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Organic chemistry students' resource selection across the submicroscopic and macroscopic domains

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Chemistry learning can be conceptualized as a pluralistic discipline that involves the coordination of different domains. Two of these domains that students regularly interact with when enrolled in chemistry courses are the submicroscopic and macroscopic. Prior literature suggests that students' understanding of the relationship between these domains is often fragmented, resulting in varying explanations for macroscopic phenomena. Often times, these alternative explanations are simply categorized as incorrect. However, this dichotomous framing risks oversimplifying how students navigate the varying domains of chemistry and how the salient features within each domain might impact the way in which students draw on learned chemical principles. This study adopts a resources perspective that traces how students draw upon, adapt, and reconstruct their conceptual resources across tasks that cue students toward submicroscopic explanations and tasks that present students with macroscopic observations. To capture how students identify relevant resources within each of these task types, data were collected from ten participants through 60 minute semi-structured interviews. Each interview consisted of two sections: macroscopic tasks based on a video of an S_N1 laboratory experiment, and submicroscopic-cued tasks using bond-line structures of reagents. Across both task types, participants were asked to explain reaction outcomes and justify the chemical principles guiding their conclusions. Findings revealed that macroscopic cues significantly shaped how students evaluated reaction principles, even when drawing on the same conceptual resources used in the submicroscopic cued tasks. Additionally, students often drew on reactionary mnemonics learned in their lectures that provided minimal interpretative utility when viewing macroscopic observations. Consequently, reasoning unfolded as task-dependent, with varying degrees of parallel resource implementation across the domains. These results underscore the need for instructional designs that afford connections between the domains of chemistry, through prioritizing sensemaking over recall to encourage conceptual flexibility.

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Introduction

Research in chemistry education has long grappled with the challenge students face in navigating between different domains of chemical knowledge, from observable phenomena to theoretical models to symbolic representations (Johnstone, 1993; Treagust *et al.*, 2003; Talanquer, 2011; Stowe and Esselman, 2022). Central to these discussions has been Johnstone's influential framework characterizing chemistry learning as coordination between macroscopic, submicroscopic, and symbolic levels (Johnstone, 1993). However, as chemical education research has progressed, the nature of these levels and their relation to one-another has been subject to ongoing reinterpretation (Talanquer, 2011; Taber, 2013). Early interpretations of this framework presented Johnstone's triad as distinct representational levels, in which chemistry is the process of translating between submicroscopic, symbolic, and macroscopic entities. Under this conceptualization, the symbolic level (*i.e.* molecular structures, chemical equations, ball-and-stick structures) is treated as a distinct representational level of chemistry that students must learn to navigate to properly map representational features from one level to the next. From this perspective, students who demonstrate representational competence might be expected to seamlessly translate between these three representational levels, recognizing how features in one level correspond to features in another (Treagust *et al.*, 2003; Kozma and Russell, 2005; Rau, 2015). Voices in the chemical education community have pushed back on this perspective of the triad, positing that characterizing symbolic

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representations as a distinct level alongside the macroscopic and submicroscopic risks obscuring its functional role in chemical thinking (Taber, 2009). Symbols describe our effort to communicate about the macroscopic, submicroscopic levels or both simultaneously (Taber, 2013). For example, the word 'liquid' is a symbol that describes the low shape rigidity of a substance at the macroscopic level. In this perspective, symbols are a distinct ontological category from macroscopic and submicroscopic levels as the latter two describe matter at different scales whereas symbols communicate an understanding. Consequently, chemistry can be conceptualized as macroscopic and submicroscopic levels that have unique and overlapping symbols. From this perspective, chemistry is not simply a process of translation between levels, but a discipline in which meaning is constructed *via* an interpretation of symbols that may be particular to one level or be applicable to both levels.

This reframing highlights a central challenge for students, which rests in determining what knowledge is relevant in response to the symbols used. Although each level rests on the same knowledge base, students may struggle to recognize how that knowledge applies when faced with highly contrasting saliant features. Research has demonstrated that students struggle in making connections between macroscopic observations and submicroscopic theoretical knowledge. When students were placed in task environments that prompted them to provide submicroscopic explanations for macroscopic observations, they were able to identify entities and properties in both domains but struggled to establish causal connections between them (Keiner and Graulich, 2020). While interventions have been proposed to make the transition between these domains more accessible by intentionally prompting students to reflect on the submicroscopic domain during their macroscopic observations, these efforts report mixed results with students facing challenges in formulating submicroscopic explanations for their observations on the macroscopic level (Galloway and Bretz, 2016; Keiner and Graulich, 2021). Therefore, students' explanations remain closely tied to the visual cues and symbols used with each domain, suggesting that the challenge lies in possessing content knowledge and recognizing its relevance within a given conceptual context.

This idea is not limited to the macroscopic level of chemistry and has been explored within the framing of symbolic representations of molecules (Farheen and Lewis, 2021; Nelsen *et al.*, 2024a, 2024b). The explicit features a molecular representation carries directly influences how a student approaches a chemical task and what chemical information they deem relevant (Nelsen *et al.*, 2024a, 2024b). Although these representations are designed to cue students toward submicroscopic principles, they do not explicitly indicate which features should be prioritized, requiring students to selectively activate and coordinate appropriate conceptual knowledge. As a result, alternating the molecular representation on parallel chemical tasks can significantly affect how a student explains a submicroscopic process (Talanquer, 2022; Nelsen *et al.*, 2024a, 2024b; Steinbach *et al.*, 2025), which demonstrates how differing symbols cue students to differing knowledge.

