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Exploring social and cognitive engagement in small groups through a community of learners (CoL) lens†

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A variety of research studies reveal the advantages of actively engaging students in the learning process through collaborative work in the classroom. However, the complex nature of the learning environment in large college general chemistry courses makes it challenging to identify the different factors that affect students' cognitive and social engagement while working on in-class tasks. To provide insights into this area, we took a closer look at students' conversations during in-class activities to characterize typical discourse patterns and expressed chemical thinking in representative student groups in samples collected in five different learning environments across four universities. For this purpose, we adapted and applied a 'Community of Learners' (CoL) theoretical perspective to characterize group activity through the analysis of student discourse. Within a CoL perspective, the extent to which a group functions as a community of learners is analyzed along five dimensions including Community of Discourse (CoD), Legitimization of Differences (LoD), Building on Ideas (BoI), Reflective Learning (RL), and Community of Practice (CoP). Our findings make explicit the complexity of analyzing student engagement in large active learning environments where a multitude of variables can affect group work. These include, among others, group size and composition, the cognitive level of the tasks, the types of cognitive processes used to complete tasks, and the motivation and willingness of students to substantively engage in disciplinary reasoning. Our results point to important considerations in the design and implementation of active learning environments that engage more students with chemical ideas at higher levels of reasoning.

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Introduction

Current reform efforts in chemistry education seek to help students develop a better understanding of core concepts, practices, and ways of thinking in the discipline. A growing body of work highlights the advantages of active learning strategies and socially mediated forms of learning in promoting positive student outcomes when implemented with fidelity (Chi and Wylie, 2014; Freeman *et al.*, 2014; Theobald *et al.*, 2020; Lombardi *et al.*, 2021). However, the complex nature of the learning environment in large collaborative college chemistry courses makes it challenging to identify the different factors that affect students' cognitive and social engagement while working on in-class tasks. To provide insights into this area, in a recent study we explored student engagement in different learning environments that fostered students' active participation in various types of classroom activities (Reid *et al.*, 2022). We were particularly interested in characterizing how the cognitive level of these tasks (*e.g.*, retrieval, comprehension, analysis) correlated with how knowledge was shared, used, or constructed during collaborative activity (knowledge dynamics) and with the social relationships and types of participation (social processing) in student groups. We found a significant association between the cognitive level of a task and student engagement, with less cognitively complex tasks resulting in fewer instances of collaboration and engagement in knowledge construction than more cognitively complex tasks.

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In the present study, we extend our investigation into student engagement in active learning environments by taking a closer look at students' conversations while completing in-class tasks to characterize typical discourse patterns and expressed chemical thinking in representative student groups in samples collected in five different college general chemistry learning environments across four universities. We analyzed student conversations to generate a fine-grained picture of students' social and cognitive engagement in the classroom. Our results provide insights into factors that affect the nature of students' conversations and the extent to which they engage with chemical concepts and ideas.

Student discourse and reasoning in chemistry

In this paper, we define discourse as the verbal and non-verbal language that people use to interact in a community (Gee, 2015). Scientific discourse, for example, often involves asking questions, forming arguments, and constructing explanations that can be shared with the scientific community to help understand new phenomena (Lemke, 1990; Osborne, 2010). As a qualitative research tool, discourse analysis allows researchers to explore the role that peer-to-peer as well as peer-to-facilitator conversations have on student learning (Gee and Green, 1998; Driver *et al.*, 2000; Mercer, 2010; Young and Talanquer, 2013; Cole *et al.*, 2014; Kulatunga *et al.*, 2014; Moon *et al.*, 2016; Repice *et al.*, 2016; Moon *et al.*, 2017; Nennig *et al.*, 2023). Research has shown that specific discourse moves such as providing reasoning, building on or challenging each other's ideas, actively listening, and requesting clarification or justification promote group understanding of chemical phenomena (Towns, 1998; Michaels *et al.*, 2008; Criswell, 2012; Michaels and O'Connor, 2015; Moon *et al.*, 2017). However, getting students to engage in these behaviors, and do it effectively, can be quite challenging (Osborne, 2010; Reid *et al.*, 2022).

Student discourse in chemistry classrooms is affected by the reasoning approaches that students adopt when working on a task. Chemistry students have been shown to rely on rule-based and case-based approaches more heavily than on model-based ways of reasoning when answering questions or solving problems (Bhattacharyya, 2006; Kraft *et al.*, 2010; Christian and Talanquer, 2012). Chemistry students are also known to overrely on tacit short-cut reasoning procedures to make quick decisions about relevant factors affecting the properties or behavior of chemical systems (Maeyer and Talanquer, 2010; McClary and Talanquer, 2011). These intuitive reasoning heuristics allow students to reduce cognitive load and generate answers through the analysis of surface features, although they often lead students astray (Talanquer, 2014).

Reliance on heuristics privileges modes of reasoning in which students build quick associations between properties and behaviors (*e.g.*, the bigger an ion is, the more stable it is). This relational reasoning has been shown to dominate students' conversations in diverse chemistry classrooms (Moreira *et al.*, 2019; Deng and Flynn, 2021). Students often also simplify the task at hand by reducing the number of variables they consider, typically to one, building simple causal model-based explanations (Grotzer, 2003; Sevian and Talanquer, 2014). For example, in predicting the polarity of a species they may consider the difference in electronegativities between bonded atoms but not the molecular geometry (Furió *et al.*, 2000).

Student engagement

In collaborative learning environments, student engagement is indicative of the degree of participation, attention, and intellectual involvement of students while completing assigned tasks (Kuh, 2009). It is commonly assumed that high levels of engagement will result in more meaningful learning and stronger student performance overall. Researchers recognize student engagement as a multidimensional construct and have sought to characterize it through the analysis of behavioral, cognitive, and emotional factors (Fredricks *et al.*, 2004; Reeve and Tseng, 2011). Naibert *et al.* (2022) suggested that the characterization of student engagement should also include a social dimension and proposed an 'umbrella of engagement' framework based on the four dimensions included in Table 1.

In this study, we sought to characterize students' social and cognitive engagement through the analysis of small group conversations while completing in-class tasks in college general chemistry classrooms. For this purpose, we adapted and applied a 'Community of Learners' (CoL) theoretical perspective (Brown and Campione, 1990; Brown, 1994) to characterize group activity through the analysis of student discourse. Within a CoL perspective, the extent to which a group functions as a community of learners can be analyzed along five major dimensions (Brown and Campione, 1990; Brown, 1994): (1) *Community of Discourse (CoD)*: students engage in a conversation in which different ideas are allowed to migrate through group talk, creating space for multiple voices to be heard. (2) *Legitimization of Differences (LoD)*: the different ideas and lived experiences of all group members are acknowledged, discussed, and considered in the construction of understandings.

Table 1 Major dimensions of student engagement

Mode of engagement	Definitions adapted from Fredricks *et al.* (2004) and Naibert *et al.* (2022)
Behavioral	Physical participation in the presented tasks
Cognitive	Exerting mental effort to comprehend ideas presented in the tasks
Social	Working with others and sharing ideas to solve presented tasks
Emotional	Feelings towards the presented tasks

(3) *Building on Ideas (BoI)*: this dimension draws on Vygotsky's work with Social Constructivism and the Zone of Proximal Development (ZPD), where members of a group are likely to have different levels of relevant understanding when working on a task (Vygotsky, 1978). All levels of understanding are welcome in the community, with ideas from different members building on each other toward higher levels of understanding. (4) *Reflective Learning (RL)*: a great deal of academic learning is active, strategic, self-conscious, self-motivated, and purposeful. Members of the community are thus expected to engage in reflection to support and evaluate progress towards the learning goals. (5) *Community of Practice (CoP)*: group members engage in the practices and modes of reasoning that are characteristic of the community, using them to complete assigned tasks and meet learning goals. These five dimensions of analysis highlight different aspects of students' engagement; social and cognitive engagement are the focus of the more fine-grained characterization of group activity in active learning environments presented in this paper.

Methods

General aim, specific goal, and research questions

This study is part of a larger project involving four research sites across the United States, and it aims to characterize critical features of in-class tasks' design, implementation, and facilitation in collaborative learning environments that promote productive student engagement. The goal of the investigation described in this contribution was to characterize students' social and cognitive engagement through the analysis of discourse patterns in small groups working on in-class tasks. Our research was guided by the following research questions:

• To what extent do small groups function as a community of learners in chemistry?

• What factors affect students' social and cognitive engagement with chemical concepts and ideas?

Classroom settings

This study took place in primarily first-year general chemistry I classes with a few observations taking place in general chemistry II classes across five different learning environments at four universities in the US. Key features of each environment are summarized in Table 2 and more details can be found in Reid *et al.* (2022). All data collection was approved by the Institutional Review Board (IRB) at each institution (approved protocol numbers are listed in Table 2). All participants provided written consent and were de-identified with assigned pseudonyms.

Data collection

To capture classroom discourse, a variety of student groups were audio and video recorded while working through in-class tasks. After the initial characterization of tasks and student engagement as described in our previous work (Reid *et al.*, 2022), a subset of tasks from each site was selected for more detailed analysis. These tasks were first selected from instances in which at least two different groups were working on the same task. For each task in this subset, we selected two groups that were behaviorally engaged in the task but exhibited different social processing and knowledge dynamics as described in Reid *et al.* (2022). These groups represented various ways in which students engaged socially and cognitively with the same task. A total of 66 conversations as students worked on 33 different tasks with various cognitive levels were selected for fine-grained analysis: three tasks from SBU, five tasks each from MTSU and UI discussion, and ten tasks each from UA and UI lecture. The dialogue in each of these cases was transcribed verbatim for analysis. The selected tasks corresponded to a variety of topics across the general chemistry curriculum, with major concepts

Table 2 Key features of each of the five learning environments observed as part of this study

Research site (IRB protocol number)	Learning environment	Identifier	Class size	Instructor type	Student to instructor ratio	Meeting frequency	Room layout
Stony Brook University (917004)	Discussion (POGIL)	SBU-D	∼150	GTA	36 : 1	80 minutes once a week	Tables set up for small group discussion
University of Iowa (201309825)	Discussion (traditional)	UI-D	∼26	GTA	26 : 1	50 minutes once a week	Tables set up for small group discussion
	Lecture (traditional)	UI-L	∼250	Professor & GTAs	62 : 1	50 minutes three times a week	Stadium style lecture hall
Middle Tennessee State University (19-2253)	Lecture (POGIL)	MTSU-L	∼24	Professor	24 : 1	Semester 1	Semester 1 tables set up for small group discussion in person
						90 minutes two times a week	Semester 2
						Semester 2	Zoom breakout rooms consisting of two in person students and two online students in a hybrid class
						55 minutes three times a week hybrid	
University of Arizona (1905584616)	Lecture (chemical thinking)	UA-L	∼220	Professor & learning assistants	30 : 1	50 minutes three times a week	Tables set up for small group discussion

including but not limited to periodic trends, electronic configurations, orbital diagrams, chemical reactions, chemical equilibrium, gas laws, stoichiometry, chemical bonding, inter- and intra-molecular forces, heat of reaction, calorimetry, entropy, and enthalpy. The ways in which these tasks were delivered to students included worksheets, student response systems, and online worksheets with immediate electronic feedback. The tasks included in this study are presented in the ESI.†

Data analysis

Data analysis focused on characterizing students' social and cognitive engagement along the five dimensions in our 'Community of Learners' framework. To better ground this analysis, each of the 66 selected conversations was coded using two different analytical frameworks: (1) student interaction discourse moves, and (2) student expressed chemical thinking. These analytical frameworks are broadly defined in their respective subsections, with both being described using the example group conversation provided below. This conversation took place between four group members regarding the task shown in Fig. 1. A more detailed application of both frameworks along with the codebooks can be found in the ESI.†

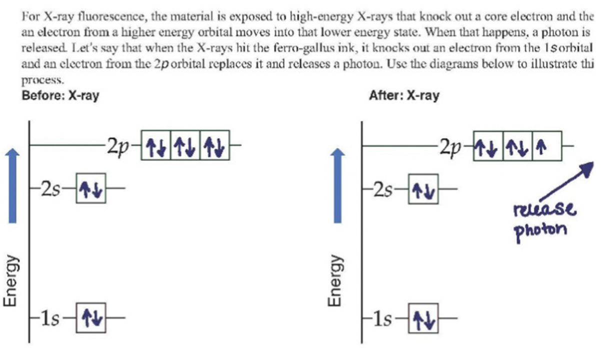


Fig. 1 Example task completed by Shakespeare, Lewis, Evans, and Dahl.

