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Different instructors—different symmetry: variation in instructional approaches and content emphasis in inorganic chemistry

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Symmetry is a foundational concept in inorganic chemistry, essential for understanding molecular properties and interactions. Yet, little is known about how instructors teach symmetry or what shapes their instructional and curricular choices. To investigate this, we analyzed classroom observations from fourteen inorganic chemistry instructors from various institutions, focusing on their use of student-centered practices and emphasis on symmetry content. We then conducted semi-structured interviews to explore the reasoning behind their decisions, using the Teacher-Centered Systemic Reform (TCSR) model to interpret influences from personal factors (*e.g.*, teaching experience), teacher thinking (*e.g.*, beliefs about teaching and learning), and contextual factors (*e.g.*, classroom layout). Minute-by-minute analyses of teaching revealed four instructional profiles (student-centered, high-interactive, low-interactive, and instructor-centered) and four content profiles, ranging from an emphasis on symmetry fundamentals (*e.g.*, symmetry elements and operations, point group assignment) to symmetry applications (*e.g.*, spectroscopy, molecular orbitals, character tables). Three themes emerged: (1) instructional approaches and content emphasis vary substantially across instructors; (2) more student-centered instructors tend to focus on foundational symmetry concepts and skills, whereas more instructor-centered instructors tend to prioritize advanced applications; and (3) instructors' beliefs and prior experiences, more than personal and contextual factors, drive instructional decisions for teaching symmetry.

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Introduction

Molecular symmetry is a key concept commonly introduced in inorganic chemistry courses, providing context for subsequent lessons on molecular bonding, structure, and spectroscopic applications (Orchin and Jaffe, 1970a, b; Cotton, 1991; Carter, 1997). According to results from a national survey of inorganic chemistry faculties, approximately 75% of instructors included symmetry and group theory in their foundational inorganic chemistry courses, and around 84% covered these topics in their advanced inorganic chemistry courses (Raker *et al.*, 2015a, b). Although symmetry is commonly taught in inorganic chemistry courses, research indicates that students often struggle to understand this concept due to its inherent complexity and the visuospatial skills it requires (Tuckey *et al.*, 1991; Wu and Shah, 2004; Nottis and Kastner, 2005; Harle and Towns, 2011). In response, a wide range of instructional tools have been developed to support student learning of symmetry operations and point group determination.

Many of these efforts focus on using physical models and manipulatives to make abstract concepts more tangible. For example, Rattanapirun and Laosinchai (2021) designed exploration-based activities using 2D and 3D manipulatives, while Niece (2019) developed customized 3D-printed models to illustrate reflection and improper rotation axes. Schiltz and Oliver-Hoyo (2012) proposed several physical model systems, such as a permanent reflection plane and a 3D-coordinate axis, to help students visualize symmetry operations. Similarly, the use of everyday objects, such as tennis balls (Herman and Lievin, 1977), tire treads (Gallian, 1990), game dice (Grafton, 2011), and dynamic paper constructions (Sein Jr, 2010) has been widely documented in the literature. Although there is no direct evidence that these objects improve student learning, they are assumed to be helpful by providing tactile and visual inputs that enhance comprehension, spark interest, and bridge the familiar with the unfamiliar (Herman and Lievin, 1977; Grafton, 2011).

Complementing these physical tools, computer simulations have emerged as powerful resources for interactive visualization. Simulations such as Symmetry@Otterbein (Johnston, 2019) and

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3D Molecular Symmetry Shockwave (Charistos *et al.*, 2005) allow students to manipulate molecular structures in 3D, providing perspectives not possible with static 2D images. Research highlights that such tools enable students to rotate and explore molecular symmetry elements from multiple viewpoints, facilitating deeper understanding of spatial relationships (Cass *et al.*, 2005; Meyer and Sargent, 2007; Tuvi-Arad and Blonder, 2010; Antonoglou *et al.*, 2011). The more recent mobile application "leARnCHEM" (Zambri and De Backere, 2023) has leveraged augmented reality to further enrich students' visualization of symmetry and molecular orbitals. Used in an undergraduate inorganic chemistry course, the application has received positive feedback for its usability and effectiveness.

Despite the availability of numerous resources to support the teaching of symmetry, little research has examined how instructors actually teach this topic or the reasoning behind their pedagogical choices (Pazicni and Popova, 2025). This gap is significant, as instructional practices have been shown to directly influence students' persistence in STEM fields. For example, in a landmark study, Seymour and Hewitt (1997) interviewed 460 STEM majors and found that poor STEM instruction ranked as the third most common reason for leaving a STEM major. Alarmingly, 90% of students who switched and 74% of those who persisted identified issues with teaching as a major factor in their decision-making. Two decades later, a follow-up study with 346 students across six institutions found similar patterns, with 96% switchers and 72% of persisting seniors continuing to report poor quality of STEM teaching as a concern in their educational experience (Thiry *et al.*, 2019).

In response to such concerns, evidence-based instructional practices (EBIPs) have been developed and widely promoted to improve STEM teaching. However, the adoption of EBIPs has remained limited, and many instructors eventually revert to more traditional approaches. A large-scale study by Stains *et al.* (2018) supported this trend by finding that traditional lecturing still dominates, accounting for 75% of class time across STEM disciplines. Similarly, Wang *et al.* (2024) reported that lecturing remains the primary mode of instruction among introductory chemistry instructors.

Faculty often cite the need to cover a broad range of content as a key barrier to adopting EBIPs. This emphasis on content coverage may stem from instructors' personal beliefs or from external pressures, such as departmental expectations, institutional policies, or accreditation requirements. However, research has shown that focusing on depth rather than breadth in content coverage can lead to improved student learning outcomes (Murdock,2008; Schwartz *et al.*, 2009; Luckie *et al.*, 2012). A recent study explored how nine chemistry assistant professors navigate these tensions by examining their perspectives on content coverage and the reasoning behind their choices (Kraft *et al.*, 2023). Most participants leaned toward a particular stance in what is often referred to as "the debate" over depth *vs.* breadth of content coverage. While some instructors were primarily influenced by personal beliefs, others' choices were shaped by contextual factors.

Although prior research has explored general teaching and content choices, it has typically focused on comparisons across disciplines (Dancy and Henderson, 2010; Stains *et al.*, 2018) or topics (Andrews *et al.*, 2019; Kraft *et al.*, 2023), without examining instruction tailored to a specific topic. Yet, instructors frequently adjust their pedagogical strategies in response to the content they teach. As such, studying instructional practices within the context of a specific topic may reveal valuable insights into how instructors navigate content-specific teaching challenges and make instructional decisions.

Symmetry is a unique topic given the freedom that inorganic chemistry instructors have regarding classroom practice and content choices (Pazicni and Popova, 2025). For example, instructors can choose among a range of molecular representations, computer visualization tools, physical models, and everyday objects to support their lessons. Instructors also have discretion in whether to emphasize conceptual understanding, procedural skills, or the applications of symmetry concepts. Additionally, they can choose the extent to which their instruction is student-centered, ranging from using guided inquiry activities (Luxford *et al.*, 2012; Southam and Lewis, 2013; Rattanapirun and Laosinchai, 2021), to incorporating engaging assignments (McKay and Boone, 2001), to implementing fully transformed course structures (Antonoglou *et al.*, 2011). This wide range of instructional choices makes symmetry a rich context for exploring how instructors make pedagogical decisions. This study, therefore, is guided by five primary research questions:

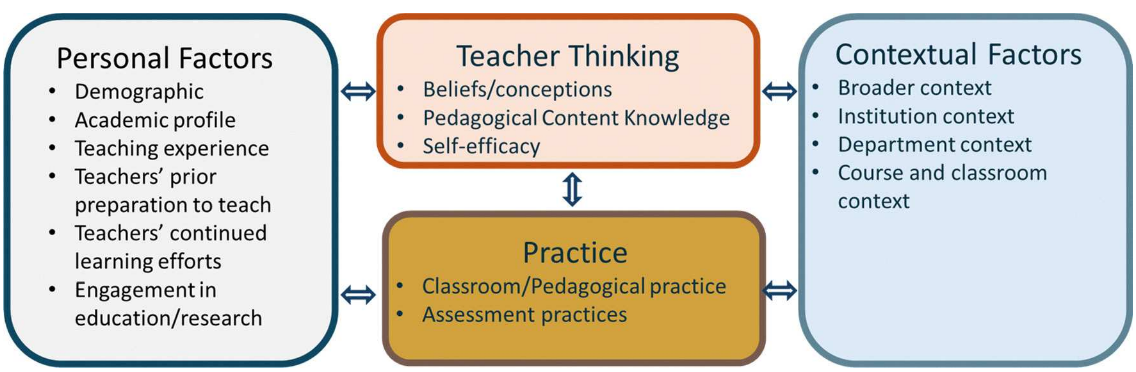

Fig. 1 Teacher-Centered Systematic Reform (TCSR) model (adapted from Gess-Newsome *et al.*, 2003).

1. What instructional activities do inorganic chemistry instructors use when teaching molecular symmetry?
2. What reasons inform instructors' decisions to select and implement their most frequently used activities?
3. What areas of content do inorganic chemistry instructors prioritize when teaching molecular symmetry?
4. What reasons inform instructors' decisions about content coverage?
5. What connections might exist between the inorganic chemistry faculty's instructional and content choices when teaching molecular symmetry?

Analytical framework

The Teacher-Centered Systemic Reform (TCSR) model served as the guiding framework for analyzing the reasons behind instructors' pedagogical decisions. Originally developed to support K-12 educational reform, the model was later adapted for use in higher education contexts (Gess-Newsome *et al.*, 2003). Grounded in an extensive review of the literature, the TCSR model offers a comprehensive lens for understanding the multiple factors that influence Instructional Practices, including Personal Factors, Teacher Thinking, and Contextual Factors (Fig. 1). Together, these elements reflect the complex, systemic nature of education, highlighting the need to consider these interrelated dimensions when examining instructional decision-making.

