 – Spring 2019
Washington State University, Department of Chemistry
CHEM 101 Introduction to Chemistry
CHEM 102 Chemistry Related to Life Sciences
CHEM 103 Concepts in Chemistry
CHEM 104 Problem Solving in General Chemistry 1
CHEM 105 Principles of Chemistry 1

MATERIALS DEVELOPED:

"Lab #3: Molecular Symmetry". Inorganic Chemistry (CHEM 314) at University of Illinois Chicago (Fall 2021-Fall 2023). Published in [89].

Formative and summative assessments, instructional materials, and syllabus. Problem Solving in General Chemistry (CHEM 104) at Washington State University (Fall 2018-Spring 2019).

SERVICE

Committee Member, Committee endowing the Leenil Noel Scholarship. 2023-2024.

Member, Nine-Month Appointment Taskforce in service of the Office of the Provost and Vice Chancellor for Academic Affairs. 2022-2023.

Steward, Graduate Employees Organization AFT Local 6297. 2020-2024.