1	Shakespeare:	Basically, one electron from the 1s goes away and one of the electrons from the 2p replaces it by going down to the 1s.
2	Lewis interrupts Shakespeare:	Okay so it goes from...
3	Shakespeare:	Because you need to fill it back up
4	Lewis:	$2p^6$ to $2p^5$ to replace the...
5	Shakespeare:	To replace the 1s which has lost energy.
6	Lewis interrupts Shakespeare:	...the one that lost an electron.
7	Shakespeare:	Yup. And then that process emits a photon basically.
8	Evans:	*huff*
9	Lewis:	[*Lewis starts interaction with TA. Hermione about their answer to the previous task.*]
10	Shakespeare:	Ah for that ummm draw these in like you did last time.
11	Evans:	All of them?
12	Shakespeare:	Just for the first diagram. So the 1s would have two electrons, 2s would have two electrons.
13	Evans:	And then 6 here? [*Pointing at 2p orbital*]
14	Shakespeare:	Yup. And then for that one, 2s is going to be the same
15	Dahl:	I was listening to [*TA. Hermione*]. What problem are we working on?
16	Shakespeare directed at Evans:	And then 2p is going to have five electrons instead of six, so the last one would just have one. And then 1s is going to have two.
17	Evans:	But then wouldn't it have to be...
18	Dahl:	So what question?
19	Evans:	So instead of ... [*pause*]
20	Shakespeare:	It says, knock out an electron from 1s, and then put one of the electrons from 2p where that 1s electron was, so everything looks the same except this is five instead of six.
21	Evans:	What does that...
22	Shakespeare interrupts Evans:	And then you released a photon.
23	Evans to Shakespeare:	Like that? [*Pointing to what they drew and wrote.*]
24	Dahl:	Yeah
25	Shakespeare:	Photon not proton.
26	Evans:	*Giggles* [*Erases proton and changes it to photon.*]
27	Lewis to TA. Hermione:	Thank you!

Student interaction discourse moves (SIDM). This analytical framework and visualization scheme allows researchers to characterize group discussion patterns during small group conversations (Nennig *et al.*, 2023). In this approach, student utterances during a conversation are segmented on a timeline and categorized into specific discourse moves using three levels of analysis: type of Interaction, Primary Intent, and Nature of Utterance (see SIDM codes and definitions in the ESI†). In our case, these analyses were carried out independently by four of the authors (HTN, NES, SF, and ZDKG) following the strategies described in detail in Nennig *et al.* (2023) and ensuring trustworthiness by using pairwise consensus. Once a group conversation was coded, the authors constructed an associated SIDM map as illustrated in Fig. 2. These maps facilitated the identification of the different ways in which students engaged socially and cognitively during in-class tasks. The SIDM maps use a combination of colors (which represents each student) and shapes (which represent the primary intent of each statement) for each utterance to make explicit the flow of a conversation as illustrated with an example in the next paragraph (see SIDM key of colors, symbols, and markers in the ESI†).

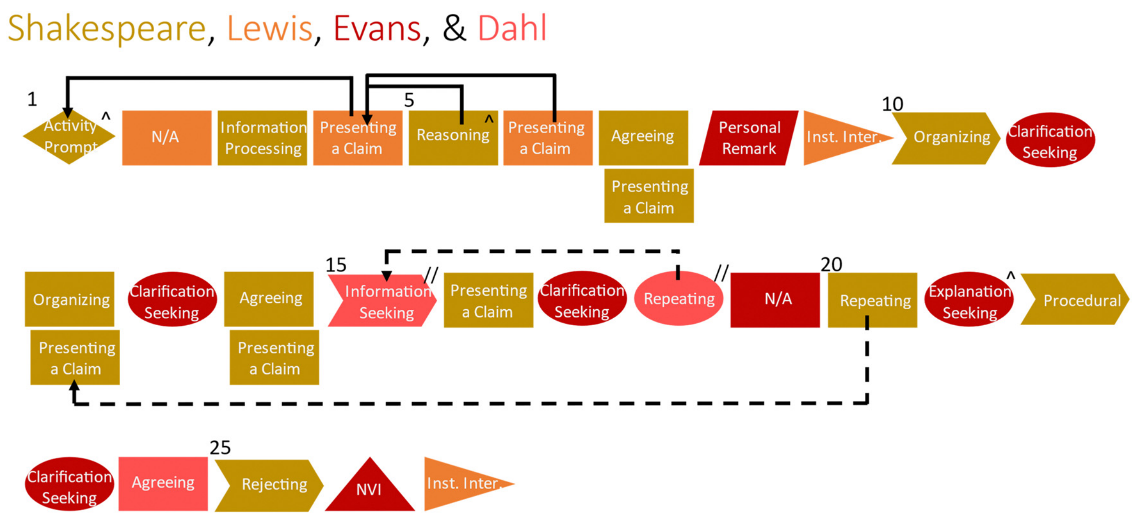


Fig. 2 Example of a SIDM map of conversation between Shakespeare, Lewis, Evans, and Dahl. Numbers at the top left corner of every 5 shapes correspond to specific utterances from the transcript. Color identification of students: Shakespeare: Gold, Lewis: Orange, Evans: Maroon, Dahl: Salmon.

The SIDM map shown in Fig. 2 depicts the transcribed conversation between the four group members working on the task shown in Fig. 1, which asked them to visually represent a process in which an electron is ejected from a 1s orbital, followed by the transition of an electron from the 2p orbital into the resulting hole (see transcript with fully applied SIDM codes in ESI†). We can see in the SIDM map that the conversation is initiated by Shakespeare, represented by the gold diamond shape, who begins by reading the task prompt. The conversation continues with Lewis interrupting the utterance by Shakespeare with an inaudible utterance, represented by the circumflex symbol and orange rectangle. The conversation between Shakespeare and Lewis continues with both building on each other's ideas, represented by the solid black arrows pointing towards the utterance being built upon. Evans joins the conversation at utterance 8 with a personal comment represented with a maroon rhombus. This is directly followed up with Lewis "leaving" the group conversation to have a separate interaction with an instructor as noted by the orange pennant. At this point on the SIDM map, Shakespeare takes a more dominant role in the conversation, responding to Evans's questions with information in a managerial way, represented by the maroon circles for Evans and gold rectangles and chevrons for Shakespeare. On a few occasions, we see Dahl attempting to contribute to the conversation by asking a question, which they later repeat, as denoted by the black dashed arrow connecting the salmon chevron and circle shapes. However, both questions are ignored as indicated by the double backslash symbols after both utterances 15 and 18. The conversation ends with Shakespeare rejecting a question asked by Evans (utterances 23–26) and Lewis concluding their conversation with the instructor.

Student expressed chemical thinking (SECT). Group conversations were also analyzed to identify the sequence of chemical concepts and ideas expressed by students while completing an in-class task and the types of cognitive processes in which they engaged. These elements were summarized in a SECT map for each conversation as illustrated in Fig. 3. One of these maps was constructed by two of the authors (MMS & VT) through paired consensus for each of the 66 conversations. The example in Fig. 3 corresponds to the same student conversation captured in the SIDM map in Fig. 2 (see transcript with fully applied SECT codes in ESI†). In this SECT map, the blue boxes summarize the chemical content uttered by students while working on the task. These utterances are separated into groups, encapsulated within the black dotted lines, based on the type of cognitive process in which students were engaged (*e.g.*, explaining, representing, summarizing). Yellow boxes below each group are used to indicate consensus ideas, products, or outcomes of each task (see SECT codes and definitions in ESI†).

Once the SIDM and SECT maps for each group conversation were generated, they were combined into a single map using arrows, brackets, and text as illustrated in Fig. 4. In these representations, large gray arrows were placed behind the group members' utterances associated with a particular cognitive process. For example, in Fig. 4 Shakespeare and Lewis are engaging in 'Explaining' from utterances 1–7, before the cognitive process shifts to 'Representing 1' starting at utterance 8. The flow of chemical ideas was represented with text and small colored arrows. When a group member presented a chemical idea, that idea was written under the utterance where it occurred. From this idea, an arrow in the color representing the group member who spoke was drawn pointing toward the progression of the conversation until another chemical idea was presented. If this idea built on the previous idea, the arrows and ideas would appear in line with one another. An example of this building of ideas can be seen in Fig. 4 under 'Explaining', where Shakespeare shares an idea at utterance 1 and a gold arrow continues through the conversation until the idea is built upon by Lewis at utterance 4. If a presented idea did not connect to the previous idea, the idea was written where it

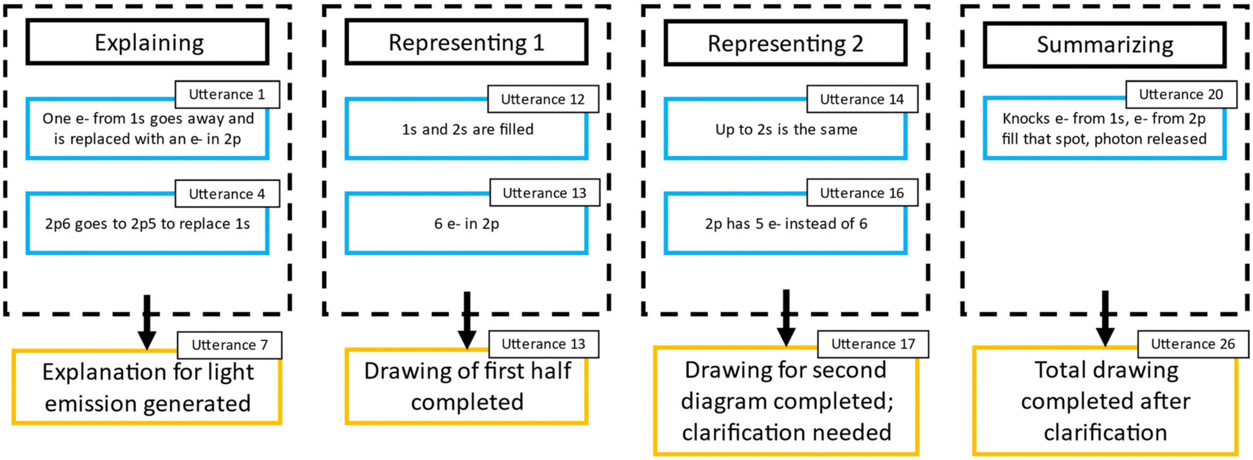


Fig. 3 Example of SECT map.

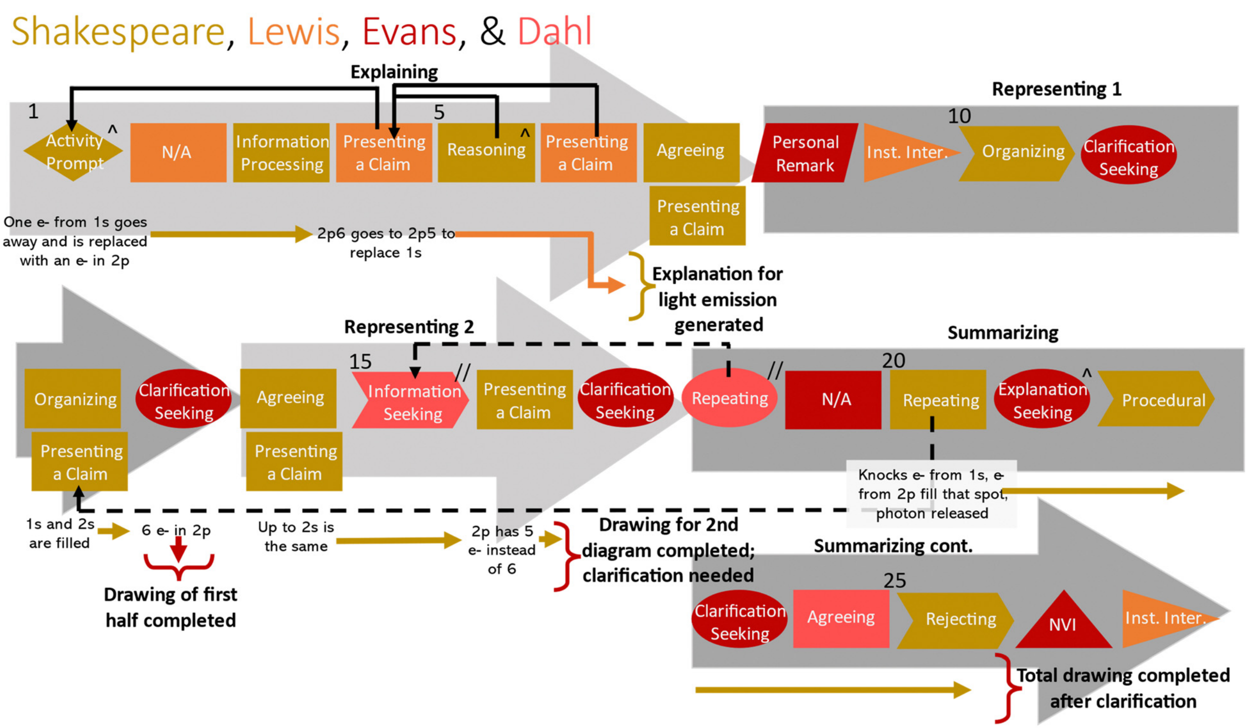


Fig. 4 Combined SIDM-SECT map of conversation between Shakespeare, Lewis, Evans, and Dahl. Numbers at the top left corner of every 5 shapes correspond to specific utterances from the transcript. Color identification of students: Shakespeare: Gold, Lewis: Orange, Evans: Maroon, Dahl: Salmon.

occurred, but slightly below the string of previous ideas. These ideas, with their representative arrows, ran parallel to each other until the group reached a consensus, agreed on the outcome of their process, or the conversation ended.