The **Personal Factors** component of the TCSR model encompasses instructors' demographic characteristics, academic profile (*e.g.*, position title, workload, job responsibilities), teaching experiences (*e.g.*, years of teaching, teaching roles), and pedagogical training (*e.g.*, participation in teaching workshops, consulting educational literature, and collaborating with colleagues who are teaching experts). Additionally, it accounts for involvement in educational or bench research activities, such as conducting research, publishing findings, and sharing results through seminars or conference presentations (Gess-Newsome *et al.*, 2003). Research supports the model's proposed link between personal factors and instructional practices. For example, Lund and Stains (2015) examined how prior exposure to EBIPs as students influenced the teaching approaches of STEM instructors. They surveyed and observed 99 chemistry, biology, and physics faculty at a Midwestern research-intensive institution, assessing their awareness and adoption of EBIPs, attitudes toward student-centered teaching, and instructional approaches. Their findings revealed that instructors who had previously experienced EBIPs as students were more likely to implement them in their classrooms. This suggests that personal experiences with evidence-based pedagogy can play a significant role in shaping teaching practices.

The **Teacher Thinking Factor** includes beliefs about teaching and learning, Pedagogical Content Knowledge (PCK) (Berry *et al.*, 2015), self-efficacy, and levels of satisfaction or dissatisfaction with current teaching approaches and student outcomes. Research shows that instructors' thinking and beliefs influence their instructional choices. For example, Popova *et al.* (2020) interviewed 19 assistant chemistry professors and analyzed their classroom practices and course materials. They found that instructors who held student-centered beliefs were more likely to implement student-centered teaching practices. However, thinking did not always fully align with practice, as some instructors' teaching beliefs were more progressive than their teaching practices, due to a variety of barriers. In other cases, dissatisfaction with current practices has been a key driver of instructional change. For example, Andrews and Lemons (2015) interviewed 17 biology instructors and found that those less inclined to adopt active learning strategies were generally satisfied with traditional lecturing, believing it to be an effective way for students to learn. This suggests that when instructors are content with their existing approach, they see little reason to change, whereas dissatisfaction may prompt them to explore new methods.

The **Contextual Factors** emphasize elements within the higher education system that can either support or hinder teaching innovation. These elements include the broader professional community, institutional environment, departmental culture, and specific classroom or course contexts. The course and classroom context have been extensively studied to explore their influence on instructors' adoption of active learning practices (Apkarian *et al.*, 2021; Yik *et al.*, 2022). STEM instructors often cite challenges such as large class sizes or fixed classroom layouts as barriers to implementing active learning strategies (Shadle *et al.*, 2017).

Notably, personal and contextual factors play an important role in shaping teacher thinking. A systematic review of Sakaria *et al.* (2023) on factors influencing mathematics teachers' PCK demonstrated that both personal factors (*e.g.*, teaching experience, educational level, professional development) and contextual factors (*e.g.*, school management) affected their PCK. Other studies have shown that experienced teachers tend to demonstrate greater knowledge than their less-experienced peers (Schoen *et al.*, 2019). Moreover, prospective teachers tend to have less PCK than in-service teachers due to their limited teaching experience and subject matter knowledge (Yilmaz and Demir, 2021). Regarding contextual factors, a supportive school climate and access to professional development opportunities (Mhakure, 2019) have both been shown to strengthen teachers' PCK. Finally, the literature demonstrates a tight interconnectedness between one's beliefs about teaching and learning and one's instructional practices (Czajka and McConnell, 2016, 2019; Douglas *et al.*, 2016; Gibbons *et al.*, 2018; Popova *et al.*, 2020).

We used the TCSR model as an analytical framework to interpret instructors' pedagogical choices. The TCSR model helped us examine how personal factors (*e.g.*, years of teaching experience, Virtual Inorganic Pedagogy Electronic Resource (VIPEr) membership), teacher thinking (*e.g.*, beliefs about teaching and learning, instructional goals), and contextual factors (*e.g.*, flipped or standard class format, class size, and classroom layout) influenced both the instructional activities and content coverage decisions related to teaching molecular symmetry. By organizing our analysis around these interconnected components, we gained a more nuanced understanding of the reasons underlying instructors' decisions and how these decisions play out in practice.

Methods

Sample

This study was conducted under the University of Wisconsin–Madison Health Sciences IRB (2022–0248). Participants were recruited using purposive sampling to target instructors who teach undergraduate inorganic chemistry courses in the United States. We used two main strategies to recruit instructors. The first strategy involved recruiting participants through various social media channels using a flyer, whereas the second strategy entailed advertising the study to members of a large inorganic chemistry community, the VIPEr. Because some institutions do not regularly teach inorganic chemistry, data collection continued across multiple semesters. As a result, a total of fourteen instructors from different institutions participated in the study over three semesters: five in Spring 2023, seven in Fall 2023, and three in Spring 2024. Table 1 summarizes the demographic information for our participants. Each instructor received a consent form at the start of the study and signed it prior to any data collection. To protect the anonymity of the participants, each was assigned a pseudonym.

Table 1 Demographic information of the participants, delineating the personal and contextual variables in alignment with the TCSR model (Fig. 1)

Personal variables		Participants, *n*
Academic rank	Professor	7
	Associate Professor	3
	Assistant Professor	3
	Teaching Assistant Professor	1
Teaching experience	>15 years	7
	6–15 years	4
	<6 years	3
VIPEr usage	Member	3
	Non-member/resource user	8
	Non-member/non-user	3
Contextual variables		**Participants, *n***
Class size	<10	4
	11–20	4
	21–50	3
	>50	3
Course level	Sophomore	3
	Junior	4
	Senior	7
Classroom layout	Active learning classroom	6
	Conference room	1
	Small amphitheater	5
	Amphitheater	2
Type of institution[a]	Research-Intensive Institution (R1, R2)	6
	Master's Colleges and Universities (ML, MM)	3
	Baccalaureate Colleges (BS)	5

[a] Based on carnegie classification: ***R1***: Doctoral Universities: very high research activity; ***R2***: Doctoral Universities: high research activity; ***ML***: Master's Colleges & Universities: larger programs; ***MM***: Master's Colleges & Universities: medium programs; ***BS***: Baccalaureate Colleges.

Classroom observations data collection and analysis

Classroom observations were collected and analyzed to examine instructors' teaching practices and content coverage related to molecular symmetry. To capture these lessons, instructors either received a video camera by mail to record their classes or coordinated with their home institution to arrange internal classroom recording support. Cameras were positioned to record the instructor's movement and instructional delivery, while avoiding capturing students' faces, except in cases where students were invited to the front of the room to participate in an activity. In these cases, if any students declined to be recorded, the instructor was instructed to guide them to a location beyond the camera's field of view.

Because the number of lessons each instructor dedicated to symmetry varied, the number of recorded sessions ranged from 2 to 9 per instructor, totaling 65 lessons across all participants. The overall video time per instructor ranged from 99 minutes (∼1.5 hours) to 452 minutes (∼7.5 hours), totaling 3511 minutes (∼58.5 hours) of video analyzed across all instructors.

Three instructors were unable to record all their planned symmetry lessons due to technical difficulties. One instructor missed the first lesson in a 3-class sequence, another missed the first lesson in a 6-class series, and a third missed two lessons (the first and fifth) in a 6-class sequence. The four missed sessions likely included key content: the first lesson often introduces the five symmetry operations, and lesson five may involve assigning point groups. Despite these missing data points, all instructors were retained in the analysis to preserve the diversity of instructional approaches represented.

Six instructors employed a flipped classroom approach (Bergmann, 2012), in which additional content was delivered outside of class through asynchronous videos. The lengths of these videos ranged from 29 minutes (∼0.5 hour) to 257 minutes (∼3 hours), depending on the instructor.

Classroom Observation Protocol for Undergraduate STEM (COPUS) (Smith *et al.*, 2013), was initially used as the protocol for analyzing classroom observations. However, after coding the first cohort, we noticed that COPUS has some limitations that prevented us from getting a more granular analysis of our dataset. First, COPUS is topic-independent, whereas our goal was to develop a more topic-specific analysis tailored to the teaching of molecular symmetry. Second, while COPUS is used to characterize how faculty and students are spending their time in the classroom, our analyses focused primarily on the instructors. Third, COPUS captures instructional activities in two-minute intervals, whereas our approach involved a more granular, minute-by-minute analysis to allow for finer resolution in capturing instructional decisions: (1) how instructors allocated time to different teaching activities, using codes adapted from the Classroom Observation Protocol for Undergraduate STEM (COPUS) (Smith *et al.*, 2013), such as lecturing and group activity, (2) how instructional time was distributed across specific molecular symmetry subtopics (*e.g.*, rotation operation, assigning point groups), and (3) the strategies instructors used to support students' 3D visualization (*e.g.*, model kits, simulations). This manuscript focuses specifically

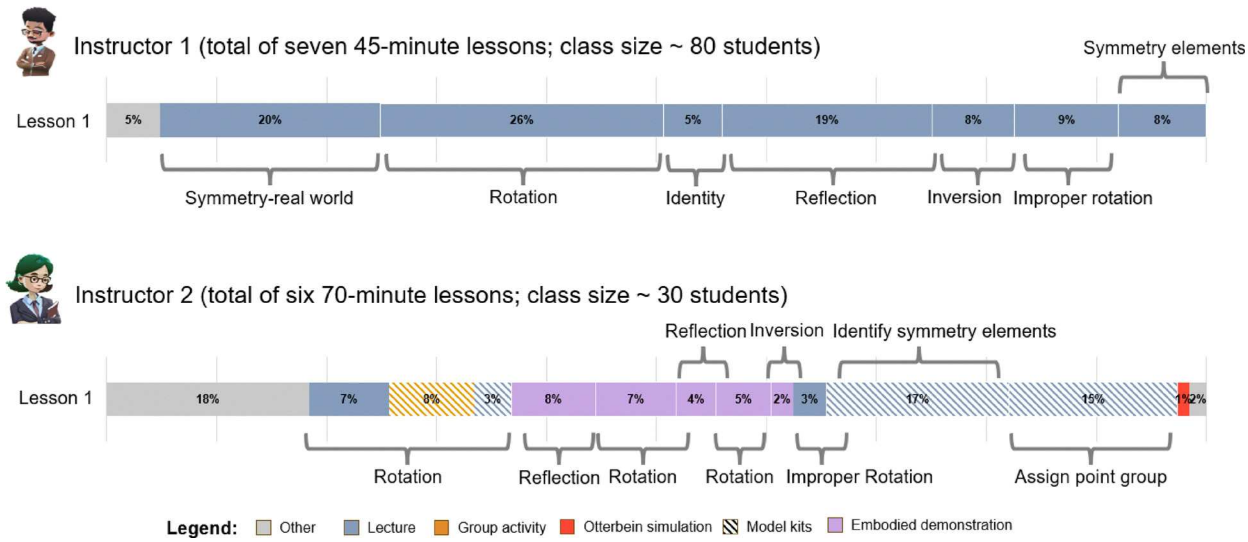

Fig. 2 Example of coding for the percentage of class time allocated to various instructional activities and symmetry subtopics by two instructors during their first symmetry lesson.

on analyzing how instructional time was allocated across different teaching activities and symmetry subtopics. We calculated the percentage of time spent on each activity and subtopic to compare these patterns across all participants. Fig. 2 presents an example of these analyses for the first lesson on symmetry taught by two different instructors.