These challenges become more pronounced when students are tasked with formulating explanations in the macroscopic domain where physical outcomes of molecular properties require students to determine the relevant submicroscopic principles and how they relate to macroscopic observations. This process is also heavily influenced by visible cues of macroscopic features that shape how the student interprets a phenomenon and considers what knowledge is relevant for explanation. The impact of observable macroscopic features on students' explanations has been captured within the literature (Ben-Zvi *et al.*, 1986; Talanquer, 2010; Paik, 2015). For example, when a solution changes color, students may attribute this observation directly to a color change in the molecules themselves. However, the relationship between student explanations and their macroscopic observations is not always direct. In many cases, students draw on submicroscopic principles they perceive as relevant in response to visible cues of macroscopic features. The degree to which these submicroscopic principles are tied to visible cues can determine how useful those principles are in practice. For instance, Abell and Bretz found that students explained dissolution by linking entropy directly to the number of particles, reasoning that entropy increases as a substance dissolves and produces more particles in solution (Abell and Bretz, 2019). In this case, students recognize the relevance of entropy but conflate it with the visible event of dissolution.

In classroom settings, alternative conceptions of this nature are often delineated as incorrect, without considering the influence of salient features on how students construct their reasoning (Carraher and Schliemann, 2002; Lobato, 2012). This dichotomous framing of correct or incorrect presents a limitation for interpreting student reasoning. When explanations are evaluated without attention to contextual factors, it becomes difficult to determine whether students' alternative conceptions reflect a stable understanding of chemical behavior across the submicroscopic and macroscopic levels of chemistry or are instead constructed in response to the contrasting salient features portrayed. Without this distinction, interpretations of student understanding risk mischaracterizing domain-dependent reasoning as conceptual deficiency. Within the current literature, it remains unclear how students might formulate explanations when similar phenomena are presented across macroscopic and submicroscopic levels. Accordingly, this study seeks to better characterize how students determine what knowledge is relevant when explaining chemical phenomena across the submicroscopic and macroscopic domains, with particular attention to how the task features shape these judgments.

Theoretical framework

The resources framework offers an alternative view on how students construct knowledge in varying contexts, emphasizing that reasoning is shaped by the framing of a learning environment (Hammer *et al.*, 2000; Elby and Hammer, 2010). This framework has been commonly used within the literature to detail variations in students' processes when they are placed into contrasting contexts (Wood *et al.*, 2014; Sheppard and Bauer, 2022; Pölloth *et al.*, 2023; Farheen *et al.*, 2024). Rather than conceptualizing knowledge as stable conceptions that can be readily applied across contexts, this perspective characterizes knowledge as fine-grained resources that are activated in response to the context presented (DiSessa, 1993; Hammer *et al.*, 2000; Louca *et al.*, 2004). From this standpoint, the conceptions that students articulate are not inherently correct or incorrect but are instead considered productive or unproductive, dependent on the given context (Elby and Hammer, 2010). For example, a student may identify iodide as a strong nucleophile based on a learned association which can be productive for classifying reaction pathways and predicting mechanisms (submicroscopic level); however, it may become misleading, as the relevance of nucleophilicity alone may be insufficient to explain the observed phenomenon (macroscopic level).

Therefore, the resources perspective is concerned with the variations in which resources are activated and how they are coordinated across contexts. Features of a task, such as the symbols used or salient visual cues play a critical role in shaping this activation (Hammer *et al.*, 2000). For instance, when presented with molecular representations in lecture, students may activate resources related to a mechanistic approach, identifying nucleophiles, electrophiles and leaving groups. However, when interpreting visible cues of a macroscopic phenomenon, such as the rate of precipitate formation, students may focus on energetic considerations in crafting an explanation. These shifts in reasoning are not indicative of conceptual inadequacies but rather reflect how students interpret the demands of a given context and selectively activate pieces of knowledge accordingly. The present study adopts a resources framework to examine how students explain reactions across chemical domains that emphasize different features of chemical information.

Research overview

This study takes the position that the critical distinction that exists between tasks in macroscopic and submicroscopic levels are how these levels are communicated and the epistemic expectations for how students explain chemical phenomena at each level. The central goal of this study is to explore how students utilize resources across these epistemically different levels. To explore these differences, students crafted explanations for parallel chemical principles when they were cued to each level. Differences in explanations were used to understand different features that may shape what students recognize as productive for explanation. In the submicroscopic-cued tasks, molecular properties are encoded in molecular representations, while in the macroscopic tasks, visual cues are present to infer the outcomes of underlying chemical processes. This design offers an opportunity to examine how variations in the features present within the levels of chemistry influence the conceptual resources students enlist to explain chemical phenomena. To guide this investigation, the following research question was developed:

How do students determine which conceptual resources are relevant when constructing explanations for organic chemistry reactions across macroscopic and submicroscopic-cued tasks?

The first set of tasks presents students with videos of macroscopic-experimental observations. Although the chemical names of the reagents are provided, symbolic representations of molecules are intentionally withheld to examine how students identify relevant knowledge from the salient features of the macroscopic level. This positions students within a phenomenological framing, where the focus is on explaining visible outcomes. In this framing, students may draw on a range of nonnormative explanatory approaches, including tautological (*e.g.*, "it reacted because a precipitate formed") anthropomorphic (*e.g.* "the molecules don't want to stay mixed") or teleological (*e.g.* "the reaction happens to produce the solid") (Talanquer, 2010). These explanatory approaches are not mutually exclusive from submicroscopic reasoning, in that a student may draw on molecular-level conceptions while still framing causality in teleological or anthropomorphic terms. Rather than focusing on the specific instances in which these types of approaches occur, the analysis focuses on the resources students' explanations are built on, as even nonnormative explanatory framings can hold productive conceptions about a phenomenon. Adopting this framing allows for the identification of how macroscopic observations shape what students perceive as relevant for explanation, and how students' submicroscopic reasoning may be directly or indirectly related to the observable features of the phenomenon.