Community of learners (CoL) characterization. The combined SIDM and SECT maps for each group conversation helped us summarize and make explicit information that facilitated the characterization of social and cognitive engagement with chemical concepts and ideas in the selected groups using the five dimensions of the CoL framework. An example of how that analysis was completed is presented in the ESI.† To visually represent the results of these analyses along each of the five dimensions we used colored circles divided into equal parts, each of them representing a different student in a group as shown in Fig. 5. A sector in a circle was colored if the corresponding student actively engaged and contributed to the conversation as defined by each dimension. If the student participated in the conversation but did not meet the given dimension's criteria, that sector was only outlined. Sectors corresponding to students not explicitly engaged in the conversations were left completely blank. Data analysis along each dimension is described and exemplified below:

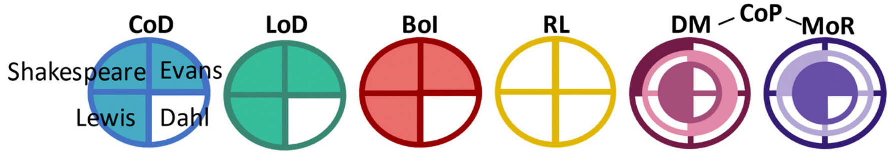


Fig. 5 Example of CoL circle maps representing social and cognitive engagement of students in a group along the five dimensions in the CoL framework.

• *Community of discourse* (CoD): this dimension characterizes the extent to which different group members actively and meaningfully contribute to the conversation. As illustrated in the CoL circle map in Fig. 5, we used a blue circle to visually represent student engagement as it pertains to this dimension. In this example, corresponding to the conversation depicted in Fig. 1–4, three students (Shakespeare, Evans, Lewis) contributed to the conversation both in terms of discourse moves that went beyond agreeing with or acknowledging other students' ideas and by adding to the progression of chemical ideas. Thus, their corresponding sectors are fully shaded. On the other hand, although Dahl participated in the conversation through discourse moves beyond agreeing or acknowledging (utterances 15 & 18), this student did not contribute any chemical ideas during their participation. Thus, their sector is only outlined. In this example, all the students explicitly engaged at some level in the conversation.

• *Legitimization of differences* (LoD): this dimension characterizes the extent to which the contributions of group members are acknowledged, discussed, and considered in the construction of understandings. This dimension is represented in Fig. 5 using a green circle with filled sectors for group members whose contributions were acknowledged and used to complete the task. The sectors of circle with only an outline correspond to the group members whose ideas were ignored, interrupted several times, or whose ideas were often dismissed by others in the group. This was determined by looking at key features from the combined SIDM-SECT maps. We evaluated the frequency and directionality of ignored, interrupted, rejecting, and rebutting moves to determine if patterns of being left out of the conversation were observed. In this example, Dahl asked questions that were ignored by other members of the group (utterances 15 & 18), and thus their sector was not filled but rather outlined.

• *Building on ideas* (BoI): this dimension characterizes the extent to which group members participate in a decentered conversation with multiple members building on each other's ideas. Students participating in this collaborative construction of ideas are identified with filled sectors in the red circle in the example in Fig. 5. The sector for group members who do not engage in building ideas is only outlined. In the example in Fig. 5, Shakespeare and Lewis build on each other's ideas as they build an explanation (utterances 1–7), and Evans joins Shakespeare later in the conversation as they build representations (see Fig. 4).

• *Reflective learning* (RL). This dimension highlights the reflective discourse moves group members used while conversing during a particular task. These moves included reflecting on past experiences that may be linked to the task at hand, identifying information that helps move the conversation forward, providing encouragement to group members, or evaluating whether a strategy is appropriate to complete a task. Members who engaged in this type of reflection during group activity would be represented with a filled-in sector in yellow, as shown in Fig. 5. In this example, none of the group members engaged in this type of reflection and their associated quarter circles are just outlined.

• *Community of practice* (CoP). This dimension characterizes the extent to which group members engaged in intellectual work in the discipline through the communication of chemical ideas and different types of reasoning. In our analysis, we subdivided this dimension into two subdimensions. The first one, *Community of Practice – Discourse Moves* (CoP-DM), characterizes group members' engagement in the conversation through various discourse moves (pink circle in Fig. 5). The second one, *Community of Practice – Modes of Reasoning* (CoP-MoR), characterizes the specific modes of reasoning expressed by students while working with chemical ideas (violet circle in Fig. 5). Using a bullseye pattern, the circle associated with the CoP-DM subdimension makes explicit the extent to which a group member engaged in sharing chemical information (inner ring), asking questions (middle ring), or providing some justification (outer ring) as summarized in Fig. 6. As with prior representations for other dimensions, a filled sector is used to indicate a member's engagement with the practice while the sectors for non-contributing individuals are just outlined. Thus, Fig. 5 indicates that Shakespeare engaged in sharing information (utterances 7, 12, 14, 16, 20, 22, & 25) and providing a justification during the conversation (utterance 5), while Evans and Dahl asked questions (Evans: utterances 11, 13, 17, 21 & 23; Dahl: utterances 15 & 18). A similar representation was used for the CoP-MoR subdimension (see Fig. 6), with the inner ring representing descriptive reasoning based on stating and contributing pieces of chemical knowledge to the conversation,

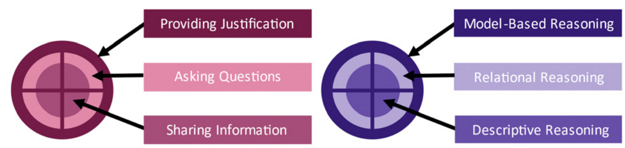


Fig. 6 Different types of engagement in the subdimensions of community of practice-discourse moves and community of practice-modes of reasoning.

the middle ring associated with relational reasoning strongly reliant on rules or associative heuristics to connect concepts or ideas, and the outer ring representing engagement in model-based reasoning in which students explicitly expressed causal links while connecting ideas (Sevian and Talanquer, 2014). Fig. 5 indicates that in this example, three students in the group (Shakespeare, Evans, Lewis) provided pieces of chemical knowledge during the conversation (Shakespeare: utterances 1, 7, 12, 14, 16, 20 & 22; Evans: utterances 13, 17 & 26; Lewis: utterance 4), but only Shakespeare engaged in relational reasoning (utterances 1, 3, 5 & 7). None of these students expressed model-based reasoning during this task.

The CoL circle maps for the 66 selected group conversations facilitated the identification of patterns in social and cognitive engagement in our sample as well as of some of the factors affecting them. To make these patterns more explicit, we quantitatively analyzed differences in the frequency with which students in the groups engaged along each dimension in our CoL framework depending on factors such as group size, cognitive level of the tasks, or type of task. We ran Chi-Square tests to identify significant differences and analyzed residuals to identify major contributors to the results. We also completed basic correlation analyses to identify potential relationships between dimensions of engagement in the CoL framework. The results of these quantitative analyses guided our identification of representative cases that we use in the findings section to highlight major qualitative differences in student engagement in the analyzed groups.

Positionality statement

We recognize that data analysis in qualitative research involving human subjects is affected by the identities and experiences of the researchers conducting the work. Authors HTN, NES, MMS, GTR, LS, and RSC are native English speakers from the US. Authors VT, ZDKG, and SF are non-native English speakers from outside of the US. Given the location of our research sites, the selected group conversations were carried out in English and included expressions from American English slang. The authors used pairwise consensus coding methods for all analyses to overcome language barriers. Authors SF, ZDKG, RSC, GTR, LS, and VT completed doctorate degrees in chemistry and are accomplished researchers in their field. Authors HTN, NES, and MMS are currently completing graduate studies in chemistry with a focus on education. Authors RSC, VT, LS, and GTR have served as instructors for introductory chemistry courses while authors MMS, HTN, and NES have collaborated as learning assistants at the same level. Authors HTN, MMS, ZDKG, and NES have been students in courses using active learning strategies, while authors RSC and VT have only experienced active learning through professional development. Our different backgrounds and experiences can be expected to affect our expectations and interpretations of students' conversations. The authors took measures to minimize the impact of their personal perspectives during data analysis and interpretation.

Major findings

The results of our investigation are based on the analysis of 66 student conversations for groups engaged in 33 different tasks across all research sites. These activities involved 84 different students in 24 different groups working in five different learning environments. Analysis of task cognitive level according to Marzano's Taxonomy of Cognitive Complexity (Marzano and Kendall, 2007) as described in our prior work (Reid *et al.*, 2022) indicated that 44.5% (15) of these tasks were at the analysis level, 44.5% (15) were at the comprehension level, and 11.0% (3) of the tasks were at the retrieval level. Close to 57.6% of these tasks used a free-answer format while the rest had a closed-response format (*e.g.*, multiple choice, rank). The selected tasks asked students to engage with the content through different types of tasks such as building interpretations, inferences, or explanations (17, 51.5%), making comparisons (6, 18.9%), completing calculations (5, 15.2%), and constructing different types of representations (4, 12.1%). Selected group conversations involved groups of varied size, with most of them corresponding to groups of four students (37, 56.1%), and the rest to groups of two (8, 12.1%), three (18, 27.3%), and five (3, 4.5%) students.

A summary of average student engagement in the selected conversations across the different dimensions of analysis in our CoL framework is presented in Table 3. The numbers in this table correspond to the average across all conversations of the percentage of students in each group that substantially engaged in the processes that each dimension helps to characterize. We present this data as a function of the number of students per group, cognitive level of the tasks, and type of task to make explicit differences within each of these variable factors. In the following paragraphs we describe general trends and highlight those dimensions that contribute significantly to the differences observed within each factor as indicated by the statistical analysis of residuals using Chi-square (see ESI,† for detailed results).

Overall, student participation during the selected in-class tasks (CoD dimension) was high with most students contributing chemical knowledge and ideas to their conversations when verbally engaged (84.1% participation on average across groups), and only a small fraction of the students did not engage in any substantive way (7.0% on average across groups). In general, most students' contributions were acknowledged and considered during discussions (LoD dimension), with only a small percentage of students experiencing dismissal or rejection of ideas (4.1% on average across groups). Most students built on each other's contributions or ideas (BoI dimension) while completing assigned tasks (71.6% on average across groups), but they only occasionally engaged in reflective practices (RL dimension) (27.3% on average across groups). From a discourse perspective (CoP-DM subdimension), most students contributed to group conversations using discourse moves related to sharing information (70.4%) and asking questions (77.9%), with fewer students providing justifications (48.0%). Student cognitive engagement with chemical concepts and

Table 3 Average across all conversations of the percentage of students in each group that substantially engaged in the processes characterized in our CoL framework. Symbols + and − are used to indicate larger (+) or smaller (−) than expected contributions to the statistical differences observed depending on group size, cognitive level of the task, and task product (see ESI for more statistical detail)

Number of conversations in each category in parenthesis		CoD	LoD	BoI	RL	CoP-DM Sharing	CoP-DM Asking	CoP-DM Justifying	CoP-MoR Descriptive	CoP-MoR Relational	CoP-MoR Model-based
Group size	2 (8)	100+	100	68.8−	6.3−	75.0	87.5	56.3	100+	50.0+	12.5+
	3 (18)	88.9	90.7	74.1	38.9+	75.9	77.8	50.0	83.3	40.7	3.7−
	4 (37)	79.7	85.8	70.9	25.7	67.6	75.7	45.9	74.3	39.2	4.1
	5 (3)	66.7−	86.7	73.3	33.3+	60.0	80.0	40.0	60.0−	26.7−	0−
Cognitive level	Retrieval (6)	90.3+	84.7	73.6	13.9−	56.9−	80.6	58.3+	74.7+	37.5	0−
	Comprehension (30)	83.3	91.4	72.3	30.0+	75.2+	77.4	46.2	77.9	33.8−	0−
	Analysis (30)	83.5	87.6	71.5	28.3	68.7	78.5	48.2	79.5	46.6+	10.2+
Task type	Calculation (10)	75.3	89.7+	65.2	42.5+	72.0+	83.8+	37.7−	67.0−	18.7−	0−
	Comparison (12)	79.6	87.9	67.5	19.4−	71.0	71.0	48.8	71.7−	53.6+	4.2
	Representation (8)	86.5	89.6	76.0	42.7+	76.0	72.9−	52.2	86.5	35.4−	0−
	Inf./Int./Expl. (34)	86.8	88.2	72.3	19.2−	66.7−	78.4	51.0	82.6	45.6+	7.8+
Overall		84.1	88.9	71.6	27.3	70.4	77.9	48.0	79.2	40.4	4.8

ideas (CoP-MoR) mostly manifested in terms of providing pieces of chemical knowledge that contributed to completing the task at hand (79.2%), with fewer students explicitly engaging in either relational (40.4%) or model-based (4.8%) reasoning.