The various teaching activities and symmetry subtopics observed in the video recordings of classes (Fig. 2) served as codes to analyze all classroom video recordings (Saldaña, 2021). To assess interrater reliability, 20% of the videos—one class session per participant—were independently coded by two researchers (LS and SH). The agreement was measured using percentage agreement on time allocation for both teaching activities and symmetry subtopics, following procedures outlined by Gisev *et al.* (2013). A time discrepancy of less than 30 seconds between coders was considered an agreement. The percentage agreement across participants ranged from 83% to 100%, except for one participant, for whom the agreement was 71% due to poor video quality. To address discrepancies, LS and SH jointly reviewed and discussed all videos with $<$100% agreement until full consensus was reached. LS then proceeded to code the remaining videos in the dataset. When uncertainties arose during this process, LS brought the relevant video clips to discuss with SH and MP, ensuring consistency in the final coding decisions.

Interview data collection and analysis

An interview protocol (see Protocol S1 in SI) was developed to gather information about each instructor's classroom context, teaching beliefs, and PCK (Berry *et al.*, 2015). PCK is an integration of knowledge and skills that an instructor employs to teach a specific topic to a defined group of students within a particular context. Drawing on Magnusson's model (1999), we structured our interview questions around four PCK components: knowledge of curriculum, knowledge of students, knowledge of instructional strategies, and knowledge of assessment. The interviews were conducted by SH before each instructor started teaching their unit on symmetry. At the time of the interviews, the classroom observation data had not yet been collected and analyzed, which prevented us from asking tailored questions about the concrete teaching activities each instructor chose to use and the symmetry subtopics they emphasized. Although the interviews did not include direct questions about instructors' reasons for these pedagogical decisions, LS reviewed all the interview transcripts to identify statements that offered reasons for using specific teaching activities and emphasizing specific subtopics. Each rationale-containing statement was coded using inductive coding (Saldaña, 2021).

To ensure interrater reliability, 20% of the dataset was independently coded by both LS and SH using a consensus coding strategy. The researchers used two developed codebooks (see Tables S2 and S3) and met after coding the data to resolve discrepancies and reach full agreement. LS then coded the remainder of the dataset. Constant-comparative analysis was used to explore patterns in instructors' reasons for their instructional decisions (Saldaña, 2021).

Results

RQ1: What instructional activities do inorganic chemistry instructors use when teaching molecular symmetry?

Across participants, eleven distinct teaching activities were observed during symmetry instruction, summarized in Table 2. These activities fell into several broad categories: student activities, lecture activities, visualization activities, and other activities not directly related to providing symmetry content.

Fig. 3 shows the percentage of time each instructor spent on different activities. For ease of interpretation, we highlight in orange the time allocated for one of the most used

Table 2 Description of each teaching activity observed during symmetry instruction

Category	Activity code	Definition
Student activities	Group activity	Students collaborate in small groups on worksheets or instructor-assigned tasks, while the instructor circulates to offer support and answer questions.
	Individual work	Students work independently on tasks, and the instructor moves around the room to provide assistance or answer questions.
	Q & A	The instructor sets aside time for students to ask questions.
	Quiz	The instructor uses class time for students to complete a quiz or test.
Lecture activities	Lecture	The instructor delivers content to the class, occasionally posing questions that may or may not receive student responses.
	Socratic lecture	The instructor presents content while frequently asking students questions and encouraging them to respond throughout the session.
	Follow-up	The instructor addresses the entire class to provide feedback or clarification following a group activity.
Visualization activities	Otterbein simulation	The instructor demonstrates symmetry operations or point group assignments using interactive simulations from the Symmetry@Otterbein website (https://symotter.org/).
	Model kits	The instructor uses physical model kits to help students visualize symmetry operations or determine point groups.
	Embodied demonstration	The instructor invites students to physically represent a molecule and perform symmetry operations by moving their bodies to illustrate spatial relationships.
Other		Activities not directly related to delivering symmetry content, such as making course announcements, returning graded work, managing administrative tasks, or engaging in casual conversation with students.

activities—group work. The use of model kits is not included in Fig. 3 because it often coincided with other activities.

Group work, which has been positioned as an indicator of active learning (Stains *et al.*, 2018; Yik *et al.*, 2022), was the most common student activity. Twelve out of fourteen instructors used it, though the time spent on it varied widely—from 1% to 54% of total symmetry instruction time. These group activities involved students working together to identify symmetry elements or assign point groups.

Based on prior work (Stains *et al.*, 2018), we adopted existing thresholds to distinguish between broad categories: lessons in which instructors spend more than 80% of their time lecturing are considered instructor-centered, and those in which more than 50% of the time is spent on group activities are considered student-centered. Lessons that fall in between are considered interactive lecture (Stains *et al.*, 2018). To provide a more fine-grained analysis, we examined the natural breaks in our data and subdivided the interactive-lecture group into low-interactive and high-interactive categories, with 45% chosen as a cutoff to separate instructors who approached but did not quite reach the 50% "student-centered" threshold. For example, Scout spent 49% of class time on group work, which we categorized as student-centered because it aligned most closely with the definition in the literature. Thus, our participants were categorized into four groups:

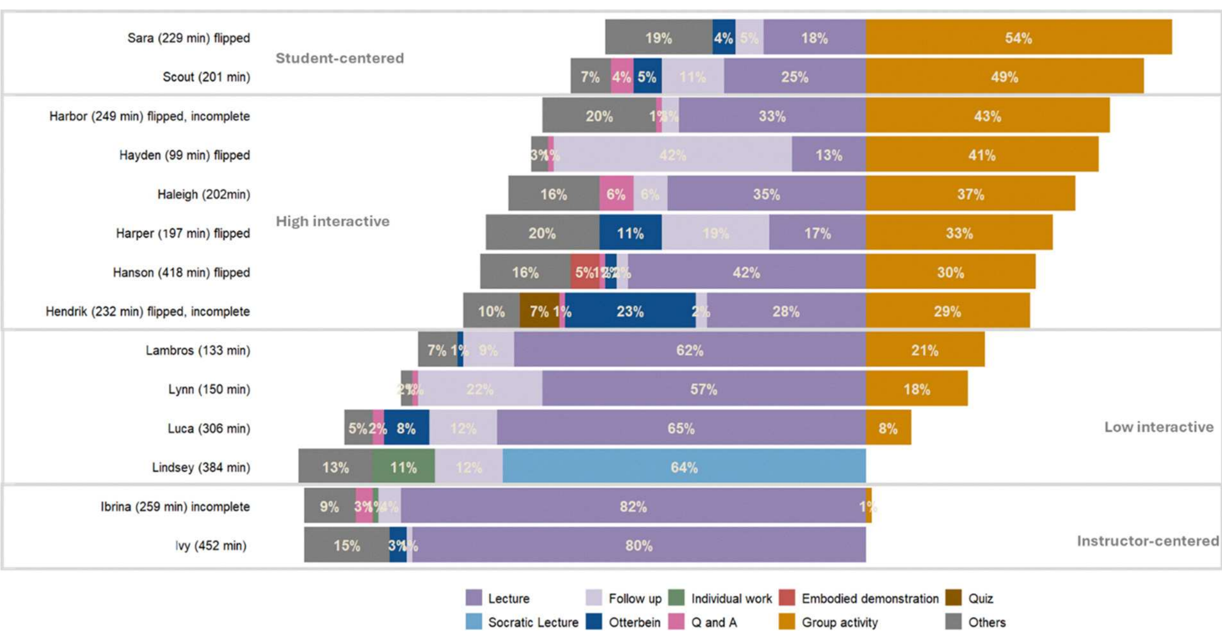

Fig. 3 Time allocation in teaching activities across participants.

(1) Student-centered (n = 2): Dedicated more than 45% of class time to group activities.

(2) High-interactive (n = 6): Dedicated 25–45% of class time to group activities.

(3) Low-interactive (n = 4): Dedicated 5–25% of class time to group activities (except for Lindsey, who engaged students through Socratic lecturing).

(4) Instructor-centered (n = 2): Dedicated around 0–5% of class time to group activities.

To protect participant anonymity, we assigned pseudonyms based on the student-centeredness of symmetry instruction. Names starting with ''S'' are used for student-centered instructors, ''H'' for high-interactive, ''L'' for low-interactive, and ''I'' for instructor-centered instructors.

The next most common student activity was *Q&A*. Nine out of fourteen instructors made time for students to ask content-related questions, typically using between 1% to 6% of the overall symmetry instruction time. Only two instructors—Lindsey (11%) and Ibrina (1%)—had students do *individual problem-solving* during class. Only one instructor, Hendrik (7%), used *quizzes* during symmetry instruction.