In the subsequent set of tasks, students are presented with symbolic representations of molecules and asked to predict and explain reaction outcomes. At the study site, these representations are used in instruction to support students' understanding of molecular structure and reactivity, directing attention to features like electron distribution, nucleophilicity, and substrate structure. Therefore, this task type positions students within a submicroscopic-cued reasoning frame, where the representational features are likely to prompt students to consider the submicroscopic entities dictating reactivity.

Methods

Research setting and participants

Ten participants were recruited from students enrolled concurrently in first semester organic chemistry lecture and lab at a large research-intensive university in the southeastern United States. An initial announcement was made in person during the Friday laboratory discussion section, and an online announcement was posted in the learning management system to reach students who may have missed the discussion section. Students were notified that participation was voluntary and would not impact their grade in the chemistry course. Participant eligibility was dependent on completion of the sixth experiment of the semester to ensure recruits were familiar with the laboratory techniques discussed in data collection. Students that replied to the call for participants and met the requirements were offered enrollment in the study.

Ethical considerations

Enrolled students were provided a description of the study procedures and were notified of their rights as participants.

They were subsequently asked to sign an informed consent granting the researchers permission to utilize the data collected from their interviews. All students that completed the interview were compensated with a 20-dollar (U.S.) gift card. This study was approved by the Institutional Review Board at the research setting (Pro00020840).

Data collection

Semi-structured interviews, approximately 60 minutes in length, were used to capture detailed accounts of participant resource usage across conceptual domains (see Fig. 1 for interview summary). The interviews were split into two sections (see Appendix Part 1 for the interview protocol). In the first section participants were presented with a video recording of portions of the sixth experiment of the semester with a voice over explanation of the materials and chemicals being used and the procedures conducted. The experimental aim was to synthesize *tert*-butyl chloride from hydrochloric acid and *tert*-butyl alcohol through an S_N1 reaction. Participants were informed that they had completed the experiment in the lab during the semester but were not told which experiment or its aim. Throughout the video, two pause-points were posed with questions asking students to interpret macroscopic observations in an experimental setting. The first point (herein labeled Macroscopic Task 1) was presented following a clip of hydrochloric acid and *tert*-butyl alcohol mixing in a separatory funnel. After the two layers settled, students were asked the following question: ''When the hydrochloric acid and *tert*-butyl alcohol are added to the separatory funnel and you begin to swirl, what is occurring at the molecular level?'' The second point (Macroscopic Task 2) appeared after a qualitative-experimental test that placed the resulting *tert*-butyl chloride in a test tube with either sodium iodine in acetone or silver nitrate in ethanol. After the formation of the precipitate in the silver nitrate test tube, participants were asked the following question: ''Why do the contents in one test tube react at a faster rate than the other test tube?'' For each of the tasks in this section of the interview, participants were asked follow-up questions to clarify the implications and the sources of their conclusions (*i.e.* ''What factors are you considering? What chemical principles did you use to make your decision?)

In the second section of the interview, participants were presented with a series of tasks that provided symbolic representations (bond-line structures) of reagents. In the initial task (Submicroscopic Cued 1), participants were presented with the bond-line structures of a secondary bromine alkyl halide and water as the solvolysis reagent. Students were asked to predict the major product(s) of the reaction and to provide the associated mechanism. In the second task (Submicroscopic Cued 2) of the section, participants were provided both the reagents and the products for a reaction between methyl iodide and potassium hydroxide in ethanol. Participants were informed that the reaction proceeded slow with low yield and were asked to identify potential causes for this issue and to provide a potential solution. Similar to the first section of the interview, participants were asked clarifying questions to explicate their assertions about reaction outcomes.

Data analysis

The interviews were transcribed using Adobe Premiere Pro talk to text software. The transcribed interviews were corrected manually. Throughout the interview, participants were informed that they could use the paper from the protocol to write down and draw out any ideas or principles they thought were relevant to the task. The paper also served as a place where participants were asked to draw out mechanisms or chemical processes they described verbally. Photos were taken of participants' drawings and were embedded into the interview transcripts. To gain familiarity with participant responses, the authors wrote summaries for each participant for each task to explore the factors participants considered within each set of tasks (40 summaries in total). Authors IN and AR individually analyzed the summaries and each inductively developed a codebook pertaining to the conceptual resources participants considered. The generated

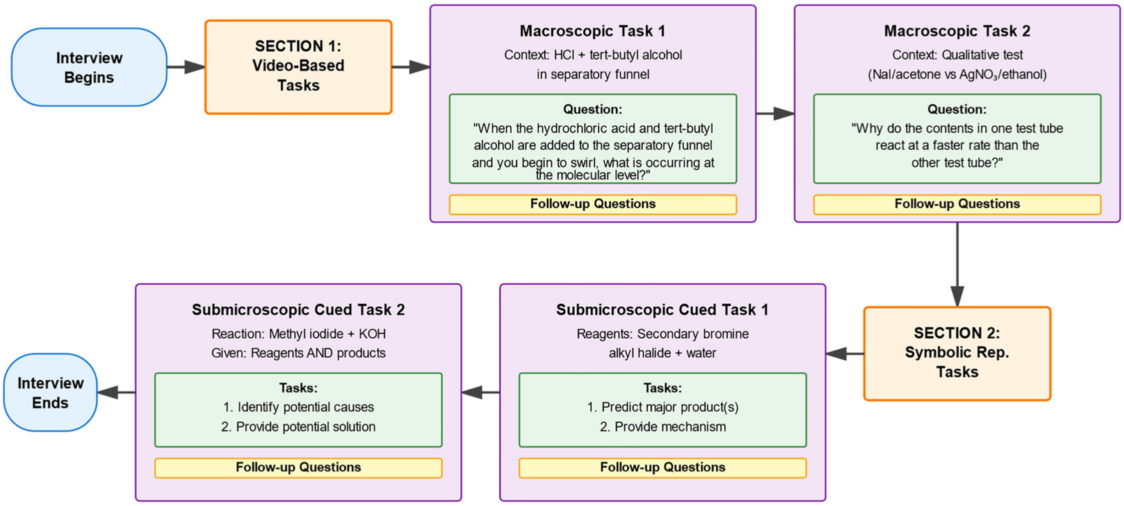


Fig. 1 Overview of semi-structured interview from data collection (made with Claude AI).