Our analysis revealed differences in student social and cognitive engagement with chemical concepts and ideas for groups of different sizes, engaged in tasks with different cognitive levels, or targeting different types of tasks. Groups with two students exhibited the highest participation (CoD) with 100% of students in the selected groups contributing to the conversation and decreasing to 88.9%, 79.7%, and 66.7% on average for groups with three, four, and five students, respectively. Legitimization of differences (LoD) was similar across groups of different sizes while building on ideas (BoI) was the lowest in groups of two (68.8%). Reflection on learning was also minimal in groups of two (6.3%) and maximal in groups of three students (38.9%). The frequency of discourse moves associated with sharing information and justifying ideas (CoP-DM) went down with increasing group size, although not significantly. Differences in cognitive engagement with chemical concepts and ideas (CoP-MoR) were noticeable between groups of two and five students. Comparatively, students in groups of two engaged the most in providing justifications, contributing chemical knowledge to their conversations, and expressing either relational or model-based reasoning in explicit ways, while students in groups of five engaged the least in these practices. Overall, the highest social and cognitive engagement was observed in groups with two or three students.

The cognitive level of the in-class tasks seemed to also affect student social and cognitive engagement. Higher student participation (CoD) was observed in tasks at the retrieval level (90.3%) than at the comprehension (83.3%) and analysis (83.5%) levels. No major differences were observed in the LoD and BoI dimensions, but reflection on learning (RL) was much lower in retrieval tasks (13.9%) than in comprehension (30.0%) and analysis (28.3%) tasks. Students working on tasks at the retrieval level more often gave justifications by providing chemical knowledge than in other tasks, while expressed modes of reasoning, either relational or model-based reasoning, were much higher when students worked on tasks at the analysis level (46.6% for relational reasoning and 10.2% for model-based reasoning in analysis tasks).

The nature of the type of task also led to observed differences in student engagement. In general, numerical tasks requiring students to do calculations had the lowest student participation (75.3%), while tasks requiring students to build inferences, interpretations, or explanations had the highest (86.8%). No major differences were observed across different types of tasks in terms of LoD or BoI, while reflection on learning was more common when students engaged in tasks that required them to complete numerical calculations (42.5%) or build representations (42.7%) than in tasks that asked them to generate comparisons (19.4%) or inferences, interpretations, or explanations (19.2%). In general, students working on calculation tasks more frequently asked questions from each other but provided fewer justifications, contributed less chemical knowledge, and engaged less in explicit reasoning, either relational or model-based, than in other types of tasks. For example, relational reasoning was the highest in comparison tasks (53.6% *vs.* 18.7% in numerical tasks), while model-based reasoning was the highest in tasks that asked for inferences, interpretations, and explanations (7.8% *vs.* 0% in numerical tasks).

Although the summary of findings presented above helps to generally characterize the extent to which students functioned as a community of learners in the selected groups, and it points to factors that affected their social and cognitive engagement, further insights can be gained by a more in-depth analysis of a few representative cases in our sample. Such analysis is presented in the following subsections and more detailed information about each case can be found in Appendix A associated with this manuscript.

Case 1

It was common in our sample (and in our broader data set) to observe major differences in the social and cognitive engagement of different student groups working on the same task. To illustrate these differences, we consider the case of two groups of students working on an analysis level task that asked them to compare two atmospheric reactions, reaction A and reaction B, and infer which of them would be faster based on the composition and structure of the reactants involved and their associated energy diagrams. The corresponding CoL circle maps for each of the groups are presented in Fig. 7. All students in Group A actively engaged with the task, building on each other's ideas, contributing chemical knowledge and ideas, and providing justifications. Most of them asked questions and expressed relational reasoning that helped the group complete the task. The following excerpt exemplifies the types of contributions different students made to their decentered conversation:

Alison: B is Lower. Lower, higher T, Lower E.
Charlie: So A is, okay isn't it collision is favored?
Beth: Okay.
Charlie: Okay, you're not wrong. But for activation energy, however.
Alison: B.
Charlie: B is favored, 'cause the slow little peak there, the apex, is slightly lower, right, the mound?
Alison: Mm hmm.
Charlie: But which one is faster? How do we know which one is faster?
. . .
Beth: I think it's A.
Alison: Is it slower, 'cause I feel like the peaks are too close to be like, it's B.
Beth: Yeah.
Charlie: Yeah. A has just that number thing going for it, you know?
. . .
Beth: Isn't B technically simpler, though?
Charlie: B?
Beth: B is only one carbon though, compared to two nitrogens. Wouldn't one carbon be simpler than two nitrogens?
Charlie: Oh you're right.

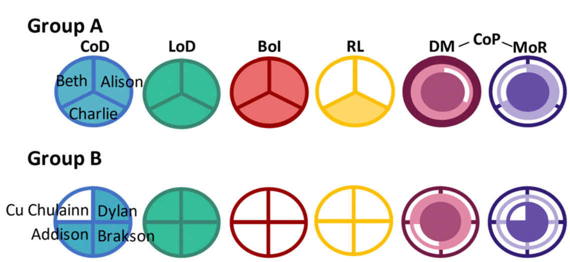


Fig. 7 CoL circle maps for two different groups working on the same task (Case 1).

In this example, we can see students in this group acknowledging, evaluating, reflecting, and building upon their ideas to generate an answer. All students presented claims and provided reasoning or made rebuttals during their conversation. In contrast, students in Group B shared ideas but did not connect them or build upon them to move their conversation forward as illustrated by this excerpt:

Brakson: Which of these reactions is favored by activation energy? What is that again?
Cu Chulainn: Wait, which one?
Dylan: What's the first one? Which of these reactions is favored by collision effectiveness?
Brakson: Collision effectiveness?
Dylan: They're both the same effectively.
Addison: I feel like the activation energy.
Dylan: A is favored by collision effectiveness. Favored by activation energy, it looks like B requires more activation, or B is less, is favored by activation energy.
Brakson: So A doesn't have as much as two?
Addison: A doesn't have much like to give a dash to the other side.

In this case, we can see students posing questions but not building upon each other answers or providing any justification for their claims.

These types of differences in student social and cognitive engagement with chemical concepts and ideas were common between groups working on the same task in our sample. In fact, there were very few instances in our sample (3/33) in which paired groups exhibited equivalent CoL patterns of engagement across all dimensions.

Case 2

This case illustrates common trends seen across conversations regarding the impact that the cognitive complexity of the tasks had on student engagement. We show in Fig. 8 the CoL circle maps for the same group of two students (Group C) working on a retrieval, a comprehension, and an analysis task. In this

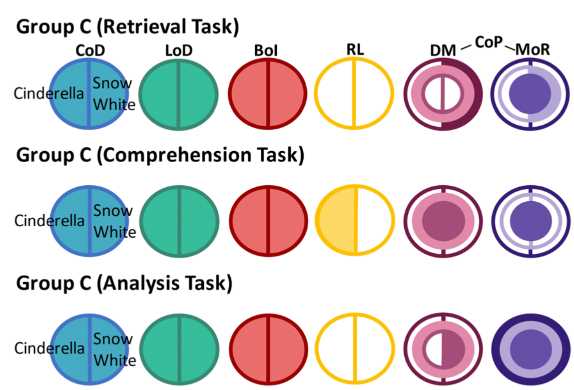


Fig. 8 CoL circle maps for the same group working on activities with different cognitive level (Case 2).

group, student participation (CoD) was high as it was common for groups of two, and there were no major differences in the LoD and BoI dimensions across the different cognitive complexities of tasks, which was characteristic for student groups in our sample. This case also exemplifies the low levels of engagement of most groups in reflective learning which, when it occurred, was more commonly observed in comprehension and analysis tasks but usually by only one person in the group. This example also illustrates the increase in relational and model-based reasoning shared while working on analysis tasks compared to retrieval and comprehension tasks. The following excerpt illustrates an example of this engagement for analysis tasks in which students are asked to analyze energy exchange when an ice cube melts in a beverage:

Cinderella: Okay…so an ice cube melts and cools the surroundings; the ice cube is the system
Snow White: mmhmm
Cinderella: So, because you only transfer heat…. the heat from the system, like from the beverage is actually entering the ice cube. Right?
Snow White: The heat from the surroundings?
Cinderella: From the drink
Snow White: From the surroundings…entering the system
Cinderella: Enters the system
Snow White: Okay…. so the system gains heat, that would be positive. Right?

In this example, students associated the melting of the ice cube with the transfer of energy from the beverage, and they began to articulate a model in which the ice cube was recognized as the system and the beverage as the surroundings. Contrast this conversation with that of the same group while working on a comprehension task that asked them to calculate how much heat was needed to transform solid ethanol at −155 °C to ethanol vapor at 78 °C:

Cinderella: Do you convert grams to moles?
Snow White: Yeah
Cinderella: What did she say n was here?
Snow White: *n* is moles
…
Snow White: This is just like an example with like units
Cinderella: She said something about changing n to m which means (interrupted)
Snow White: Oh yeah if it's like, so this is the like molar heat capacity
Cinderella: Oooooh right
Snow White: But then the other one is specific heat capacity and that one has the equation of like $q = mc\Delta T$

In this case, students simply identified and shared pieces of knowledge to identify the procedure to follow.

Case 3

Model-based reasoning was only observed in groups working on tasks at the analysis level and only in a few instances. It was also common for only one or two members in a group to engage in this type of reasoning when it occurred. Fig. 9 depicts the CoL circle map for a representative group in which model-based reasoning was observed. In this case, Group D was provided with a graph representing the potential energy as a function of distance between two bonding atoms of carbon and between two bonding atoms of hydrogen and asked to infer which bond was shorter and which was stronger. During this task, three of the four students were involved in the conversation with Chuck and Donna being the more cognitively involved. Ali took a smaller support role by answering clarification questions and Brittany did not make any observable contributions. This is an excerpt of their conversation:

Chuck: So if you move them either way, they just want to go back. So it stays bonded together. Um, and that's what the graph shows. It shows like looking at the left side, you know it's super far away from each other. Like, no, that's from super close. No they have to get really close to see that huge spike, then they shoot away from each other. Then you have that valley. That's like that's the bond getting to the bottom because you have no potential energy, they're really close to each other, but while staying in the comfortable range of repulsion. Then you have going towards the right, where you have bumping apart but wanting to get closer
Donna: So by longer is you're talking about like that space in between range?
Chuck: I think that distance. So that would be CC?
Donna: Because hydrogen.
Chuck: Because they have that stronger of a pull, they just can't get that close because they have a lot stronger repulsion.
Donna: So CC is stronger and longer?
Chuck: Yes. If you watch like in the simulation, what you get to is a lot bigger atoms. They have a lot more force behind them, so they have a lot more repulsion. So they can't get that close to each other. So they get that bigger distance.

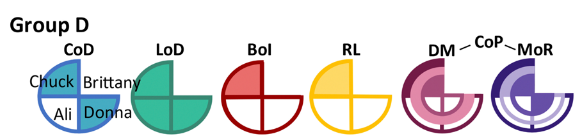


Fig. 9 CoL circle map for a group engaged in model-based reasoning (Case 3).

In this example, Chuck engages in model-based reasoning and refers to an interactive simulation used in class that showed how the potential energy of interacting atoms changed as one atom was moved closer to the other. This group's engagement is illustrative of most of the instances of model-based reasoning observed in our sample. Students rarely spontaneously deployed a model as a cognitive tool to work through tasks unless they were explicitly prompted to do so, or they had recently engaged with a modeling tool. As this case also illustrates, participation in model use was often constrained to a few students in a group. These students often dominated the conversation, which could result in more frequent rejection of other people's ideas. Instances of model-based reasoning were also commonly associated with more instances of relational reasoning.

Case 4

Our analysis revealed a significant correlation (Pearson correlation $r = 0.26$) between students' building on each other's ideas (BoI) and engaging in reflective learning (RL). This latter practice manifested in different forms such as explicitly relying on past experiences to guide or support group activity, motivating group work, or assessing strategies and contributions. Fig. 10 depicts the CoL circle map for a group that illustrates this association. In this task, Group E was asked to evaluate the veracity of a set of statements referring to different box diagrams for the ground state electron configurations of an atom of nitrogen. The group had one disengaged member (Jasmine) but otherwise demonstrated strong engagement. Participating students put forth chemical knowledge, included each other in the conversation, and built on each other's ideas. Two of the students engaged in reflective learning by identifying information that helped move the conversation forward, as illustrated in the following excerpt:

Tiana: Down down
Moana: No, you go...so for like 1s for like H, it would be one up
Tiana: Mmmhhmm
Moana: And then helium would be one down and then up one down. So, you fill the 1s first
Tiana: So, then it's ground state yeah
Mulan: So, it does need to specify to be ground state
Tiana: But it did need to?
Mulan: It did
Tiana: Okay okay, so it's all of them
Mulan: Yes

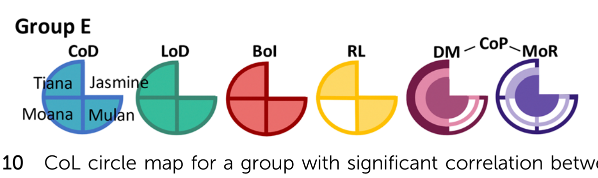


Fig. 10 CoL circle map for a group with significant correlation between the BoI and RL dimensions (Case 4).