The lecture activities category was dominated by *traditional lecture*, with thirteen instructors relying on it between 13% and 82% of the overall symmetry instruction time. One instructor's, Lindsey, lecturing approach differed from the others, as she relied on *Socratic lecturing* (64%) by frequently asking questions to encourage students to think about the content and provide answers. All instructors also used *follow-up lecture*. This involved addressing the entire class to provide feedback or clarification following group activities. Depending on the instructor, follow-up was used between 1% and 42% of the overall symmetry class time.

In the visualization activities category, eight of fourteen instructors used *Otterbein simulations* (Johnston, 2019) to help students visualize symmetry operations in 3D. The time devoted to this activity varied by instructor, ranging from 2% to 23% of class time. For example, Luka spent approximately 8% of the overall class time demonstrating how to use the Otterbein website to identify symmetry operations and practice point group assignment using Otterbein's ''challenge'' function. During the demonstration, students were expected to follow along on their own computers. One instructor, Hanson, used *embodied demonstrations*. For approximately 5% of the class time, students acted as atoms and moved around at the front of the classroom to represent different symmetry operations. This strategy involves not only full-body movement but also gesturing, which aligns with recent findings on students' use of gestures when reasoning through symmetry-related tasks (Markut and Wink, 2024).

Finally, although Fig. 3 does not account for the time instructors spent using *molecular model kits*, as this activity overlapped with others, ten instructors incorporated them as tools for teaching symmetry. However, the extent of use varied widely, from as little as 5% to as much as 80% of class time. Of these ten, nine engaged students with the model kits to varying degrees, while one instructor used them solely for demonstration, without students interacting with the model kits.

RQ2: What reasons inform instructors' decisions to select and implement their most frequently used activities?

To explore the reasons behind instructional choices in relation to the most frequently used activities (*i.e.*, relative proportion of group work *vs.* lecture and other activities), we compared the four identified groups—instructor-centered, low-interactive, high-interactive, and student-centered—to investigate whether instructors in each group shared common influences or reasoning patterns, focusing on personal, contextual, and teacher thinking factors (Fig. 1).

Personal factors. Instructors' years of teaching experience and involvement in the VIPEr community are the key personal factors that we examined to explore patterns behind teaching activities choices. No clear trends were observed between either of these factors and the student-centeredness of participants' teaching. As shown in Fig. 4a, instructors with more teaching experience were not necessarily more student-centered than those with fewer years of experience, and *vice versa*. Similarly, Fig. 4b shows that instructor's VIPEr use did not consistently align with student-centered teaching.

In interviews, many instructors mentioned using the VIPEr website and their Discord community to find teaching resources. However, most did not describe specific symmetry

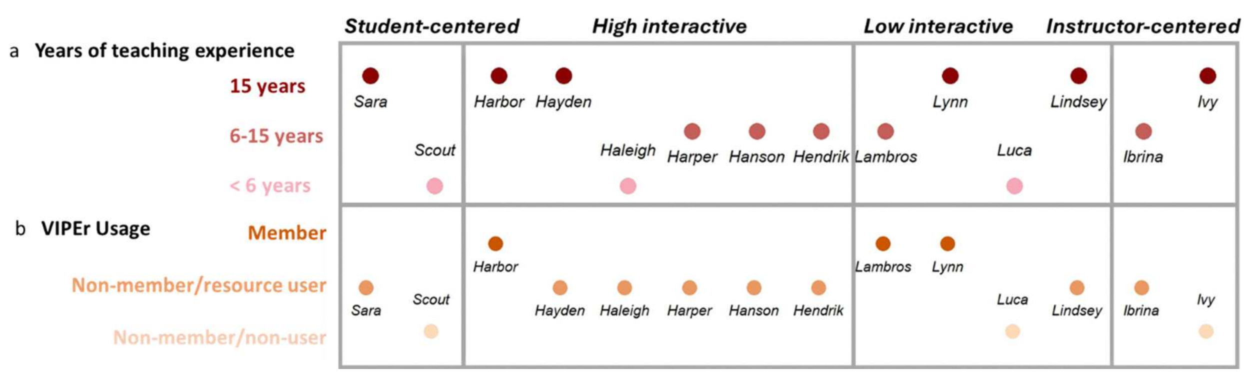

Fig. 4 The relationships between student-centeredness of symmetry teaching and (a) instructors' years of teaching experience and (b) VIPEr membership/usage.

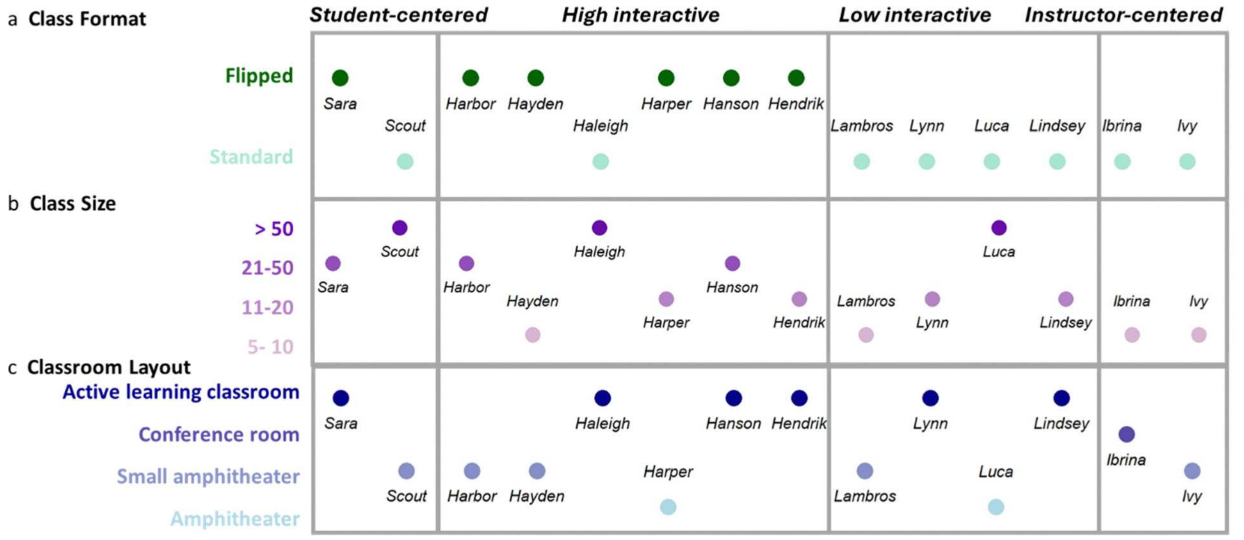

Fig. 5 The relationships between student-centeredness of symmetry teaching and (a) class format, (b) class size, and (c) classroom layout.

activities they implemented from these platforms, with the exception of Hendrick, who shared a memorable example:

"My favorite is, um, when we're not in class, and they'll just see me in the hallway, and they'll point out a random object, and they'll be like, that's a, that's a C_{2v} point group... And that's my favorite. That's... when I know they're really getting it... I think they do it because I have a day where I do ***point group battles****, and I'll just like show molecules on the screen and break 'em into teams and have 'em battle it out one at a time. And I'll throw a lot of, um, objects up there, like arc, flags, signs, and architecture, and that,* ***that was another one I got from my Ionic VIPEr****. That's a fun, that's a fun symmetry day. They really enjoyed being able to do that. Or they'll say like, 'oh, you've ruined me, 'cause now I look at everything as a point group' [laughs]."*

Hendrick's example illustrates how a well-designed, engaging activity adapted from VIPEr can help students develop a lasting understanding of symmetry.

Contextual factors. We also examined several contextual factors that might influence instructors' decisions about teaching activities: class format (flipped *vs.* standard), class size, and classroom layout (*e.g.*, active learning classroom, conference room, small amphitheater, or traditional amphitheater). As shown in Fig. 5a, instructors who used a flipped classroom format (Bergmann, 2012) tended to incorporate more group work during class. In contrast, no clear patterns emerged between class size and the degree of student-centered instruction (Fig. 5b). Instructors with both large and small class sizes appeared across all four instructional style groups. Similarly, classroom layout did not

Table 3 Teacher thinking about reasons for their instructional choices, organized based on instructors' beliefs about how students learn and their reflections on their personal and contextual factors

	Instructor-centered (n = 2)	Low-interactive (n = 4)	High-interactive (n = 6)	Student-centered (n = 2)
Teacher thinking: beliefs about how students learn				
Students learn when listening to a well-organized, scaffolded lecture	n = 2			
Students learn when listening to a lecture that transmits concepts		n = 1		
Students learn when engaging in group work			n = 3	n = 2
Teacher thinking: perceptions of personal factors				
Instructor had a *negative* experience with students not participating in group work	n = 1			
Instructor had a *negative* experience with active learning because students are overwhelmed	n = 1			
Instructor believes they lack group work facilitation skills (n = 1)	n = 1			
Instructor had a *positive* experience with group work because they got feedback on students' learning		n = 1		
Instructor had a *positive* experience with students participating in group work			n = 1	n = 2
Teacher thinking: perceptions of contextual factors				
Classroom layout is *conducive* to active learning	n = 1	n = 2	n = 2	n = 1
Class size is *conducive* to active learning	n = 1	n = 2	n = 2	
Classroom layout is a *barrier* for active learning			n = 2	n = 1
Class size is a *barrier* for active learning	n = 1			

show a consistent relationship with instructional approach (Fig. 5c).

Teacher thinking. Teacher thinking was explored through interviews with instructors to capture reasons for their instructional choices. The results were summarized based on patterns in reasoning in relation to the student-centeredness of teaching: instructor-centered, low-interactive, high-interactive, and student-centered (Table 3). As shown in Table 3, these profiles differ not only in how instructors conceptualize student learning but also in their perceptions of the personal experiences and contextual constraints that shape their instructional decisions.

Instructors' beliefs about how students learn appeared to align strongly with their instructional profiles. Instructor-centered and low-interactive instructors emphasized lecture as the primary vehicle for learning. For example, a low-interactive instructor, Lambros, described: "*I'm giving them information or different types of techniques that they can then synthesize their own information. But, in the real world, a lot of times doing that involves just transmitting information*." Instructor-centered instructors, in particular, emphasized that a well-scaffolded lecture can be an effective teaching strategy. While the level of cognitive engagement may differ from that fostered through group work, scaffolding during lecture has been shown to help students organize their thinking and enhance notetaking, supporting a more meaningful engagement with content (Kiewra *et al.*, 1995; deWinstanley and Bjork, 2002).