codebooks were compared, and disagreements were discussed until agreement was reached regarding the contents of a preliminary codebook. The preliminary codebook was applied individually by authors IN and AR to two of the ten transcripts. Thereafter, IN and AR discussed the applicability of the codes and their proficiency in capturing the concepts students were using. This process was repeated two additional times (three iterations total), with each iteration revealing areas for refinement (details provided in the supplementary information (SI)).

The final codebook (see Appendix Part 2) was made up of six parent codes each comprised of 2–4 subcodes for a total of 17 distinct concepts that students utilized throughout the tasks. This codebook structure provided a path for tracking the general category of concepts students used across each set of tasks along with the specific ways they invoked them. As a result, we were able to directly explore our research question by characterizing how conceptual resources were mobilized and adapted in response to the domain-specific factors of the tasks. Notably, the codebook includes one parent code that exclusively applies to the macroscopic tasks (*Visible Cue Interpretation*). IN and AR elected to include this code to explore instances where the macroscopic observations were considered by students as resources to consider in their reasoning.

Using the final codebook, consensus coding was carried out by IN and AR on two transcripts at a time, and disagreements were discussed until full agreement was reached. Disagreements generally pertained to subcode granularity. Each disagreement was resolved through discussion involving re-reading the transcript segment being coded within the larger conversational context, referencing the participant's drawings when applicable, and referring to the codebook definitions. For cases where participants' responses were more complex, a second round of consensus coding was conducted. The coded transcripts were analyzed to draw associations and distinctions between the conceptual resources each participant reasoned within each set of tasks. This was accomplished by formulating a table that tracked the general (parent codes) categories of concepts that students used (see Table S1 in SI) and a table tracking the specific (subcodes) ways their responses changed (see Table S2 in SI). Once these comparisons were drawn, variations in conceptual resources were identified to uncover how domain-specific factors influenced how participants invoked or modified a conceptual resource. Part of this analysis involved tracing how students employed and interpreted each conceptual resource, revealing how the same resource could serve distinct purposes depending on the epistemic demands of the task. This process resulted in four major themes on how participants leveraged, modified, or reinterpreted conceptual resources.

Results

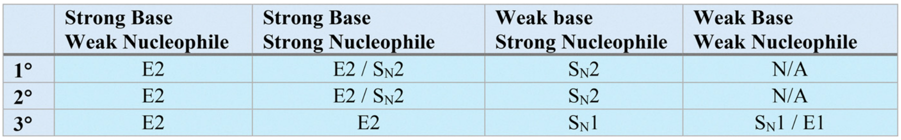
The four themes presented below represent non-exclusive patterns characterizing how participants selected and utilized conceptual resources in the macroscopic and submicroscopic cued tasks. Rather than serving as categorical groupings of participants, these themes describe the ways in which conceptual resources were enacted and interpreted.

Theme 1: memorized reagent associations as relevant conceptual resources across tasks

One of the prominent conceptual resources utilized by participants involved invoking memorized associations between reagent types and expected reaction outcomes. All 10 participants invoked reagent-reaction associations in the submicroscopic cued tasks, while three participants (P1, P9, P10) adapted this resource to the macroscopic tasks. These associations originated from a lecture-based reactivity chart that summarized expected patterns of reactivity for substitution and elimination reactions (Fig. 2) and often served as a mnemonic device for determining reaction outcomes without engaging deeply with underlying molecular properties.

Participants frequently used this resource as an initial point of reference when interpreting bond-line representations in the submicroscopic cued tasks. For instance, Participant 3 explicitly referenced this chart when explaining their reasoning for Submicroscopic Task 1, stating "that chart. It's like a color-coded chart that says like the conditions of the conditions required for each of, like the mechanisms like E1 and E2 and S_N1 and S_N2 to happen." In doing so, participants relied on surface-level categorizations based on substrate connectivity, nucleophile/base strength, and solvent type to categorize reactions. While this approach enabled participants to efficiently identify reaction types, it often resulted in simplified reasoning. Participants rarely articulated how these features mechanistically contributed to the reaction pathway, instead treating them as indicators of a particular outcome. This was evident in Participant 6's focus on connectivity, as they claimed "If I remember, I know one can have a primary, so I'm assuming it would be an E1. I'm not sure if E1 can have secondary or tertiary." Participant 2 similarly concluded, "I said elimination because I know H_2O is not a strong nucleophile."

Although most participants relied on these associations primarily in submicroscopic cued tasks, a subset (P1, P9, P10)



	Strong Base Weak Nucleophile	Strong Base Strong Nucleophile	Weak base Strong Nucleophile	Weak Base Weak Nucleophile
1°	E2	E2 / S_N2	S_N2	N/A
2°	E2	E2 / S_N2	S_N2	N/A
3°	E2	E2	S_N1	S_N1 / E1

Fig. 2 Participants often referred to, and sometimes sketched, a chart from their lecture course to categorize reactions based on the properties of its reagents. The image above is a recreation of participant's drawings. The numbers in the left-most column indicate substrate connectivity and the top row denotes the nucleophilic/basic strength of a reagent.

recognized them as relevant in the macroscopic domain. For these participants, reagent-reaction associations acted as a conceptual resource that allowed for mapping observable changes onto familiar reactivity patterns. For instance, Participant 1 brought forth reagent associations to interpret their macroscopic observations in Macroscopic Task 2, reasoning "…the cloudy solution is actually the silver nitrate with ethanol, but we can actually confirm this when we look at the reaction…tertiary halogens, as we said before, like react better with weak nucleophiles and so this corresponds."