In this example, Tiana and Mulan supported their group work by recognizing that their evaluation of the box diagrams should be based on the ground state configuration for the atom, which motivated further contributions and allowed the group to successfully complete the task. In other cases, students built upon a past experience shared by another student or the evaluation of a contribution by a different group member.

Case 5

In this last case, we describe and analyze how productive struggle with confusion led a few groups in our sample to engage with chemical concepts and ideas more substantively. Fig. 11 depicts the CoL circle maps for two groups engaged with a task that required them to rank the chemical species F^-, Ne, and Na^+ in order of increasing size. The question was multiple choice and was delivered through an online system that provided immediate feedback after an answer was selected. Students were given multiple attempts to complete the task. Group F was comprised of four students but only two of them participated in this conversation. Their short interaction is transcribed below:

Dan: It should go...um...does it go smallest to biggest or biggest to smallest? ...Smallest to biggest. Ok. It should go F, Ne, Na then.
[*Alan enters that response but finds that it is wrong*]
Dan: Ok so it's the opposite then...Wait, are those pluses and stuff? My bad. If there's pluses and stuff, then it's different.
Alan: Wait, aren't they...don't they all go to neon, or no?
Dan: Yeah, Na goes to neon.
Alan: Wait. The F goes to neon too.
Dan: Oh, that's minus. Yeah but, so, hmm.
Alan: That makes no sense. That makes absolutely no sense.
Dan: I mean, I guess we can try the last one [choice] again? [*Sees that it is correct*] Ok! I don't know.
Alan: I guess because it's still a sodium. Ok whatever.

Students in Group F seemed to select a first answer simply based on the location of the atoms in the periodic

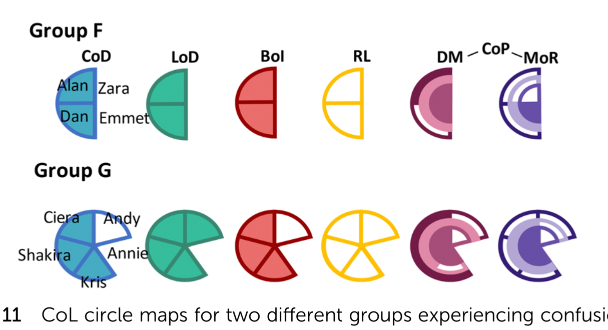


Fig. 11 CoL circle maps for two different groups experiencing confusion while working on the same task (Case 5).

table (potential heuristic association of the number of protons/electrons with atomic size). The feedback they received prompted students to suggest that the electrical charges may affect the answer and to realize that all species had the same number of electrons (all 'go to Neon'). This realization caused confusion, which remained unresolved as they managed to select the correct answer in their second attempt, stopping their discussion. This tendency to adopt a 'product-oriented' approach to the in-class tasks in which engagement with chemical concepts and ideas stopped once an answer was generated, independently of whether confusions had been resolved or groups members had built a strong rationale for their response was common in many of the selected groups in our study.

We can contrast this conversation with that of Group G, comprised of five students with only four of them explicitly interacting during the task. In this case, Group G also experienced confusion but they engaged in a conversation that allowed them to partially resolve it:

Shakira: Okay wait. Normally, it would be Ne, F, Na. This is on normal occasion. If it wasn't a plus or minus, but because this one is a plus. It means it literally has no electrons at all.
Kris: Ummm, it has electrons but because it is a cation...
Ciera: Cations are generally smaller.
Kris: Yeah and the protons will attract the electrons.
Shakira: In this case, wouldn't it? Because Na would only have one electron.
Ciera: No, no, you are thinking about plus charges because in this case the valence electrons just drops by one.
Shakira: But there was only one electron
Kris: The more electron it has, the more energy it requires.
Ciera: Wait, let's look up the periodic table. Look, it lost one valence electron. It still has electrons.
Shakira: What?
Ciera: Like there's three orbitals and then the 3rd orbital just lost one and now it has 2 orbitals but it still has electrons.
Shakira: Wait, how do you know that?
Ciera: You look at the periods and...
Shakira: Ohh okay okay.
...
Shakira: Yeah so the radii gets smaller because the ionization energy and the electronegativity are getting bigger so the atom is just pulling the electron close together.
Andy: So Na^+, do you think of it as Ne or Na with a cation?
Shakira: Na with a cation and because it is a cation, it has less electrons and it gets smaller.
Andy: Ohh okay, that's why I was confused.
Shakira: Ohh and also Ne and F are switched because F^- is an anion.

In this excerpt, we can see students engaging in a variety of discourse moves and productively struggling with chemical concepts until the confusion is resolved. Although students did not reach the normative understanding by the end of their conversation (Na^+ does not have fewer electrons than Ne or F^-), their willingness to struggle with relevant chemical ideas helped them advance their understanding.

Discussion

Our study allowed us to characterize the effect of several factors on students' social and cognitive engagement with chemical concepts and ideas during in-class tasks in large collaborative learning environments along five different dimensions in our 'Community of Learners' (CoL) framework. Through the analysis of combined 'Student Interaction Discourse Moves' (SIDM) and 'Student Engagement in Chemical Thinking' (SECT) maps detailing the nature and content of students' conversations, we gained insights into the extent to which students engage with one another and with chemical ideas while completing in-class tasks. Our findings make explicit the complexity of analyzing student engagement in large active learning environments where a multitude of variables can affect group work. These include, among others, group size and composition, the cognitive level of the tasks, the type of cognitive processing that the tasks demand, and the motivation and willingness of students to substantively engage in disciplinary reasoning. Student engagement is known to be a multidimensional construct spanning cognitive, behavioral, and affective dimensions (Fredricks *et al.*, 2004; Naibert *et al.*, 2022), influenced by a variety of factors such as students' prior knowledge (Dong *et al.*, 2020), motivation (Linnenbrink-Garcia *et al.*, 2016; King and Datu, 2017), emotions (Pekrun *et al.*, 2002), and social interactions (Reid *et al.*, 2022).

Most students in the groups in our sample engaged actively in collaborative work, sharing and building upon each other's ideas, acknowledging and recognizing their contributions, asking questions, justifying claims, and contributing chemical knowledge to their conversations. Smaller groups with two or three students engaged more frequently in processes characteristic of a 'community of learners' than larger groups. Nevertheless, all types of groups working across different types of tasks showed little engagement in reflective practices during collaborative activity. This may be due to the lack of explicit prompting within the task structure to engage in such practices or to the lack of modeling of such behaviors by the instructors. Existing research suggests that many students do not spontaneously engage in reflection about their understanding and thus require explicit scaffolding in this area (Davis, 2003; Guo, 2022). Our findings suggest that engaging in reflecting practices support students' building on each other ideas, enriching the conversations.

The cognitive level of the tasks and the nature of the cognitive processing they require seemed to have their major impact on expressed modes of reasoning in the 'Community of Practice' (CoP) dimension in our framework. Tasks at the analysis level in our sample were the only ones in which students explicitly engaged in model-based reasoning, and they also engaged in relational reasoning more frequently than in retrieval and comprehension tasks. Analysis tasks that prompted model-based reasoning tended to ask students to generate inferences, interpretations, or explanations. Numerical tasks were more likely to lead to less collaborative work and less explicit engagement in disciplinary practices (both in terms of discourse moves and modes of reasoning). In general, students in the selected groups often completed assigned tasks by connecting pieces of knowledge without much explicit chemical reasoning. When reasoning was expressed, it tended to be mostly relational based on the construction of simple associations without explicit causal links. These lower levels of explicit cognitive engagement during group activity in chemistry classes have been reported by other authors (Moon *et al.*, 2016; Deng and Flynn, 2021; Tiffany *et al.*, 2023). In our case, higher levels of reasoning were manifested by only a few students in a group, who tended to dominate the conversations or take on tutoring roles, increasing the likelihood of rejection of other people's ideas.

Across all selected conversations (and the larger data set), the number of cases in which different groups of students working on the same task engaged at similar levels across all CoL dimensions was quite low. Our analysis does not allow us to identify the various factors that may be responsible for this outcome. We speculate, however, that factors such as specific group composition and task placement within a lesson might play a major role in student social and cognitive engagement. Pecore *et al.* (2017) found that student engagement significantly increases when students have formal prior knowledge relevant to the assigned task. Students' prior experiences with other tasks also affect their engagement with subsequent tasks (Newton *et al.*, 2020). Successful performance in prior tasks can positively affect performance in subsequent tasks for some students, while 'attention residue' from working on prior tasks may impede performance for other students (particularly perceiving prior tasks as incomplete). These findings suggest that engagement is likely dependent on the specific prior knowledge and experiences of the different individuals in a group relative to the content, level, and type of task on which they work and its placement within an instructional sequence.

Our findings also highlight the positive role of students' productive struggle with confusion when they have the motivation and disposition to engage with chemical concepts and ideas to advance their understanding. A point of struggle is defined as an impasse in a task that must be overcome to move forward in a task (Keen and Sevian, 2022). This struggle is considered productive when students work to build a shared understanding that helps them move forward in the task solving process (Hiebert and Grouws, 2007; Keen and Sevian, 2022). The initial confusion stimulates engagement in sense-making (Manz, 2015) and the collaborative engagement with ideas helps students improve their conceptual understanding (Kapur, 2014). Sengupta-Irving and Agarwal (2017) assert that students working on a task that falls within their collaborative Zone of Proximal Development (ZPD) are more likely to engage in productive struggle. They note that 'whether or not students are working within their ZPD and engaged in productive struggle is a function of the task, their past experiences and knowledge, their moment-to-moment interactions, and what support the teacher and classroom context offer' (p. 119). Based on our findings, we would add that participating in productive struggle also demands the motivation and disposition to engage with disciplinary ideas, which is affected by how students frame the task (Petritis *et al.*, 2021; Keen and Sevian, 2022).

Researchers have found that students often frame in-class tasks in two major ways. One of them, identified as the 'classroom game' (Hutchison and Hammer, 2010) or 'doing the lesson' frame (Jiménez-Aleixandre *et al.*, 2000) is product-oriented, focused on completing the task with the minimum cognitive effort. The other, identified as the 'making sense' or 'doing science' game, is process-oriented and focused on developing meaningful understanding. Based on the low level of explicit engagement in either relational or model-based reasoning in our sample, we suspect many of the observed groups implicitly applied a product-oriented approach to in-class work. However, the high levels of variation in how different groups of students approached the same tasks and how the same group of students engaged with different tasks, suggest that students' frames may not be fixed and that their engagement is affected by several variables that are specific to each group, such as students' relative knowledge in each task (*i.e.*, the extent to which the task falls within their collaborative ZPD), prior experiences within and outside the classroom, and group dynamics at the moment.

Limitations

The generalizability of our findings is limited by the relatively small number of student groups selected for analysis across learning environments and research sites. We sought to select representative groups based on results from our prior study (Reid *et al.*, 2022), but observed actions and conversations may not be generalizable to all settings and populations. Most of the in-class tasks in our sample were from the first semester of college general chemistry and may not be representative of all types of tasks present in a chemistry curriculum. Our findings emerged from the analysis of explicit interactions registered in audio and video recordings, which are only a proxy for actual intellectual engagement with the chemical ideas presented in the tasks. Observations were conducted in classes taught by different instructors with a variety of approaches to design, implementation, and monitoring of student group work. Thus, our findings are affected by multiple variables that are quite difficult to control.

Implications

The findings of our study highlight the many factors that can affect how student groups cognitively and socially engage with in-class tasks in large introductory chemistry classrooms. Our results indicate that designing and orchestrating active learning environments in which students meaningfully engage with chemical ideas and collectively participate in model-based reasoning are not easy tasks. Instructors must carefully reflect on how a task's characteristics such as the nature of the task, its cognitive level, and its placement within a lesson interact with different groups' characteristics such as their size, the prior knowledge and experiences of different group participants, and the different manners in which students may frame the task. Achieving high levels of homogeneity in how different groups socially and cognitively engage with any given task may thus be quite challenging in very large classes with diverse student populations.

Most student groups in our sample did not explicitly engage in reflective practices, which in our study correlated with more students building on each other's ideas and generating richer conversations. This result suggests that group activity would benefit from the inclusion of explicit prompts that scaffold students for productive reflection (Davis, 2003) and direct them to reflect on their understandings (Davis, 2000). Students in the groups analyzed in our investigation mostly engaged in descriptive and relational reasoning across all types of tasks, although conceptual tasks (*e.g.*, comparison tasks, inference/interpretation/explanation tasks) at the analysis level resulted in more instances of model-based reasoning. This finding points to the need to not only more carefully evaluate the type and level of cognitive processes in which we ask students to engage, but the critical importance of reframing how students conceptualize in-class tasks. Most students in our sample seemed to adopt a product-oriented approach (Jiménez-Aleixandre *et al.*, 2000) focused on generating the correct answers with minimum cognitive effort. This framing likely fostered reliance on memory and short-cut intuitive heuristics rather than model-based reasoning. Investing time in developing productive classroom norms that intrinsically value engagement in sense-making seems to be critical to reframe students' approaches to group work (Becker *et al.*, 2013).