In contrast, high-interactive and student-centered instructors emphasized group work as central to the learning process. A high-interactive instructor, Haleigh, explained: "*I don't really believe that I'm able to like just transmit knowledge to students. I think that students have to spend time thinking about the material and working through it, um, on their own or in small groups to make those new connections and have those aha moments*." These patterns suggest that inorganic chemistry instructors' symmetry teaching is tightly linked to their epistemological beliefs about how knowledge is constructed, whether through transmission or interaction.

Personal experiences with group work and active learning also played an important role in shaping instructors' pedagogical choices. Instructor-centered instructors reported negative experiences, such as students not participating in group work or being overwhelmed by active learning, which contributed to their continued reliance on lecture-based instruction. One instructor-centered instructor, Ibrina, even described her lack of skills in facilitating group work: "*I've team-taught with some faculty in humanities, and I watch them lead discussions [during group work] and I'm like, oh, I don't know how to do that. You know, like, and so like, there are things I get better at, but I'm not especially gifted at*."

In contrast, low-interactive, high-interactive, and student-centered instructors generally reported positive experiences with group activities. These experiences were often described as affirming, such as when group work provided meaningful feedback or visibly engaged students in the learning process. For example, a low-interactive instructor, Lynn explained: "*When they're working on problems and I'm, I'm bouncing around the room, um, I think from there I'm getting the feedback of like, okay, they are all not seeing something or they're all seeing something*." Some instructors who use active learning acknowledged that it can be challenging to engage all students, but these difficulties did not deter them from continuing to use interactive strategies. For example, high-interactive instructor, Hendrik, explained: "*If my students are not as talkative or if they're a little more reserved and quieter, I think it's a little harder for me to, to teach it the way I like to teach it [using group work]. Um, so I have to, I have to make a point, a concerted effort to really focus on those individuals and try to go and talk to them and, uh, pull it out of them*." Hendrik's approach illustrates a commitment to adapting his teaching to support student engagement, even when faced with participation challenges. This stands in contrast to instructor-centered faculty, who often viewed a lack of student participation as a reason to avoid group work altogether, rather than experimenting with new strategies to encourage engagement. Additionally, in contrast to the low-interactive and high-interactive instructors, *all* student-centered instructors shared positive experiences with student participation in group work, suggesting that these experiences may reinforce more student-centered approaches.

Contextual constraints, such as classroom layout and class size, were also considered by instructors across all profiles, though perceptions were not consistent with profile placement. Even though most instructor-centered and low-interactive instructors described their classroom layouts and class sizes as conducive to active learning, they leaned heavily on lecturing. For example, low-interactive instructor, Lynn, highlighted that her smaller class size, allows her to more frequently engage with students: "*I think the class size affects it in that I don't think I'd be able to do quite as much as I do if the size were 30, um, in terms of getting around and talking to everyone*." Despite her small class size, Lynn spends 79% of the entire class time on traditional and follow-up lecturing, and only 18% on group work.

In contrast, some high-interactive and student-centered instructors identified classroom layout and class size as barriers to active learning, which are some of the commonly recognized barriers to educational reform (Shadle *et al.*, 2017). Notably, these barriers did not deter them from incorporating a considerable amount of group work into their teaching. These inconsistencies between instructors' reflections on their classroom layout/class size and student-centeredness of their teaching align with and somewhat explain the lack of clear patterns observed in Fig. 5b and c.

RQ3: What areas of content do inorganic chemistry instructors prioritize when teaching molecular symmetry?

Instructors covered fifteen distinct symmetry-related subtopics, which we organized into two overarching categories: symmetry fundamentals and symmetry applications (Fig. 6). The symmetry fundamentals category includes: (1) symmetry in general (*e.g.*, introduction, definition, real-world examples), (2) symmetry operations such as identity, (3) rotation, (4) reflection, (5)

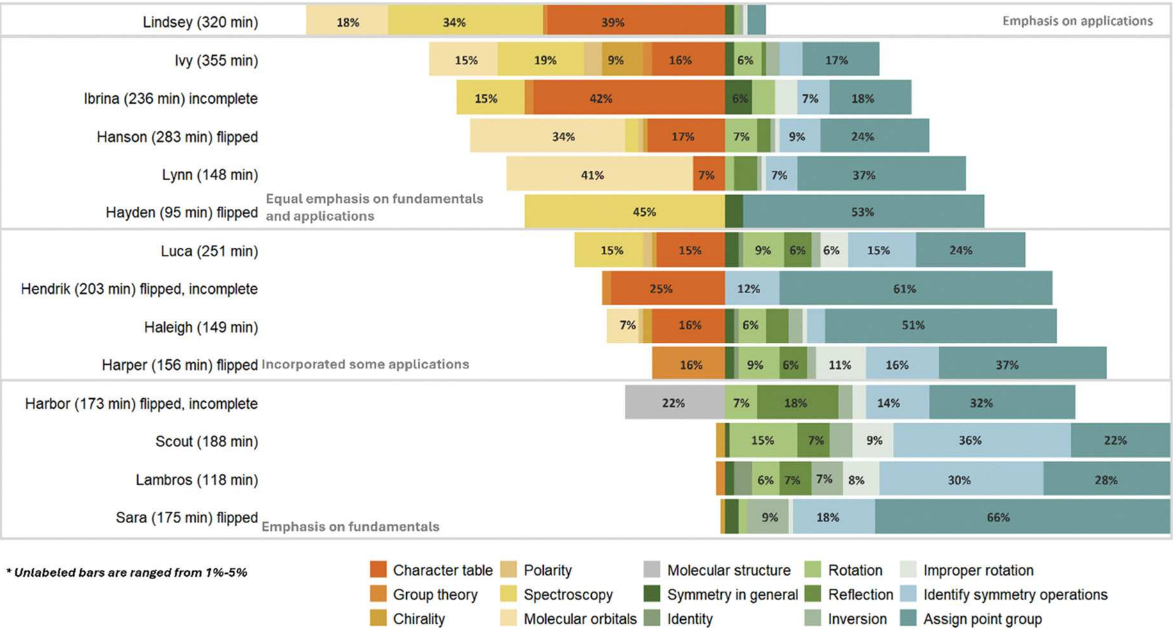

Fig. 6 Time allocation in content coverage across the participants. The total teaching times do not match those in Fig. 3 because we excluded the time spent on "Other" (*e.g.*, announcements, administrative tasks) as non-symmetry-related content, and on "Quizzes" as we could not determine the specific topics covered in quizzes.

inversion, (6) improper rotation, (7) tasks such as identifying and performing symmetry operations, and (8) assigning point groups. The symmetry applications category includes discussion of: (9) character tables, (10) group theory, (11) chirality, (12) polarity, (13) spectroscopy, and (14) molecular orbitals. One subtopic—molecular structure—did not fit into either category. In this case, instructor Harbor started her unit on symmetry by discussing molecular structure. Specifically, she reviewed VSEPR theory and helped students recall how to identify bond lengths and bond angles of different molecules. Harbor likely helped her students connect the new symmetry material to the previous concepts learned in prior courses (Scanlon *et al.*, 2018). Unlike the other subtopics, molecular structure serves as prerequisite knowledge for understanding symmetry, rather than being part of the symmetry content itself, which is why this subtopic was not viewed as a symmetry fundamental or application.

We found a very notable variability in instructors' content choices. Based on the percentage of time each instructor dedicated to symmetry fundamentals *versus* symmetry applications, participants were classified into four groups (Fig. 6):

(1) Emphasis on applications (n = 1): Dedicated more than 90% of class time to teaching symmetry applications.

(2) Equal emphasis on fundamentals and applications (n = 5): Dedicated approximately similar class time to teach symmetry fundamentals and applications.

(3) Incorporated some applications (n = 4): Dedicated most of their class time to symmetry fundamentals, with only some time explaining symmetry applications.

(4) Emphasis on fundamentals (n = 4): Dedicated more than 95% of their class time to teaching symmetry fundamentals.

When focusing on symmetry fundamentals, all instructors dedicated most of their class time to helping students identify symmetry operations in molecules and assign point groups, rather than explicitly teaching each individual operation in depth. This instructional focus suggests that instructors may assume students are already familiar with basic symmetry operations or can acquire them quickly in the context of more applied tasks, such as point group assignment. However, a closer examination of content coverage reveals some troubling inconsistencies and missed opportunities to support student learning, particularly for teaching individual symmetry operations (Fig. S1).

Identity (E) was covered by only four instructors, who spent the least amount of time on it. This likely reflects its conceptual simplicity and the fact that many students intuitively grasp the idea of "doing nothing" to a molecule. In addition, identity is not emphasized in earlier coursework or everyday experiences, but it's also rarely a source of confusion, so instructors may see little need to focus on it.

Rotation (Cn) and **reflection (σ)** received the most attention, with twelve and nine instructors covering them, respectively. This is likely due to these operations being relatively familiar to students, especially because of prior courses such as general chemistry, organic chemistry, or geometry. Students have encountered ideas of rotational and mirror symmetry in molecular shapes (*e.g.*, trigonal planar, tetrahedral, *etc.*) and everyday objects. The extensive focus on these operations may not be as productive. Since these operations are more familiar, students often require less conceptual scaffolding to grasp them compared to more abstract symmetry operations.