However, the activation of reagent associations within a macroscopic framing was not always productive. For instance, Participant 9 showed hesitancy in their reasoning when encountering unfamiliar forms of reagents, noting, "So the chloride anion is a strong nucleophile. So is it that it would undergo… S_N1….I think because it's bulky so it wouldn't undergo S_N2 and Cl minus isn't strong enough to function as a base… So E2 is not possible. So I think we would undergo S_N2…I don't know if I'm just inventing something here." Upon further explanation, it became apparent that the uncertainty emerged when the participant encountered chloride in an unfamiliar form (HCl), as they reasoned "I'm saying that this mechanism (S_N2) that I'm trying to demonstrate usually works when it's like NaCl or KCl, okay. To catalyze it. So I don't know if that makes any sense at all." This example highlights how similar features across conceptual domains can become difficult to interpret when their ontological role is perceived differently, such that students may not recognize them as serving the same function.

Theme 2: molecular property reasoning redirected by macroscopic observations

In several cases, although participants recognized the relevance of similar conceptual resources across both task types, the macroscopic observations introduced a competing layer of complexity that shaped how and whether those conceptions could be meaningfully applied. Four participants (P2, P3, P5, P8) engaged with the submicroscopic properties of the reagents during the macroscopic tasks, drawing on conceptual resources that reappeared when they worked through the submicroscopic-cued tasks. These participants struggled to effectively utilize these conceptions in the macroscopic domain. The macroscopic observations introduced an additional layer of complexity, requiring students to reconcile what they observed at the macroscopic level with their conceptual resources, a demand that was not present in the submicroscopic-cued tasks where those same conceptions could be applied more directly.

Participant 8's explanations across the tasks illustrates the impact of the macroscopic observations on student explanations. After watching the video of the experimental procedure in Macroscopic Task 2, Participant 8 recognized the reagents and classified both sodium iodide and silver nitrate as strong nucleophiles based on electron-donor ability, stating, "So sodium iodide is a strong nucleophile… and silver nitrate would be very willing to like transfer its electrons… so it's probably the strong nucleophile." However, after a closer look at the macroscopic events, the participant recognized that no precipitate formed in the sodium iodide test tube, and revised his designation of sodium iodide as a strong nucleophile, offering an explanation focused on the impact of steric hindrance to account for the absence of a reaction: "it's (sodium iodide) not really a strong nucleophile… it wouldn't want to transfer its electrons to such a strictly hindered [carbon]." Later, in Submicroscopic Cued Task 1, the participant drew on the same initial underlying conception, assigning nucleophilic strength based on electron-donor ability: "I know water… is a weak base and a weak nucleophile because it doesn't want to give up its own two lone pairs." The participant extended this reasoning productively, drawing on nucleophilic strength as a determinant of reactivity to identify the mechanism the reaction would undergo. Therefore, while Participant 8 recognized the relevance of nucleophile strength as a relevant resource across task types, the macroscopic events added a layer of complexity that complicated how those resources could be meaningfully applied.

A similar pattern was observed for Participants 2, 3, and 5, as they identified similar molecular properties in both the macroscopic and submicroscopic-cued tasks, but offered alternative explanations as a consequence of their macroscopic observations. The properties students drew on included nucleophilic strength, charge distribution, and substrate connectivity. For example, in Macroscopic Task 1 Participant 2 identified partial charges using electronegativity, stating, "chlorine is more electronegative than carbon… making carbon partially positive." Participants 3 and 5 extended this idea when discussing Macroscopic Task 2 to define nucleophiles in terms of electron availability, and used this conception to briefly review the general mechanism of nuclephilic reactions. Participant 3 defined nucleophiles in terms of electron richness, explaining that "an electron-rich atom attacks…a carbon electrophilic center," and on this basis classified iodine as a strong nucleophile given its availability of electrons. When participants attempted to relate these molecular properties to their macroscopic observations, they encountered difficulty and shifted the focus of their explanations. This was particularly evident in Macroscopic Task 2, where, similar to Participant 8, all three participants struggled to explain the absence of a precipitate in the sodium iodide test tube. Having identified iodide as a strong nucleophile, participants anticipated the reaction to proceed more readily. In response, Participants 3 and 5 attention drew toward an explanation dependent on stability, suggesting that iodine's stability in its ionic form reduced its reactivity. As Participant 3 explained "I think it has to do with…the strong nucleophiles are typically like the halogens – so like bromine, iodine, I think is how you say it, fluorine – and like the halogens, because they're already at like a stable state. They just don't react as quickly with anything else." Alternatively, Participant 2's explanation pivoted toward the macroscopic observation itself, proposing that the reaction may have occurred but was not visible due to solubility: "I think it's probably because it dissolves in the solution. That's why we're not able to see it (sodium iodide)…but silver chloride, it doesn't dissolve and it forms a precipitate." Ultimately, these cases convey the added layer of complexity the macroscopic domains brings when students attempt to relate submicroscopic conceptions to observable events. Although participants initially drew upon similar conceptual resources across task types, the macroscopic events shaped which aspects of those resources were recognized as relevant, leading to shifts in how explanations were constructed.