Our findings also highlight the crucial role of struggling with confusion in fostering productive conversations between students in a group. The outcome of productive struggle, however, is likely quite sensitive to different factors such as students' relative knowledge, the nature of group interactions, and students' disposition and motivation (Sengupta-Irving and Agarwal, 2017; Keen and Sevian, 2022). Differentiating between productive struggle and frustration that shuts down student engagement requires careful monitoring by the instructor to determine when and how to intervene. The present study did not consider the impact that an instructor's interactions with a group can have on their cognitive and social engagement, one more factor that needs to be considered in analyzing student engagement in active learning environments.

In addition to the implications for instruction, there are multiple pathways for further research based on the work discussed in this report. Studies that investigate the affective aspects of student engagement, such as motivation and attitudes, could provide insights into how instructors may design more engaging tasks that promote productive cognitive and social engagement. Larger scale studies that investigate the way students interact with chemical knowledge based on task design would reveal how educators can foster higher levels of student reasoning. Quantitative studies looking at correlations between types of student engagement and the multiple factors that seem to affect it should be completed to provide insights into how educators may design learning environments that succeed in engaging all students with chemical ideas at higher levels of reasoning.

Author contributions

RSC, GTR, LS, and VT contributed to funding acquisition, study conceptualization, project administration and supervision, and writing (review and editing). HTN, NES, MMS, SF, and ZDKG contributed to the investigation through data collection, curation, and formal analysis, as well as writing (review and editing). HTN, MMS, RSC, and VT contributed to formal overall analysis of collected data and writing of the original draft, including visualization of main findings.

Conflicts of interest

There are no conflicts to declare.

Appendix A. Case studies

Table A1 In-class tasks, combined SIDM-SECT maps, and associated CoL circle maps for the representative conversations of Case 1 in the manuscript

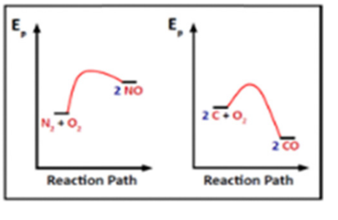
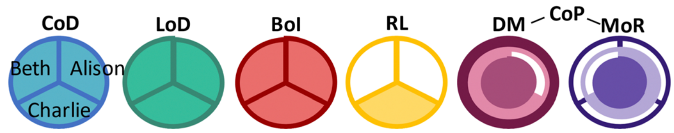
Case 1		
Group A & B Task Question format: dichotomous Cognitive level of task: analysis Type of task: comparison	Let's Think The energy diagrams for two important atmospheric reactions are shown: Which of these reactions is more favored by collision effectiveness? Which of these reactions is more favored by activation energy? Which of these reactions is likely to be fast?	A. $N_2(g) + O_2(g) \rightarrow 2NO(g)$ B. $2C(s) + O_2(g) \rightarrow 2CO(g)$ 

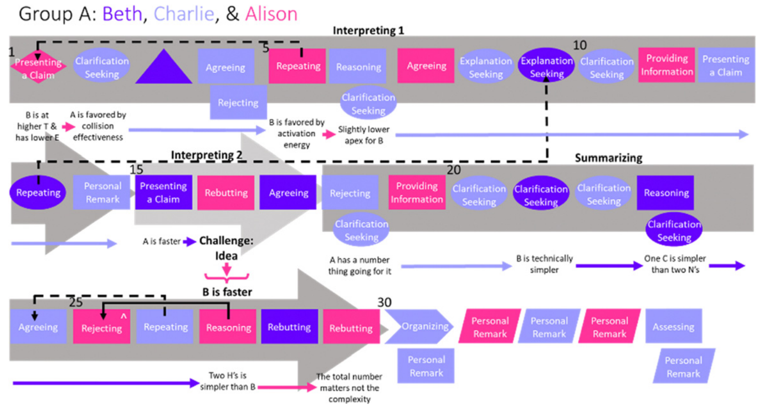
Table A1 (*continued*)

Case 1

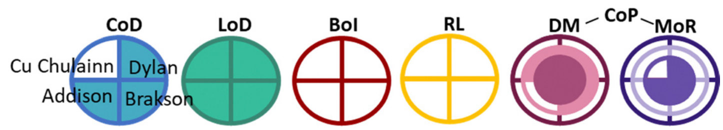
Group A
Social processing: collaborative
Knowledge dynamic:
Knowledge construction



SIDM.SECT map for Group A



Group B
Social processing: tutoring
Knowledge dynamic:
Knowledge construction



SIDM.SECT map for Group B

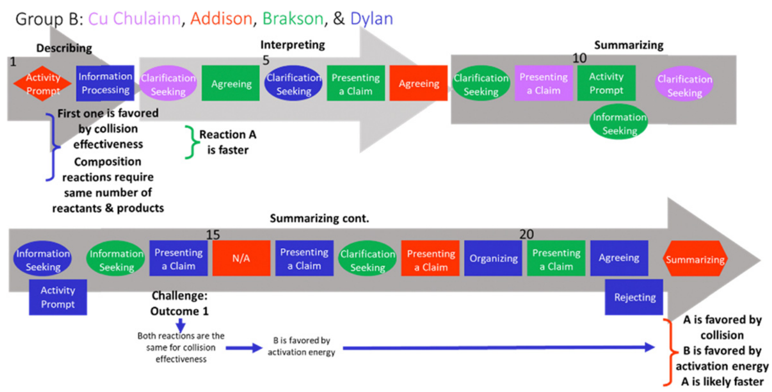


Table A2 In-class tasks, combined SIDM-SECT maps, and associated CoL circle maps for the representative conversations of Case 2 in the manuscript

Case 2

Group C (retrieval) task
Question format: multiple selection

Cognitive level of task: retrieval
Type of task: interpretation

Learning catalytics question
What information can be obtained from point B on the potential energy diagram shown?
A. Bond length
B. Effective nuclear charge
C. Electronegativity
D. Bond dissociation Energy

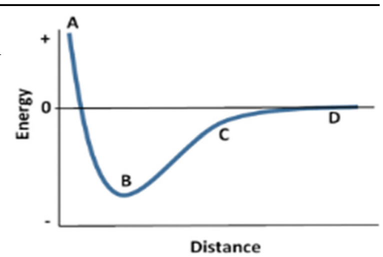
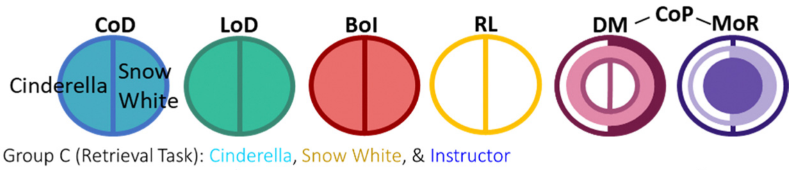


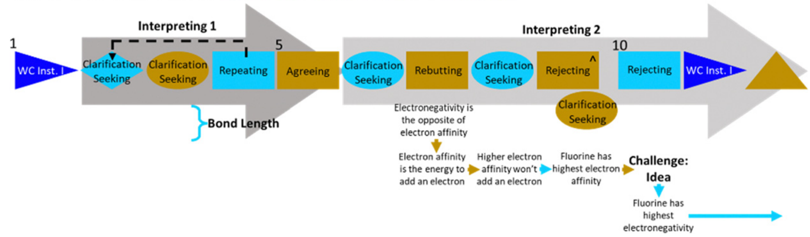
Table A2 (*continued*)

Case 2

Group C (retrieval task)
Social processing: non-interactive/individual
Knowledge dynamic: knowledge sharing



SIDM.SECT map for Group C (retrieval task)



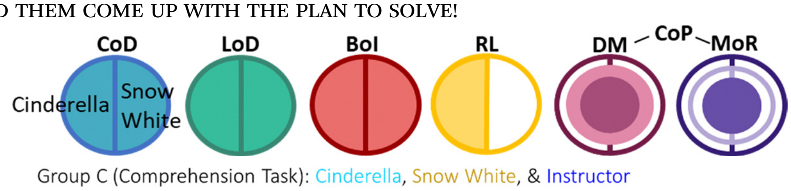
Group C (comprehension) task
Question format: free response

Excerise: phase changes & heat capacity
Ethanol (C_2H_5O, MW = 46.1 g mol^{-1}) melts at -114 °C and boils at 78 °C. The enthalpy of fusion of ethanol is 5.02 kJ mol^{-1} and its enthalpy of vaporization is 38.56 kJ mol^{-1}. The specific heats of solid and liquid ethanol are 0.97 J g^{-1} K^{-1} and 2.3 J g^{-1} K^{-1}.
How much heat is required to convert 42.0 grams of solid ethanol at -155 °C to ethanol vapor at 78 °C?

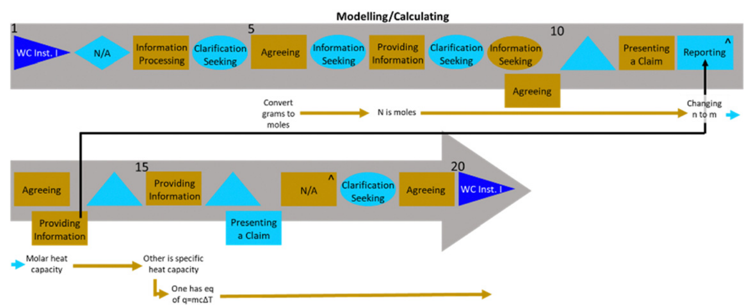
Cognitive level of task: comprehension
Type of task: other

ONLY HAD THEM COME UP WITH THE PLAN TO SOLVE!

Group C (comprehension task)
Social processing: collaborative
Knowledge dynamic:
Knowledge sharing



SIDM.SECT map for Group C (comprehension task)



Group C (analysis) task
Question format: matching

Matching
Identify each energy exchange as heat or work and determine whether the sigh of heat or work (relative to the system) is positive or negative.

Cognitive level of task: analysis

A. An ice cube melts and cools the surrounding beverage (the ice cube is the system) 1. Heat, positive

Type of task: inference

B. A metal cylinder is rolled up a ramp (the cylinder is the system) 2. Work, positive
C. Steam condenses on skin, causing a burn (steam is the system) 3. Heat, negative

Group C (analysis task)
Social processing: collaborative
Knowledge dynamic:
Knowledge sharing

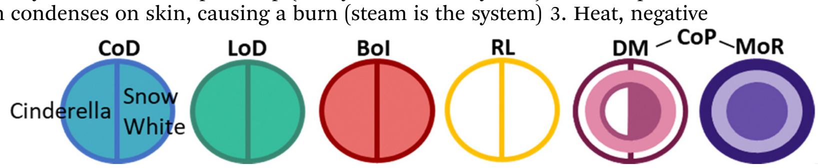


Table A2 (*continued*)

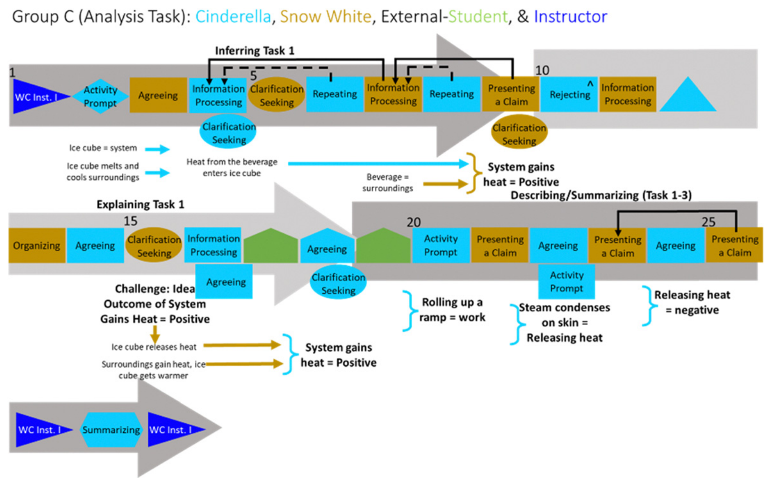
Case 2	
SIDM.SECT map for Group C (analysis task)	

Table A3 In-class tasks, combined SIDM-SECT maps, and associated CoL circle maps for the representative conversations of Case 3 in the manuscript