Inversion (i) and **improper rotation (Sn)** were taught by eleven instructors each. These operations are more abstract and are typically not emphasized in prior coursework or encountered in daily life. As such, students are less likely to have prior knowledge to draw from and might find these operations more cognitively demanding, especially improper rotation. The lower focus on these operations, especially improper rotation, raises concerns, especially given that among the five symmetry operations, improper rotation was identified by most instructors (nine out of fourteen) as the most difficult for students to recognize and understand, largely due to its complexity. As instructors shared during interviews:

*"...They [students] seem bored when I introduce [them] to **rotation** and **reflection**, and, like, they can answer the questions about it [rotation and reflection] really easily. Um, okay. But once we get to **improper rotation**, they're like, 'Wait, what?' [laughs]."*—Haleigh

*"The **improper rotation**, it's just like the fact that you can have a composite thing. So, following where the atoms go, I mean, I expect them to struggle with lots of it. **Rotations** are good. Mirrors [**reflections**] are typically good. They have a lot of trouble finding all of them [at the same time]."*—Harbor

While many instructors identified improper rotation as particularly difficult for students, this recognition did not consistently translate into extended instructional time on the topic. This may reflect a need to balance instructional time across the curriculum, cover downstream applications, or manage students' cognitive load. Alternatively, instructors may assume that students already understand the components of improper rotation—rotation and reflection—and therefore underestimate the need for dedicated practice given its complexity. However, the lack of time devoted to this challenging subtopic may limit students' ability to develop a deep understanding, particularly if it is not revisited in later applications.

Two instructors, Hayden and Hendrick, did not teach any symmetry operations during class. Both were among the six instructors who used a flipped course structure (Fig. S2). However, unlike the other four, who introduced symmetry operations in both their pre-class videos (asynchronous) and in-class instruction (synchronous), Hayden and Hendrick covered these operations only briefly in their asynchronous videos and used class time exclusively for practicing point group assignments.

Factoring in the asynchronous content from the six flipped-course instructors (Fig. S2) resulted in minimal changes to instructors' placement within the four content coverage groups. Five of the six instructors remain in their original groups, meaning that these instructors display a very similar content coverage focus in both their pre-class videos and during in-class instruction. This suggests a belief in reinforcing content through repetition to support student understanding. However, Hendrick can be shifted from the "incorporated some applications" group to the "equal emphasis on fundamentals and applications" group, as his asynchronous videos dedicated substantial time to symmetry applications (*e.g.*, character tables, spectroscopy, and molecular orbitals).

Finally, across all instructors, symmetry applications similarly show a very high degree of variability in both topic selection and time allocation. While character tables, spectroscopy, and molecular orbitals were the most frequently addressed subtopics in this category (Fig. 6 and Fig. S2), they were still taught by only a subset of instructors and to varying degrees. This inconsistency, evident in both symmetry fundamentals and applications, suggests a lack of consensus within the inorganic chemistry teaching community regarding which symmetry-related content is most essential for student learning.

RQ4: What reasons informed instructors' decisions about content coverage?

To explore the reasons behind instructional choices in relationship to symmetry content coverage, we compared the four identified groups—emphasis on applications, equal emphasis on fundamentals and applications, incorporated some applications, and emphasis on fundamentals—to investigate whether instructors in each group shared common influences or reasoning patterns, focusing on personal, contextual, and teacher thinking factors.

Personal factors. No clear patterns emerged between instructors' symmetry content choices and their years of teaching experience or involvement in the VIPEr community. As shown in Fig. 7a, both less experienced and more experienced instructors were distributed across all four content coverage groups, indicating that experience alone did not predict emphasis on fundamentals or applications. Similarly, Fig. 7b shows that VIPEr use or membership did not consistently align with a

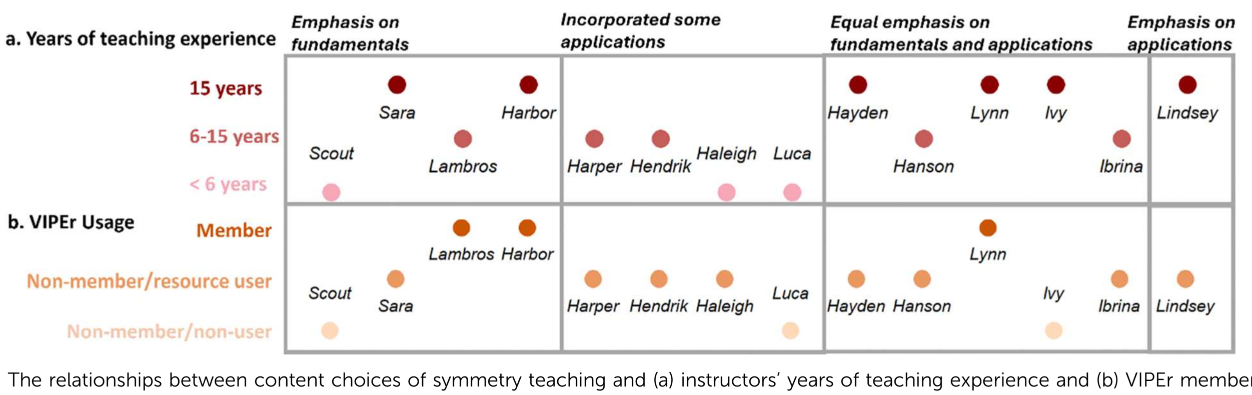

Fig. 7 The relationships between content choices of symmetry teaching and (a) instructors' years of teaching experience and (b) VIPEr membership/usage.

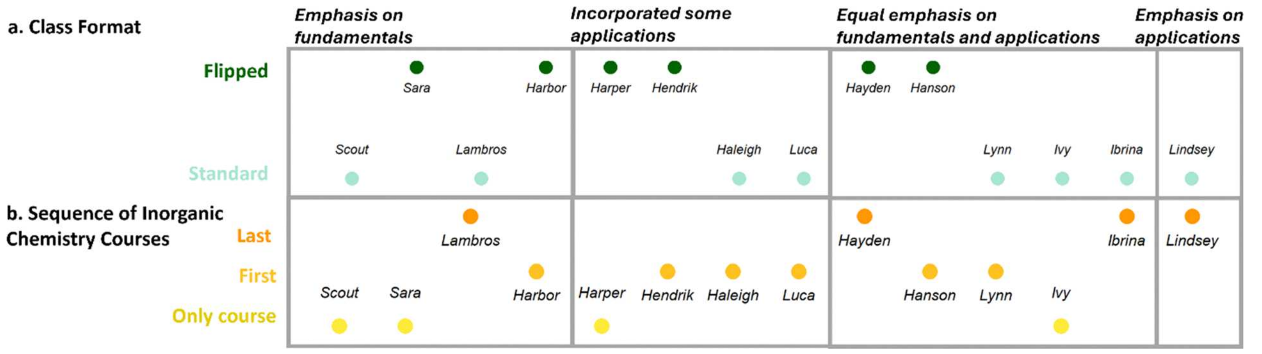

Fig. 8 The relationships between content choices of symmetry teaching and (a) instructors' course format, as well as (b) course sequence.

greater emphasis on applications over fundamentals, or *vice versa*.

Contextual factors. We examined two contextual factors that could potentially influence instructors' decisions about symmetry content coverage: course format (*e.g.*, flipped *vs.* standard) and course sequence within the curriculum (*e.g.*, standalone course, first in a sequence, or terminal course). As shown in Fig. 8a, instructors who used flipped course formats did not necessarily emphasize more applications than those teaching in a standard format. Similarly, no clear patterns emerged based on the sequence of the inorganic chemistry course (Fig. 8b).

Teacher thinking. To better understand instructors' rationale for their emphasis on symmetry fundamentals *versus* applications, we analyzed interview responses about the factors influencing their instructional decisions. Table 4 summarizes the various reasons instructors provided, organized by their symmetry content coverage group.

A lack of students' prior knowledge of symmetry was the most common justification among instructors. All instructors in the first three groups in Table 4 cited this as a key reason for prioritizing or maintaining coverage of fundamentals. For example, Luka shared: "*I assume very much that there's, uh, really no academic prior knowledge of symmetry*." Sara communicated a slightly different perspective on students' prior knowledge of symmetry. Still, she concurred with Luka that students' prior knowledge of symmetry is lacking: "*So, I think they've seen it [symmetry] in popular contexts, um, maybe non-science. But they've also seen it, most of them have seen it in some fashion in a scientific context also, but not to the same degree that we talk about it here*." These data indicate widespread recognition that students typically enter inorganic chemistry courses having little practice with symmetry problems, which likely drives the need for emphasizing fundamentals.

Another prominent concern among instructors in the first three groups was that the topic of symmetry, particularly its applications, felt overwhelming for students. This is exemplified in Sara's quote: "*And the first time I did it, I taught it basically the way my advisor had taught it in the graduate class. And it just like overwhelmed my students. They had no clue. They were like, 'we don't even know what language you're speaking'*." Similarly, Hayden explained: "*Um, I, I, I do sometimes find myself when we're at other places in the class and, you know, doing spectroscopy and realizing that, hmm, maybe they're not quite, they're still struggling with the symmetry aspects of this, so we need to go back and, and, uh, and, and teach them that again*." These perceptions may explain the relatively limited coverage of applications in some courses, as instructors attempt to simplify coverage of symmetry.

Table 4 Teacher thinking about the reasons for their symmetry content-coverage choices

Reasons for content choices	Emphasis on fundamentals (n = 4)	Some applications (n = 4)	Equal emphasis (n = 5)	Emphasis on applications (n = 1)
Teacher thinking: student-related beliefs and observations				
Students lack prior knowledge of symmetry	n = 4	n = 4	n = 5	
Per student feedback, symmetry applications are too overwhelming	n = 1	n = 3	n = 3	
Fundamentals help students develop visuo-spatial ability	n = 1	n = 1	n = 1	
Teacher thinking: instructional sequencing ideas				
Fundamentals are covered in a prerequisite course		n = 1		n = 1
Fundamentals are covered in pre-class videos		n = 1		
Fundamentals are necessary for learning applications	n = 2			
Both fundamentals and applications are necessary for a thorough understanding			n = 2	
Teacher thinking: perceptions of contextual influences				
Time is a barrier to covering more information	n = 1		n = 2	
Colleagues inspire to emphasize applications			n = 1	n = 1

Three instructors across different groups cited that a focus on fundamentals helps students develop visuospatial ability, which is critical for success in symmetry-based reasoning. For example, Harper explained: "*I take more time to like show examples, walk through sample problems, um, uh, try and get students kind of see, practice their spatial reasoning skills a little bit with those concepts*."