Theme 3: visual cues conflated with submicroscopic processes

In several instances, participants directly relied on macroscopic observations as primary cues for constructing their explanations, using visible features as the basis for predicting and interpreting reaction behavior. Five participants (P3, P4, P6, P7, P10) initially referenced macroscopic observations descriptively but as they continued to reason, the observations developed into diagnostic resources. This approach contrasts with their strategies in the submicroscopic cued tasks, where explanations were grounded in reagent associations.

The prominence of macroscopic cue reliance was especially evident in Macroscopic Task 1, where participants highlighted the immiscibility of *tert*-butyl alcohol and hydrochloric acid. Participants 6 and 10 interpreted this observation as repulsion between the molecules in the separatory funnel, concluding that the reagents were not reacting. Participant 6 explained this through an analogy, stating ''my brain is just going to oil and water. I'm assuming like for example, like when you mix oil and water, the oil separates but never fully mixes with the water.'' In contrast, Participant 3 acknowledged that bonds were in fact breaking and forming, but only when layers were actively mixed, reasoning ''I think it's temporary because after you swirl it and then the two layers form again, it's like they (bonds) break apart. That's how I think about it.'' Similarly, Participant 4 proposed that a reaction was occurring but not proceeding fully, suggesting that the separation of layers indicated an unfavorable process that would require additional energy to proceed.

Participant 4 extended this energetic conception to Macroscopic Task 2, reframing the reaction in kinetic terms, attributing the lower reactivity of the sodium iodide test tube to a higher activation energy, explaining ''Well, the activation energy... is the energy that you that is required to start a reaction. And I'm guessing the test tube one, the activation energy is pretty low, which is why we were able to well like complete the reaction faster.'' A similar pattern was observed for Participant 6, who used reaction rate as a conceptual resource for determining reaction type in Macroscopic Task 2. Observing that the silver nitrate reaction proceeded more quickly, the participant postulated: ''I'm assuming the faster reaction was an S_N2 reaction. And the one that didn't react as fast was an S_N1.'' When elaborating, the participant reasoned that she has an association between the S_N2 mechanism and ''extreme reactions'', largely due to the concerted nature of the S_N2 mechanism. Interestingly, aspects of this conceptual resource appeared in the submicroscopic-cued tasks, where Participants 6 and 10 assigned reaction types based on the number of mechanistic steps they drew. Their reliance on this strategy reflected difficulty recalling the memorized reactivity chart, as Participant 6 explained: ''I'm trying to remember the table that he gave us. I don't have it memorized yet. I would put it under the one either as an S_N1 or E1 reaction just because it looks like it only has one step; I don't think it would have two steps.'' These cases illustrate how students' conflation between macroscopic cues and molecular properties potentially resulted from their uncertainties in their foundational understanding of submicroscopic principles.

Theme 4: reconstructing resources across conceptual domains

Instances were also observed where participants reinterpreted the meaning of conceptual resources in response to the salient features within each set of tasks. In these cases, students applied similar conceptual resources across task types, while simultaneously adapting them to align with domain-specific demands. Seven participants (P1, P2, P3, P5, P7, P8, P10) demonstrated this pattern with at least one core conceptual resource. While the same terminology was often used across task types (*e.g.*, ''reactivity,'' ''stability,'' ''steric hindrance'') the underlying meaning of these resources changed.

This shift was evident in how participants used the concept of reactivity. In the macroscopic tasks, reactivity was often invoked as a direct explanation for observable outcomes, functioning as a descriptive account of whether substances would visibly react. For instance, Participant 2 explained the presence of a precipitate in one test tube and its absence in another by suggesting that ''they (the molecules) were able to react with each other because like certain conditions were met,'' framing reactivity as a property that determined whether a reaction would occur. Participant 10 demonstrated a similar approach, treating the formation of a precipitate as evidence of reactivity between an acid and base, using the production of a ''salt'' as an indicator of a successful interaction. In these cases, reactivity operated as an explanatory label for macroscopic observations rather than as a construct grounded in molecular properties. In contrast, when engaging with the submicroscopic cued tasks, reactivity was reinterpreted as a consequence of molecular properties. For instance, Participant 10 reframed their reactivity resource, relating solvent properties to molecular interactions, reasoning ''I think aprotic means non-polar, so the solvent would have to be non-polar in that way. So if it's nonpolar, I think it like helps neutralize more and everything flows easily.'' Here, the conceptual resource shifts from a tautological utility to a mechanistic utility, where interactions at the molecular level are connected to ideas of polarity and solvation.

A similar shift was observed in participants' use of stability. In the macroscopic tasks, stability was often treated as an inherent property of the observable reaction. For instance, when working with Macroscopic Task 2, Participant 7 put forth ''I think that cloudy look is like the reaction occurring. But because that reaction isn't stable, it just reverts back to like it, being clear.'' However, in the submicroscopic cued tasks, stability was recontextualized as a consequence of molecular structure. Participant 7 later described stability in terms of substitution patterns, noting that a structure ''would be more stable since it has that double bond [and] will have four groups attached.'' In this case, stability shifted from a tautological explanation of observable behavior to a property emerging from molecular configuration.

The concept of steric hindrance followed a similar pattern. In the macroscopic tasks, participants used steric hindrance to account for slower reaction rates or the absence of a visible change. For example, Participant 7 reasoned ''It (the reaction) occurs due to the fact of the interaction between the two and then as a result… there's a lot of steric hindrance and that typically slows down the reaction.'' Participants 2 and 10 echoed this idea in Macroscopic Task 2, identifying steric hindrance as the barrier to the formation of a precipitate. However, when presented with symbolic representations in the submicroscopic cued tasks, participants began to conceptualize steric hindrance in terms of spatial and electronic feature ''The H and O bond. Basically due to those bonds there is like a electron density cloud of sorts that like surrounds it so when there's other compounds of chemicals trying to attach to it, it makes it very hard to do so due to the fact of that like electron cloud going on slash like the steric like hindrance going on'' (Participant 7). Collectively, these examples illustrate that participants did not always apply fixed conceptual definitions across task types. Instead, they reconstructed the meaning of familiar resources in ways that aligned with the features made salient in each task. As participants moved between the macroscopic and submicroscopic domains, the same terminology was retained, but its underlying meaning shifted to accommodate the demands of the conceptual domain.