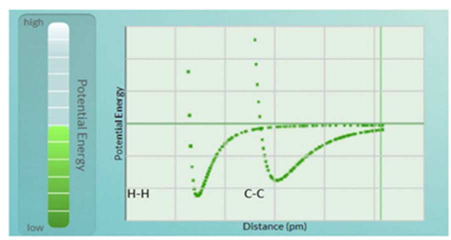
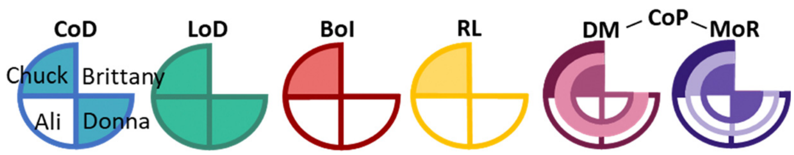
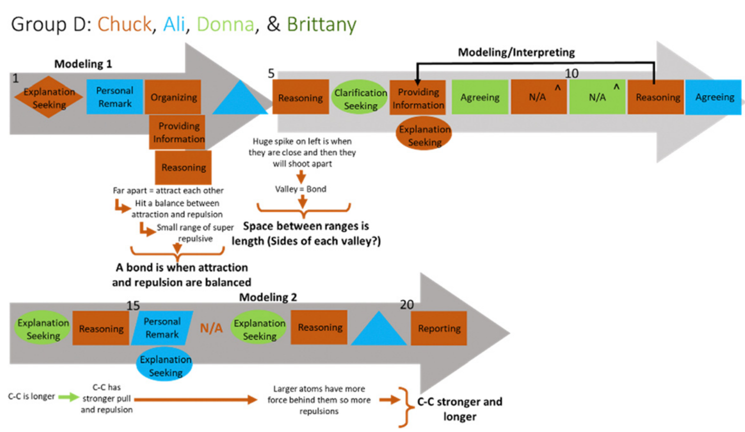
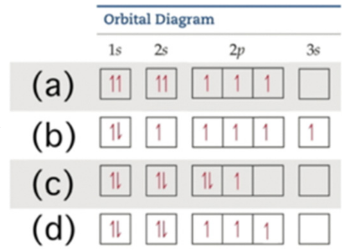
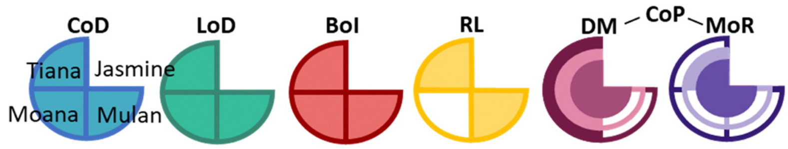
Case 3		
Group D task Question format: free response Cognitive level of task: analysis Type of task: comparison	Let's think Which chemical bond is longer? Which chemical bond is stronger?	
Group D Social processing: tutoring Knowledge dynamic: Knowledge sharing		
SIDM.SECT map for Group D		

Table A4 In-class tasks, combined SIDM-SECT maps, and associated CoL circle maps for the representative conversations of Case 4 in the manuscript

Case 4		
Group E task Question format: multiple selection Cognitive level of task: retrieval Type of task: explanation/ interpretation	Many choice Which of the following is/are true? A. It can't be (a) because of Hund's rules B. It can't be (b) because the 3s is getting filled before the 2s is filled C. It can't be (c) because 2p needs to half fill before the first 2p becomes paired D. It is (d) because of Hund's rules E. The question did not need to specify ground state	
Group E Social processing: domination Knowledge dynamic: Knowledge sharing		
SIDM.SECT map for Group E		

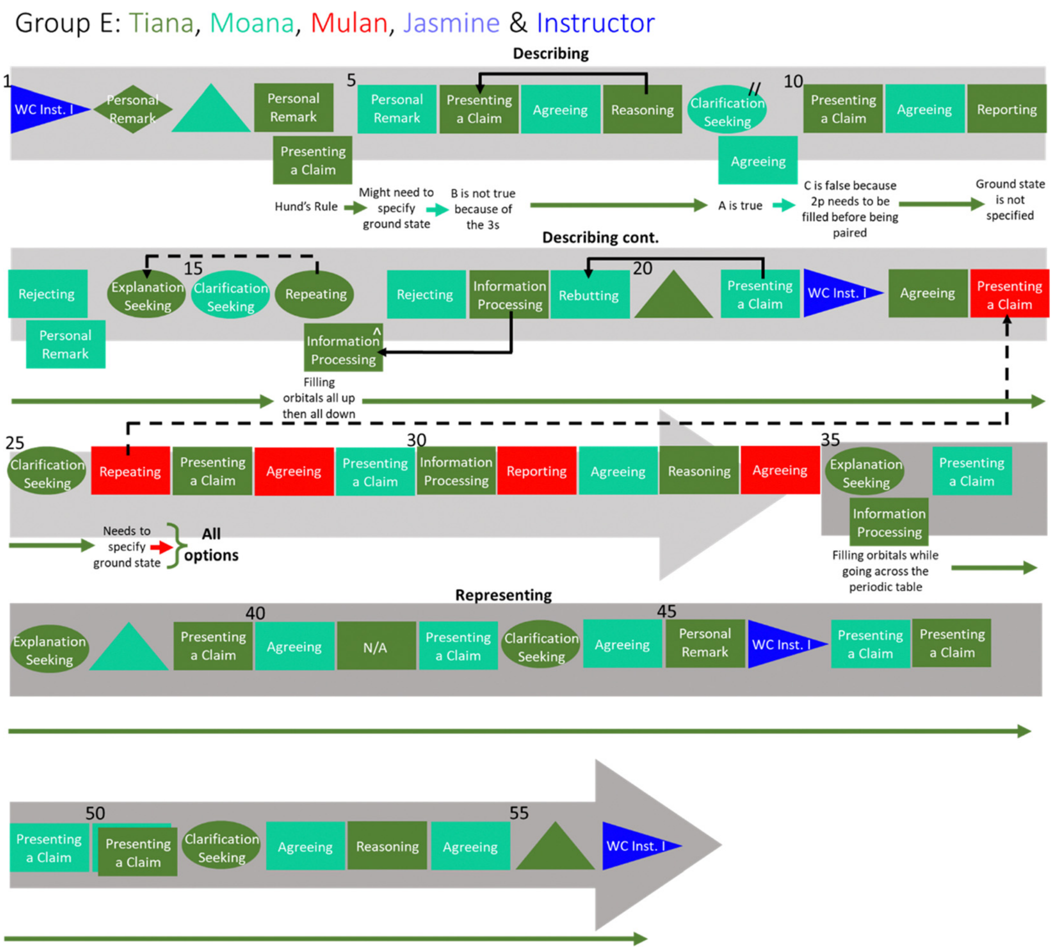


Table A5 In-class tasks, combined SIDM-SECT maps, and associated CoL circle maps for the representative conversations of Case 5 in the manuscript

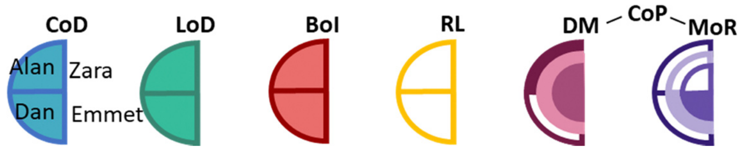
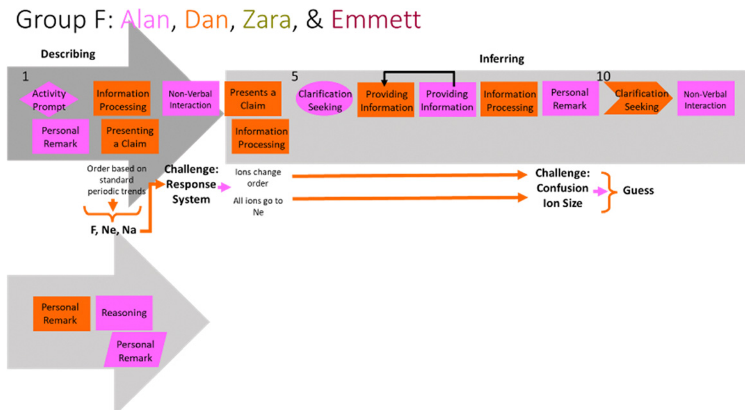
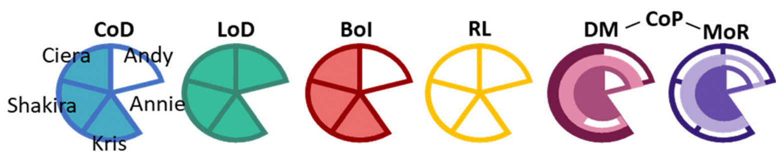
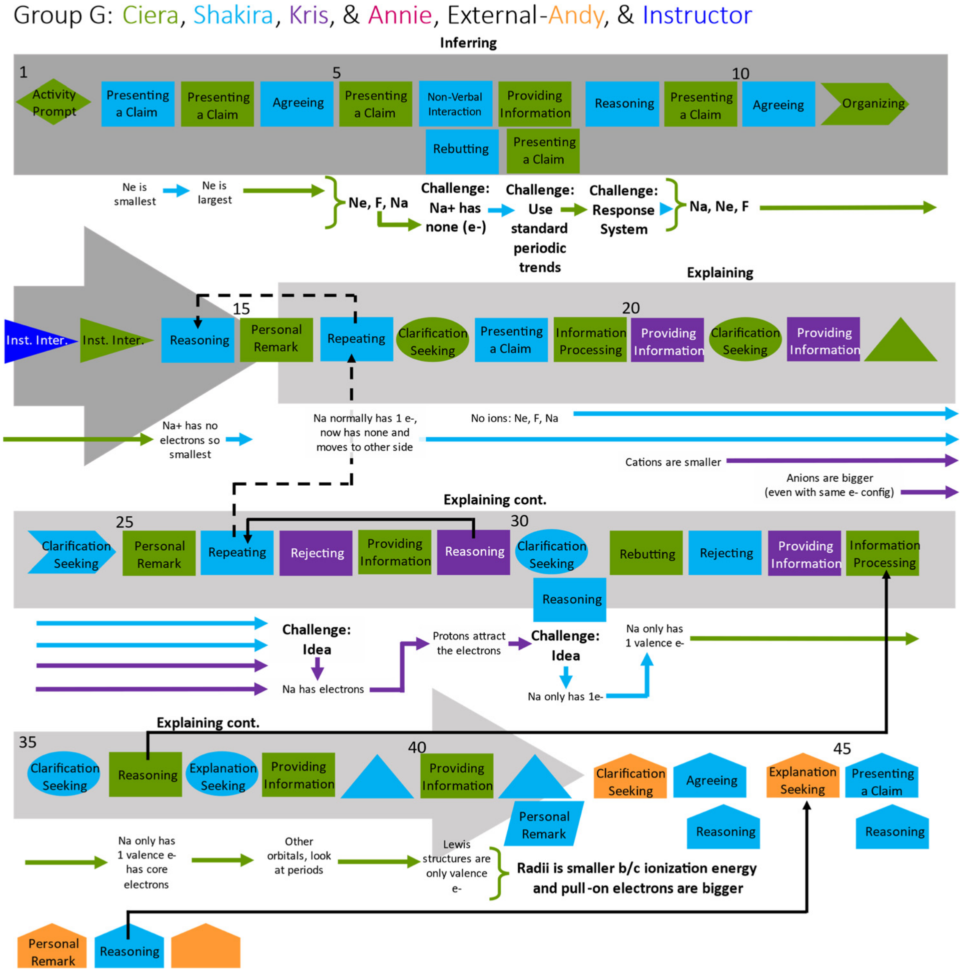
Case 5	
Group F & G task Question format: multiple choice/rank Cognitive level of task: comprehension Type of task: comparison	Consider F^-, Ne, and Na^+. How should the radii of F^-, Ne, and Na^+ compare? • $F^- < Ne < Na^+$ • $F^- < Na^+ < Ne$ • $Ne < F^- < Na^+$ • $Ne < Na^+ < F^-$ • $Na^+ < F^- < Ne$ • $Na^+ < Ne < F^-$
Group F Social processing: domination Knowledge dynamic: Knowledge sharing	
SIDM.SECT map for Group F	
Group G Social processing: tutoring Knowledge dynamic: Knowledge construction	

Table A5 (*continued*)

Case 5
SIDM.SECT map for Group G



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References

Becker N., Rasmussen C., Sweeney G., Wawro M., Towns M., and Cole R., (2013), Reasoning using particulate nature of matter: an example of a sociochemical norm in a university-level physical chemistry class, *Chem. Educ. Res. Pract.*, **14**(1), 81–94, DOI: 10.1039/C2RP20085F.

Bhattacharyya G., (2006), Practitioner development in organic chemistry: How graduate students conceptualize organic acids, *Chem. Educ. Res. Pract.*, **7**(4), 240–247, DOI: 10.1039/B5RP90024G.

Brown A. L., (1994), The advancement of learning. *Educ. Res.*, **23**(8), 4–12, DOI: 10.2307/1176856.

Brown A. L. and Campione J. C., (1990), Communities of learning and thinking, or a context by any other name. *Contrib. Hum. Dev.*, **21**, 108–126, DOI: 10.1159/000418984.