Some instructors who prioritized or included more fundamentals highlighted the role of fundamentals in supporting later learning. For example, two instructors in the "emphasis on fundamentals" group highlighted that a strong foundation is necessary to understand applications. For example, Sara stated: "*I only really teach up through point groups and that's it. Um, so I do teach it, and they do understand it, but they mostly use it to understand coordination chemistry and molecular orbital bonding that happens later in class*."

Two instructors in the "equal emphasis" group believed that it was critical to connect fundamentals to applications for thorough understanding. Ivy highlighted this idea by saying: "*The first part of the lectures is usually like just getting out the terms and getting out the descriptions, and here's all the basic things. And then we jump off the cliff into a little more depth. So, I'm giving them both depth and breadth*."

Three instructors cited course structure or sequencing as influencing their decisions. For instance, those in the "incorporated some applications" and "emphasis on applications" groups sometimes assumed that fundamentals were already covered in prerequisite courses or pre-class videos, allowing them to shift focus to applications during class.

Time constraints were mentioned by instructors in both the "emphasis on fundamentals" and "equal emphasis" groups, signaling a shared challenge across coverage styles in fitting both fundamentals and applications into limited instructional time.

Finally, two instructors, one in the "equal emphasis" group and one in the "emphasis on applications" group, indicated that colleagues in academia and/or industry influenced their choice to include more applications, suggesting that peer influence plays a role in some content decisions. For example, Lindsey described the following:

"*I had a former student who works in industry, and he was like saying something along the lines of, 'everything that I need is in the infrared spectrum. You know, why is this glue delaminating? I can look at that with infrared and figure everything else out from there.' Now, he didn't specifically call out symmetry and group theory, but he definitely pointed out the fact that this is a tool that they can use*."

RQ5: What connections might exist between inorganic chemistry faculty' instructional and content choices when teaching molecular symmetry?

To examine connections between instructional and curriculum choices, we grouped the instructors into smaller groups due to the small sample size ($N = 14$) for examining such patterns. As such, we grouped the "student-centered" and "high-interactive" instructors into the "more student-centered" group ($n = 8$) and the "low-interactive" and "instructor-centered" instructors into the "more instructor-centered" group ($n = 6$). Similarly, we grouped the "incorporated some applications" and "emphasis on fundamentals" instructors into the "more emphasis on fundamentals" group ($n = 8$) and the "emphasis on applications" and "equal emphasis" instructors into the "more emphasis on applications" group ($n = 6$). Fig. 9 shows the relationship between inorganic chemistry instructors' teaching and content choices when teaching molecular symmetry. We found that student-centered instructors are more likely to place greater emphasis on fundamentals, whereas instructor-centered instructors are more likely to place greater emphasis on applications.

When examining connections between instructional activities and content coverage choices in more nuance by focusing on time allocation during symmetry lessons, we found corroborating patterns. Most instructors facilitate more group work activities when teaching symmetry fundamentals (Fig. S3),

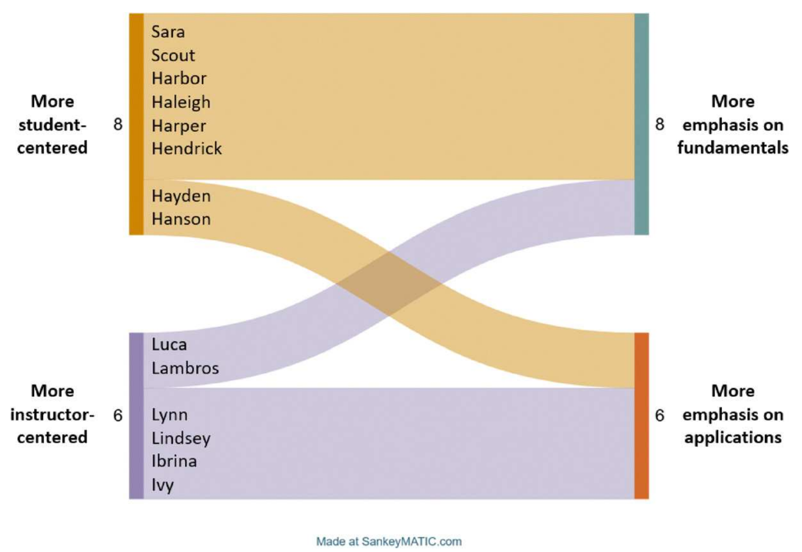

Fig. 9 The relationship between inorganic chemistry faculty' instructional and content choices when teaching molecular symmetry.

particularly by devoting time to practice identifying symmetry operations and assigning point groups. We also found that most instructors use mostly lecturing when teaching symmetry applications (Fig. S4).

Limitations

This study has several limitations. First, while the sample size is robust for a qualitative study, especially one that triangulates a very large amount of video observation data with interviews, it is relatively small for drawing definitive conclusions about nuanced patterns. For example, our findings should be interpreted with caution when analyzing the intersection of instructional style and content emphasis, or the relative influence of teacher thinking, personal factors, and contextual constraints on pedagogical decisions (see Themes 2 and 3 below). As an exploratory study, these findings are best viewed as a foundation for future research. Larger-scale studies are needed to support and deepen these insights.

Second, there is a potential for selection bias. Participants were recruited through social media and the VIPEr community, which likely attracted instructors who were already open to reflecting on and sharing their teaching practices. Additionally, since all participants were from the United States, the study reflects a single higher education culture, which may limit the transferability of the findings to international contexts. However, despite these limitations, the in-depth analysis of classroom observations from fourteen instructors across various institutions teaching the same topic provides rich insight into a range of instructional approaches. Additionally, we found that VIPEr community participation does not impact instructors' teaching strategies and symmetry content choices, which reduces concerns about selection bias.

Fourth, the study did not include an interview protocol specifically designed to probe instructors' reasons for their pedagogical choices related to instructional activities and content emphasis. As a result, some important motivations may not have been fully captured. Future research could build on these findings by incorporating interviews or other methods to more directly explore the reasoning behind instructional and curriculum decisions.

Lastly, although we considered multiple contextual and personal factors that might influence instruction, it is possible that other relevant factors were not identified or explored. More research is needed to uncover the complex interplay between individual, institutional, and disciplinary influences on symmetry teaching.

Conclusions and discussion

Three themes were developed based on our findings: (1) instructional strategies and content emphasis in teaching symmetry vary substantially across instructors, (2) more student-centered instructors tend to focus on foundational symmetry concepts and skills, whereas more instructor-centered instructors tend to prioritize advanced applications, and (3) instructors' thinking, rather than their personal and contextual factors, drives their instructional and content decisions for teaching symmetry.

Theme 1: Instructional strategies and content emphasis in teaching symmetry vary substantially across instructors.

A central theme emerging from this study is the substantial variation in both instructional strategies and content coverage in teaching molecular symmetry in inorganic chemistry courses. Across the fourteen instructors, there was no dominant or standardized approach to symmetry instruction. Instead, we observed a broad spectrum of teaching practices, ranging from student-centered to instructor-centered. Specifically, we identified eleven distinct instructional activities used by the inorganic chemistry instructors during lessons on molecular symmetry. These activities were broadly categorized into student activities, lecture activities, visualization activities, and other activities not directly related to symmetry content. The substantial variation in the teaching activities used and the differences in the visualization tools to support student visuospatial ability (Wu and Shah, 2004; Harle and Towns, 2011) may lead to vastly different student outcomes. Notably, only half of the inorganic chemistry instructors in our study relied heavily on lecturing when teaching symmetry. This finding differs from other studies, which have found that lecturing remains the primary mode of instruction among STEM instructors (Stains *et al.*, 2018) or introductory chemistry instructors (Wang *et al.*, 2024).

Likewise, there was notable variation in content prioritization, with some instructors emphasizing applications and others focusing almost exclusively on symmetry fundamentals. Fourteen of the fifteen subtopics that we identified were grouped into two overarching categories: symmetry fundamentals and symmetry applications. Instructors were further categorized into four content emphasis groups, ranging from emphasis on applications to emphasis on fundamentals. When it comes to symmetry fundamentals, most instructors emphasized practicing identifying symmetry operations and assigning point groups rather than scaffolding individual symmetry operations. Notably, instructors tended to allocate less time to conceptually challenging operations, such as improper rotation, despite identifying it as particularly difficult for students. This mismatch between perceived difficulty and instructional time raises concerns about whether students are receiving adequate support for mastering one of the most conceptually demanding symmetry operations. When it comes to applications, while character tables, spectroscopy, and molecular orbitals were the most taught, they were still inconsistently addressed, further underscoring a lack of consensus regarding essential symmetry content. Such inconsistency in content coverage may contribute to unequal learning experiences across courses and institutions, making it difficult to ensure a common foundational understanding of molecular symmetry for all students. The variation in content coverage emphasis may be explained by previously reported differences in chemistry instructors' stances on "the debate" between depth and breadth of content coverage (Kraft *et al.*, 2023).

This variation reflects a broader lack of consensus within the inorganic chemistry community regarding what content is most essential and how it should be taught to promote student learning of symmetry. While some level of flexibility in instructional style is expected due to differences in teaching context and student populations, the degree of inconsistency observed raises concerns. Students taking inorganic chemistry courses at different institutions, or even with different instructors at the same institution, may leave with vastly different understandings of molecular symmetry, depending on which activities, representations, and subtopics they were exposed to.

To our knowledge, this study is the first to systematically document the instructional strategies employed by inorganic chemistry instructors using video observations. While our focus here is on characterizing these strategies, an important next step is to examine how they influence student outcomes. Future research should extend this work by linking specific instructional strategies to measures of student learning, engagement, and persistence in inorganic chemistry courses. Similarly, future research should examine how the content emphasis in teaching symmetry may impact students' learning outcomes.

Theme 2: More student-centered instructors tend to focus on foundational symmetry concepts and skills, whereas more instructor-centered instructors tend to prioritize advanced applications.