Discussion

The distinct but interconnected domains of chemistry pose challenges for students (Keiner and Graulich, 2020; Keiner and Graulich, 2021). Student explanations of macroscopic phenomena are frequently described as disconnected from the submicroscopic domain, as students struggle to draw causal connections between observed behaviors and chemical properties (Prieto *et al.*, 1989; Hesse III and Anderson, 1992; Abraham *et al.*, 1994; Calik and Ayas, 2005; Talanquer, 2008; Yan and Talanquer, 2015). The present study builds on previous work by examining how students identify and use relevant resources across these conceptual domains to explain and predict chemical reactions. The discussion that follows explores how these patterns manifest in students' reasoning and the factors that shape their selection and use of conceptual resources.

Conceptual domain as a mediator of resource interpretation

A central finding was that salient features at the macroscopic level, influence participants' estimation of the relevance of a resource and its implications. From students' final conclusions about reaction outcomes at the macroscopic and submicroscopic cued tasks, one might conclude that their conceptions were altogether different. However, by looking intently at the process participants underwent to reach their final conclusions, it was clear that students often recognized parallels between the two conceptual domains and the resources that were relevant to explaining molecular behavior. This process materialized in two different ways. Participants 2, 3, 5, and 8 viewed reagents in the macroscopic level similarly to how they utilized the symbolic representations in the submicroscopic cued tasks, attending to conceptual resources related to atomic and molecular properties when explaining reactivity. Nevertheless, when students struggled in relating their conceptual resources to the observed outcomes, reasoning often shifted toward more simplified explanations, either generalizing a submicroscopic principle or integrating visible changes to reconcile their thinking with the outcome (as shown in Theme 2). Similarly, participants frequently invoked the same chemical principles across task types yet reconstructed their implications to align with the epistemic demands of each domain. This suggests that while students recognized the importance of underlying principles such as reactivity, stability and steric hindrance their interpretations were shaped by their prior knowledge and the observable outcomes of the task (as shown in Theme 4). This finding aligns with prior work showing that while students may recognize the relevance of a conceptual resource in explaining a macroscopic event, they often struggle to connect it to the underlying submicroscopic causal mechanisms (Keiner and Graulich, 2020; Keiner and Graulich, 2021).

Consequently, conceptual resource selection and use are shaped by an interaction between participants' prior knowledge and how they interpret the features of the learning environment. This interplay allows for a wide range of interpretations, as the relationship between macroscopic observations and relevant conceptual resources may differ from learner to learner. This was clear in Macroscopic Task 2, where Participant 2 interpreted a precipitate as evidence of a favorable reaction, whereas Participant 10 associated the same white precipitate as a salt, categorizing the process as an acid–base reaction, and shaping how he interpreted the properties of the reagents. Such differences illustrate how learners' prior knowledge informs the resources they draw upon, while contextual features influence how those resources are applied (Smith and Manzano, 2010; DuBrow *et al.*, 2017; Shin *et al.*, 2021). Echoing prior calls in the literature, instruction may be strengthened by helping students bridge experiences across domains of chemistry, thereby reducing the influence of domain-specific cues and providing opportunities to connect macroscopic observations with underlying submicroscopic principles (Harrison and Treagust, 2000; Treagust *et al.*, 2003; Chandrasegaran *et al.*, 2011; Keiner and Graulich, 2020; Keiner and Graulich, 2021).

Memorized associations as both scaffold and constraint in resource usage across tasks

Additionally, this study revealed that students' reliance on memorized associations with symbolic representational features further shapes how principles are retrieved and applied. For some learners, these memory-based resources provided a stable scaffold that facilitates continuity across the conceptual domains (as in Theme 1), while for others they created obstacles when the students' associations remained confined to the submicroscopic domain in which they were initially learned (as in Theme 3). This finding reflects and contextualizes a theme in the literature, where students struggle to transition between the submicroscopic and macroscopic domains when crafting explanations (Griffiths and Preston, 1992; Gilbert and Treagust, 2009; Keiner and Graulich, 2020). For Participants 1 and 9, recalling reagent–reaction associations provided a direct path to explaining reaction outcomes, even when they were not directly cued to consider submicroscopic explanations. For these students, the stability of their memorized knowledge supported continuity in reasoning and even enabled them to draw on these resources to make sense of macroscopic observations. This finding aligns with prior research suggesting that mnemonic reasoning can be productive for students when utilized with the proper cues in an appropriate context (Kahneman and Klein, 2009; Talanquer, 2014). However, for many students, reliance on memorization hinders their ability to reason flexibly across the domains (Grove *et al.*, 2012; Talanquer, 2014; Anzovino and Bretz, 2015; Anzovino and Bretz, 2016). Participants 4, 6, and 10 exemplified this challenge in that they struggled to recall information from the reaction tables and defaulted to more explicit macroscopic cues, rather than constructing explanations from submicroscopic resources (observed in Theme 3). Similar findings have been reported in the literature, where students have difficulty transitioning from the phenomenological level of chemistry to the atomic-molecular level, conflating macroscopic observations with molecular properties (Ben-Zvi *et al.*, 1986; Griffiths and Preston, 1992; Gabel, 1999; Talanquer, 2006; Talanquer, 2008). When learners rely heavily on memorized associations, introducing new visual features or representational forms imposes additional working memory demands, which can interfere with resource retrieval and adaptation (Opitz and Kubik, 2024). In the present study, recalling memorized reactions while simultaneously processing macroscopic observations appeared cognitively taxing, potentially impacting consistency in the resources used across the task types (Balter and Raymond, 2023). The repercussions of a memorization-centered approach to learning organic chemistry thus extend beyond the submicroscopic domain and can impact how students interpret macroscopic observations. When molecular properties are presented as contextualized rules rather than mechanistic relationships, students lack a foundation for interpreting how those properties manifest in physical phenomena. The resulting disconnect is, therefore, a reflection of the limited meaning those resources hold within their learned framework. Therefore, the framework that students are equipped with must be expanded to consider the underlying principles guiding the rules they have memorized. This begins with deemphasis on producing the correct answer and a focus on encouraging students to consider the driving forces of reactions and their relationship to observable outcomes (Button *et al.*, 2023). Recommendations to support this transition are discussed below.