Chi M. T. H. and Wylie R., (2014), The ICAP Framework: Linking cognitive engagement to active learning outcomes. *Educ. Psychol.*, **49**(4), 219–243, DOI: 10.1080/00461520.2014.965823.

Christian K. and Talanquer V., (2012), Modes of reasoning in self-initiated study groups in chemistry, *Chem. Educ. Res. Pract.*, **13**(3), 286–295, DOI: 10.1039/C2RP20010D.

Cole R. S., Becker N., and Stanford C., (2014), Discourse analysis as a tool to examine teaching and learning in the classroom, in *Tools of Chemistry Education Research*, ACS Symposium Series. American Chemical Society, pp. 61–81, DOI: 10.1021/bk-2014-1166.ch004.

Criswell B. A., (2012), Reducing the degrees of freedom in chemistry classroom conversations, *Chem. Educ. Res. Pract.*, **13**(1), 17–29, DOI: 10.1039/C2RP00002D.

Davis E. A., (2000), Scaffolding students' knowledge integration: prompts for reflection in KIE, *Int. J. Sci. Educ.*, **22**(8), 819–837, DOI: 10.1080/095006900412293.

Davis E. A., (2003), Prompting middle school science students for productive reflection: generic and directed prompts. *J. Learn. Sci.*, **12**(1), 91–142, DOI: 10.1207/S15327809JLS1201_4.

Deng J. M. and Flynn A. B., (2021), Reasoning, granularity, and comparisons in students' arguments on two organic chemistry items, *Chem. Educ. Res. Pract.*, **22**(3), 749–771, DOI: 10.1039/D0RP00320D.

Dong A., Jong M. S.-Y., and King R. B., (2020), How does prior knowledge influence learning engagement? The mediating roles of cognitive load and help-seeking, *Front. Psychol.*, **11**, 591203.

Driver R., Newton P., and Osborne J., (2000), Establishing the norms of scientific argumentation in classrooms. *Sci. Educ.*, **84**(3), 287–312, DOI: 10.1002/(SICI)1098-237X(200005)84:3<287::AID-SCE1>3.0.CO;2-A.

Fredricks J. A., Blumenfeld P. C., and Paris A. H., (2004), School engagement: potential of the concept, state of the evidence, *Rev. Educ. Res.*, **74**(1), 59–109, DOI: 10.3102/00346543074001059.

Freeman S., Eddy S. L., McDonough M., Smith M. K., Okoroafor N., Jordt H., and Wenderoth M. P., (2014), Active learning increases student performance in science, engineering, and mathematics, *Proc. Natl. Acad. Sci. U. S. A.*, **111**(23), 8410, DOI: 10.1073/pnas.1319030111.

Furió C., Calatayud M. L., Bárcenas S. L., and Padilla O. M., (2000), Functional fixedness and functional reduction as common sense reasonings in chemical equilibrium and in geometry and polarity of molecules. *Sci. Educ.*, **84**(5), 545–565, DOI: 10.1002/1098-237X(200009)84:5<545::AID-SCE1>3.0.CO;2-1.

Gee J. P., (2015), *Social linguistics and literacies: Ideology in discourses*, 5th edn, Routledge.

Gee J. P. and Green J. L., (1998), Discourse analysis, learning, and social practice: a methodological study, *Rev. Res. Educ.*, **23**(1), 119–169, DOI: 10.3102/0091732X023001119.

Grotzer T., (2003), Learning to understand the forms of causality implicit in scientifically accepted explanations, *Stud. Sci. Educ.*, **39**, 1–74, DOI: 10.1080/03057260308560195.

Guo L., (2022), How should reflection be supported in higher education?—A meta-analysis of reflection interventions, *Reflective Pract.*, **23**(1), 118–146, DOI: 10.1080/14623943.2021.1995856.

Hiebert J. and Grouws D., (2007), The effect of classroom mathematics teaching on students' learning, in *Second Handbook of Research on Mathematics Teaching and Learning*, pp. 371–404.

Hutchison P. and Hammer D., (2010), Attending to student epistemological framing in a science classroom, *Sci. Educ.*, **94**(3), 506–524, DOI: 10.1002/sce.20373.

Jiménez-Aleixandre M. P., Bugallo Rodríguez A., and Duschl R. A., (2000), "Doing the lesson" or "doing science": argument in high school genetics. *Sci. Educ.*, **84**(6), 757–792, DOI: 10.1002/1098-237X(200011)84:6<757::AID-SCE5>3.0.CO;2-F.

Kapur M., (2014), Productive failure in learning math, *Cogn. Sci.*, **38**(5), 1008–1022, DOI: 10.1111/cogs.12107.

Keen C. and Sevian H., (2022), Qualifying domains of student struggle in undergraduate general chemistry laboratory, *Chem. Educ. Res. Pract.*, **23**(1), 12–37, DOI: 10.1039/D1RP00051A.

King R. B. and Datu J. A. D., (2017), Materialism does not pay: materialistic students have lower motivation, engagement, and achievement. *Contemp. Educ. Psychol.*, **49**, 289–301, DOI: 10.1016/j.cedpsych.2017.03.003.

Kraft A., Strickland A. M., and Bhattacharyya G., (2010), Reasonable reasoning: multi-variate problem-solving in organic chemistry, *Chem. Educ. Res. Pract.*, **11**(4), 281–292, DOI: 10.1039/C0RP90003F.

Kuh G. D., (2009), What student affairs professionals need to know about student engagement, *J. Coll. Stud. Dev.*, **50**(6), 683–706, DOI: 10.1353/csd.0.0099.

Kulatunga U., Moog R. S., and Lewis J. E., (2014), Use of Toulmin's argumentation scheme for student discourse to gain insight about guided inquiry activities in college chemistry. *J. Coll. Sci. Teach.*, **43**(5), 78–86.

Lemke J. L., (1990), *Talking science: Language, learning, and values*, Ablex Pub. Corp.

Linnenbrink-Garcia L., Patall E. A., and Pekrun R., (2016), Adaptive motivation and emotion in education: research and principles for instructional design, *Policy Insights Behav. Brain Sci*, **3**(2), 228–236, DOI: 10.1177/2372732216644450.

Lombardi D., Shipley T. F., Bailey J. M., Bretones P. S., Prather E. E., Ballen C. J., *et al.*, (2021), The curious construct of active learning, *Psychol. Sci. Public Interest*, **22**(1), 8–43, DOI: 10.1177/1529100620973974.

Maeyer J. and Talanquer V., (2010), The role of intuitive heuristics in students' thinking: ranking chemical substances, *Sci. Educ.*, **94**(6), 963–984, DOI: 10.1002/sce.20397.

Manz E., (2015), Representing student argumentation as functionally emergent from scientific activity, *Rev. Educ. Res.*, **85**(4), 553–590, DOI: 10.3102/0034654314558490.

Marzano R. J. and Kendall J. S., (2007), *The new taxonomy of educational objectives*.

McClary L. and Talanquer V., (2011), Heuristic reasoning in chemistry: making decisions about acid strength, *Int. J. Sci. Educ.*, **33**, 1433–1454, DOI: 10.1080/09500693.2010.528463.

Mercer N., (2010), The analysis of classroom talk: methods and methodologies, *Br. J. Educ. Psychol.*, **80**(1), 1–14, DOI: 10.1348/000709909X479853.

Michaels S. and O'Connor C., (2015), Conceptualizing talk moves as tools, in *Socializing Intelligence Through Academic Talk and Dialogue*, Resnick L. B., Asterhan C. S. C. and Clarke S. N. (ed.), American Educational Research Association, pp. 347–362.

Michaels S., O'Connor C., and Resnick L. B., (2008), Deliberative discourse idealized and realized: accountable talk in the classroom and in civic life, *Stud. Philos. Educ.*, **27**(4), 283–297, DOI: 10.1007/s11217-007-9071-1.

Moon A., Stanford C., Cole R., and Towns M., (2016), The nature of students' chemical reasoning employed in scientific argumentation in physical chemistry, *Chem. Educ. Res. Pract.*, **17**(2), 353–364, DOI: 10.1039/C5RP00207A.

Moon A., Stanford C., Cole R., and Towns M., (2017), Decentering: a characteristic of effective student–student discourse in inquiry-oriented physical chemistry classrooms, *J. Chem. Educ.*, **94**(7), 829–836, DOI: 10.1021/acs.jchemed.6b00856.

Moreira P., Marzabal A., and Talanquer V., (2019), Using a mechanistic framework to characterise chemistry students' reasoning in written explanations, *Chem. Educ. Res. Pract.*, **20**(1), 120–131, DOI: 10.1039/C8RP00159F.

Naibert N., Vaughan E. B., Brevick K., and Barbera J., (2022), Exploring student perceptions of behavioral, cognitive, and emotional engagement at the activity level in general chemistry, *J. Chem. Educ.*, **99**(3), 1358–1367, DOI: 10.1021/acs.jchemed.1c01051.

Nennig H. T., States N. E., Montgomery M. T., Spurgeon S. G., and Cole R. S., (2023), Student interaction discourse moves: characterizing and visualizing student discourse patterns, *Discip. Interdiscip. Sci. Educ. Res.*, **5**(1), 2, DOI: 10.1186/s43031-022-00068-9.

Newton D. W., LePine J. A., Kim J. K., Wellman N., and Bush J. T., (2020), Taking engagement to task: the nature and functioning of task engagement across transitions, *J. Appl. Psychol.*, **105**, 1–18, DOI: 10.1037/apl0000428.

Osborne J., (2010), Arguing to learn in science: the role of collaborative, critical discourse, *Science*, **328**(5977), 463, DOI: 10.1126/science.1183944.

Pecore J. L., Kirchgessner M. L., Demetrikopoulos M. K., Carruth L. L., and Frantz K. J., (2017), Formal lessons improve informal educational experiences: the influence of prior knowledge on student engagement, *Visit. Stud.*, **20**(1), 89–104, DOI: 10.1080/10645578.2017.1297134.

Pekrun R., Goetz T., Titz W., and Perry R. P., (2002), Academic emotions in students' self-regulated learning and achievement: a program of qualitative and quantitative research, *Educ. Psychol.*, **37**, 91–105, DOI: 10.1207/S15326985EP3702_4.

Petritis S. J., Kelley C., and Talanquer V., (2021), Exploring the impact of the framing of a laboratory experiment on the nature of student argumentation, *Chem. Educ. Res. Pract.*, **22**(1), 105–121, DOI: 10.1039/D0RP00268B.

Reeve J. and Tseng C.-M., (2011), Agency as a fourth aspect of students' engagement during learning activities, *Contemp. Educ. Psychol.*, **36**(4), 257–267, DOI: 10.1016/j.cedpsych.2011.05.002.

Reid J. W., Kirbulut Gunes Z. D., Fateh S., Fatima A., Macrie-Shuck M., Nennig H. T., *et al.*, (2022), Investigating patterns of student engagement during collaborative activities in undergraduate chemistry courses, *Chem. Educ. Res. Pract.*, **23**(1), 173–188, DOI: 10.1039/D1RP00227A.

Repice M. D., Keith Sawyer R., Hogrebe M. C., Brown P. L., Luesse S. B., Gealy D. J., and Frey R. F., (2016), Talking through the problems: a study of discourse in peer-led small groups, *Chem. Educ. Res. Pract.*, **17**(3), 555–568, DOI: 10.1039/C5RP00154D.

Sengupta-Irving T. and Agarwal P., (2017), Conceptualizing perseverance in problem solving as collective enterprise, *Math. Think. Learn.*, **19**(2), 115–138, DOI: 10.1080/10986065.2017.1295417.

Sevian H. and Talanquer V., (2014), Rethinking chemistry: a learning progression on chemical thinking, *Chem. Educ. Res. Pract.*, **15**(1), 10–23, DOI: 10.1039/C3RP00111C.

Talanquer V., (2014), Chemistry education: ten heuristics to tame, *J. Chem. Educ.*, **91**(8), 1091–1097, DOI: 10.1021/ed4008765.

Theobald E. J., Hill M. J., Tran E., Agrawal S., Arroyo E. N., Behling S., *et al.*, (2020), Active learning narrows achievement gaps for underrepresented students in undergraduate science, technology, engineering, and math, *Proc. Natl. Acad. Sci. U. S. A.*, **117**(12), 6476, DOI: 10.1073/pnas.1916903117.

Tiffany G., Grieger K., Johnson K., and Nyachwaya J., (2023), Characterizing students' peer–peer questions: frequency, nature, responses and learning. *Chem. Educ. Res. Pract.*, DOI: 10.1039/D2RP00146B.

Towns M., (1998), How do I get my students to work together? Getting cooperative learning started in chemistry. *J. Chem. Educ.*, **75**(1), 67, DOI: 10.1021/ed075p67.

Vygotsky L., (1978), *Mind in society*, Harvard University Press, DOI: 10.2307/j.ctvjf9vz4.

Young K. K. and Talanquer V., (2013), Effect of different types of small-group activities on students' conversations, *J. Chem. Educ.*, **90**(9), 1123–1129, DOI: 10.1021/ed400049a.