One additional theme emerged when considering the intersection between instructional style and content coverage focus. We found that more student-centered instructors were more likely to emphasize symmetry fundamentals, whereas more instructor-centered instructors were more likely to emphasize applications. This finding may reflect a difference in pedagogical priorities: more student-centered instructors may aim to cultivate deeper understanding but of a smaller amount of content, supporting students in developing robust understanding of symmetry fundamentals through group work activities. Conversely, more instructor-centered instructors may prioritize exposing students to a broader range of content. In such classrooms, lectures can be used efficiently to deliver a wider range of topics, including symmetry applications such as character tables, spectroscopy, and molecular orbital theory, albeit with less emphasis on conceptual scaffolding or opportunities for students to engage deeply with the material. These patterns also suggest that students in instructor-centered courses may encounter a broader range of applications without the robust foundation necessary to fully understand them, while those in student-centered courses may develop a deeper, yet more limited, understanding of symmetry. These trade-offs highlight the importance of carefully considering learning goals and instructional approaches in symmetry instruction. Given prior research showing that emphasizing depth over breadth can enhance student learning outcomes (Murdock, 2008; Schwartz *et al.*, 2009; Luckie *et al.*, 2012), the inorganic chemistry community should critically examine how to strike an optimal balance between teaching symmetry fundamentals and applications to support student learning.

Theme 3: Instructors' thinking, rather than their personal and contextual factors, drives their instructional and content decisions for teaching symmetry.

Using the TCSR model, we examined the extent to which teacher thinking, personal factors, and contextual factors shape instructors' decisions about teaching activities and content coverage. Table 5 summarizes these patterns.

Instructors' **personal factors**, such as years of teaching experience and their engagement with the VIPEr community, did not show clear patterns related to either instructional approach or content emphasis. VIPEr community involvement did not have a notable impact; while VIPEr provides valuable teaching materials and fosters community, this electronic resource does not explicitly focus on promoting active learning or training instructors in how to effectively implement student-centered strategies. Similarly, although this resource contains numerous activities, it does not promote a specific curriculum or content emphasis. As a result, instructors may engage with the community without changing their teaching or curriculum practices.

Instructors' **contextual factors**, such as class size, classroom layout, and course sequencing, also did not show clear patterns related to instructional approach and/or content emphasis. Our findings align with those from Stains and colleagues (2018), who also conducted classroom observations of lessons taught by 548 STEM instructors and found that flexible classroom layouts and small course sizes do not necessarily lead to an increase in student-centered practices. In contrast, our findings do not align with those from another large study that used self-report surveys from 2382 chemistry, mathematics, and physics

Table 5 The impact of personal factors, contextual factors, and teacher thinking on instructional and content decisions for teaching symmetry

Categories	Factors	Instructional approach	Content emphasis
Personal factors	Years of teaching experience	No	No
	VIPEr community involvement	No	No
Contextual factors	Class format	Yes[a]	No
	Class size	No	n/a
	Classroom layout	No	n/a
	Course sequence	n/a	No
Teacher thinking	Beliefs & observations about students	Yes	Yes
	Perceptions of contextual influences	No[a]	potentially
	Experiences and self-efficacy	Yes	n/a
	Instructional sequencing ideas	n/a	potentially

[a] To fully understand the impact of these factors, please read the discussion, as their influence is nuanced.

instructors (Yik *et al.*, 2022). Yik and colleagues found that large class sizes are associated with a higher percentage of time spent lecturing, and a classroom layout conducive to group work is associated with a decrease in percent time spent lecturing.

While class format (flipped *vs.* traditional) appeared to be the only contextual factor associated with increased use of group work, this relationship warrants deeper interpretation through the lens of the TCSR model, which emphasizes the interconnectedness of personal, contextual, and teacher thinking factors. Although we positioned the flipped class format (Bergmann, 2012) as a contextual variable, the decision to adopt this format likely reflects deeper aspects of teacher thinking. Flipping a course requires significant time, planning, and effort. Instructors who choose this approach often do so because they view active learning as central to their teaching philosophy. In this sense, the use of a flipped classroom is not merely a contextual circumstance, but an intentional instructional design choice grounded in a belief that in-class time should prioritize student-centered engagement. Thus, the adoption of a flipped format may be better understood as an expression of teacher thinking rather than a purely contextual factor. Overall, our findings align with those of a large quantitative study by Srinivasan *et al.* (2018), which found that the use of flipped classrooms by chemistry faculty is significantly associated with the use of active learning instructional practices.

Finally, **teacher thinking** was strongly associated with both instructional approach and content emphasis. Most instructors cited students' lack of prior knowledge and the perceived complexity of symmetry, especially its applications, as central reasons for explaining their teaching choices. While some responded by doubling down on fundamentals, others attempted to strike a balance by incorporating applications to support conceptual connections. These decisions appeared to be shaped by instructors' pedagogical beliefs and past teaching experiences. For example, instructors' beliefs about student learning are strongly aligned with their instructional style, corroborating findings from previous studies with chemistry instructors (Gibbons *et al.*, 2018; Popova *et al.*, 2020). Specifically, instructors in the student-centered or high-interactive categories tended to incorporate group activities based on their belief that students learn best through active engagement. This perspective aligns with prior research in physics, which found that active learning strategies can enhance student interest and improve academic performance (Fencl and Scheel, 2005). Similar results were reported in the meta-analysis by Freeman *et al.* (2014), which demonstrated that active learning improves outcomes across STEM disciplines. Personal teaching experiences and self-efficacy to facilitate active learning also played a pivotal role. Instructors who had negative experiences with group work tended to avoid student-centered approaches, whereas those who had seen its benefits more readily embraced active learning. This aligns with previous research emphasizing that effective facilitation by the instructor is critical for active learning activities (Forslund Frykedal and Hammar Chiriac, 2018; Masek *et al.*, 2021) and that student engagement is key to the effectiveness of group work (Forslund Frykedal and Hammar Chiriac, 2018; Mintzes and Walter, 2020).

Perceptions of contextual influences (*e.g.*, colleagues) and instructional sequencing ideas (*e.g.*, consideration of content coverage in previous courses or in pre-class videos) were associated with content emphasis only for some instructors. Further research with a larger sample is needed to clarify the role these factors play in shaping content coverage decisions.

Perceptions of other contextual factors, such as classroom layout and class size, did not consistently align with instructional style. Some instructor-centered instructors described their classrooms as well-suited for active learning, yet relied on lecture, while some student-centered instructors reported considerable contextual barriers but still prioritized group work. These instructors likely find a way around these barriers due to their beliefs about what makes for effective learning and their positive experiences facilitating group work activities. These findings suggest that beliefs about what makes for effective teaching and learning may outweigh contextual constraints in shaping instructional choices. Previous research has shown that faculty desire for student success is a major driver toward educational reform and classroom experimentation with active learning techniques (Shadle *et al.*, 2017).

Implications

The substantial variation in both instructional strategies and content emphasis results in highly inconsistent exposure to molecular symmetry for students. This lack of alignment across instructors and institutions may result in unequal preparation for advanced coursework or research. This variation may have real impacts on students, such as differences in foundational understanding, preparedness for applications, or sense of confidence in upper-level coursework or graduate programs. For example, some students pursuing graduate programs in chemistry describe facing challenges transitioning into their rigorous graduate programs, often struggling with unrealistic expectations of prior knowledge (Jones, *et al.*, 2025). Our findings demonstrate that it might not be reasonable to expect students to enter graduate programs with specific prior knowledge, given that they may receive very different instruction in their undergraduate programs. Given the substantial variability in what symmetry content is covered, community dialogue around core learning goals may help ensure greater consistency and transparency in student preparation. While some variation is understandable between lower-level and advanced inorganic chemistry courses, the community needs to intentionally consider learning outcomes related to symmetry for each of these types of courses.

Furthermore, the finding that many instructors devote little time to the most difficult symmetry operation—improper rotation—despite identifying it as particularly challenging, suggests a mismatch between perceived student needs and instructional choices. This could reflect time constraints, lack of instructional resources, or uncertainty about how to teach these concepts effectively. To address this issue, professional development efforts could help instructors prioritize more conceptually challenging content, offering concrete tools and strategies for supporting student understanding. Such professional development could also provide instructors with opportunities to reflect on their own assumptions about what matters most in symmetry instruction and why. Facilitated community dialogue and feedback could help instructors recognize the potential impact of their choices.

A particularly useful direction for faculty professional development is to help instructors intentionally reflect on whether their current content emphasis supports their intended learning outcomes. Faculty development might help instructors reflect on how their instructional choices, whether emphasizing foundational understanding or broader applications, align with their intended learning outcomes and support student learning. Conversely, if exposure to a wide range of applications is a priority, then a breadth-oriented approach may be more appropriate; however, it must still be balanced with sufficient scaffolding and rely on student-centered strategies.

Relatedly, another important area for faculty professional development is supporting inorganic chemistry instructors in adopting student-centered practices, especially since our findings indicate that some participants had negative experiences or lacked confidence in facilitating active learning. While institutional constraints, such as class size or room layout, are commonly cited as barriers (Shadle *et al.*, 2017), our study shows that these contextual factors do not necessarily dictate instructional practices. Instead, instructors who believe in the value of active learning find ways to implement it, even in environments not designed for it. This finding underscores the importance of reflecting on teaching beliefs and practices as a strategy for promoting student-centered teaching. Initiatives that focus solely on course materials or infrastructure will likely fall short if they do not also attend to instructor beliefs, self-efficacy, and values.

In summary, teaching practices are not primarily shaped by what instructors have access to, but rather by what they believe, how they interpret their classroom realities, and how confident they feel in navigating complex content with their students. Professional development, curricular reform, and community-level change efforts in inorganic chemistry should center on this reality if they aim to foster more equitable and evidence-based learning experiences for all students.

Ethical considerations

This study was conducted under the University of Wisconsin–Madison Health Sciences IRB (2022–0248).

Conflicts of interest

There are no conflicts to declare.

Data availability

The datasets generated and analyzed in this study are not publicly available due to the potential for participant identification and confidentiality agreements. However, de-identified excerpts of the data may be made available from the corresponding author upon reasonable request.

The supplementary information includes the interview protocol, codebooks used to analyze pedagogical activity and content coverage choices, as well as several figures that highlight trends in the data. See DOI: **https://doi.org/10.1039/d5rp00275c**.

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