Implications

This study examined how students formulate explanations for chemical behavior in the varying domains of chemistry, revealing how salient cues can shape students' consideration and implementation of relevant resources. University-level chemistry frequently requires students to apply the same principles across different learning environments, most notably in the laboratory, where students must connect the submicroscopic theoretical models introduced in lecture with macroscopic observations. However, prior literature has reported that simple recall and mnemonics is often encouraged in both laboratory and lecture classrooms, as a focus is placed on obtaining the correct answer or synthesizing the correct product (Grove and Bretz, 2012; DeKorver and Towns, 2016; Taber, 2020). The repercussions of this approach were evident in this study as participants frequently attempted to draw from memorized reagent associations they learned in their lecture classroom but struggled to rationalize how they related to their observations in the macroscopic tasks. Consequently, one implication from this work is that instruction may benefit from incorporating exercises where sensemaking, rather than correctness, is the primary objective (Button *et al.*, 2023). Activities that foreground the why behind reactivity allow learners to build conceptions rooted in mechanistic principles that can be applied flexibly across conceptual domains rather than encourage reliance on reagent-reaction associations. However, encouraging such a shift in reasoning is not easily accomplished. Research has shown that students often default to resources that lead to the most direct path to the correct answer, particularly when assignments and feedback emphasize accuracy over reasoning (Nelsen *et al.*, 2024a, 2024b). To disrupt this pattern, studies have proposed the inclusion of open-ended tasks with no known solution, to compel students to evaluate varying explanations rather than recall predetermined answers (Button *et al.*, 2023; Nelsen *et al.*, 2024a, 2024b). This aligns with emerging evidence suggesting that molecular representations that explicitly visualize molecular properties can further support students in reasoning about the driving forces of reactivity (Linenberger *et al.*, 2011; Host *et al.*, 2012; Talanquer, 2022). Although the effectiveness of sensemaking activities in bridging varying domains of chemistry has not yet been systematically evaluated, these tools show promise for reinforcing the common foundation that underlies varying epistemic framings.

Further support can be offered to students through prompting them to consider the framing of the proposed task and the knowledge that might be relevant. Explicitly framed prompts make the process of context-sensitive reasoning visible to students that might view the macroscopic and submicroscopic domains of chemistry differently. For instance, when students observe differences in rates of precipitate formation, an instructor might prompt ''What influence does nucleophile strength have on the rates of precipitate formation'' rather than ''Why does one reaction occur faster than the other.'' The former question explicitly bridges the submicroscopic concept (nucleophile strength) with the macroscopic observation (precipitation rate), while the latter leaves the connection implicit. The former offers two benefits. First, it allows the instructor to probe how a student might interpret submicroscopic entities within the macroscopic domain (laboratory setting) revealing student-constructed connections. Information garnered from this exercise can inform instructional revisions that better support student recognition of productive resources. Second, it provides a bridge for students to begin to recognize the overlap between the different lenses of chemistry, rather than assuming the connection is inherent. By specifying the submicroscopic principle at play, the instructor models reasoning across conceptual domains that students are expected to develop. Talanquer (2026) offers an additional method for developing a bridge between contexts known as comparative analysis tasks where teachers can ask students to analyze the same phenomenon through alternative contextual framings. For instance, course materials (*i.e.*, practice problems, lecture materials, formative assessments) can be redesigned to integrate side-by-side analyses of reactionary principles and their corresponding observable outcomes (*e.g.*, formation of a precipitate or solubility differences) prompting students to make explicit connections between submicroscopic principles and empirical evidence. Such integrative approaches promote a contextual dialogue enabling students to view chemical phenomena as coherent across conceptual domains rather than fragmented. Designing instruction that intentionally aligns representational reasoning with physical observation may foster the type of conceptual flexibility necessary for connections to be made between the submicroscopic and macroscopic domains of chemistry.

This flexibility is not an isolated gain. Understanding the relationship between the macroscopic and submicroscopic domains is an essential competency in chemistry learning, as it serves as a prerequisite for transferring principles across the discipline's many contexts and applications. This necessity is rooted in the pluralistic nature of chemistry itself. Talanquer argues that chemistry is a discipline that requires learners to navigate among multiple modes of reasoning, each of which may examine the same phenomenon through a different explanatory lens (Talanquer, 2026). Central to this navigation is the process of conceptual reframing or the ability to reinterpret a phenomenon by shifting between alternative explanatory lenses. The progression of a chemical reaction, for example, can be examined through energetic, mechanistic, or kinetic framings, with the chosen framing determined by the explanatory goal at hand. Critically, each of these framings carries some connection to the submicroscopic level, stipulating that relating macroscopic observations to submicroscopic phenomena is not merely one skill among many, but rather the entry point to the alternative explanatory lenses used to make sense of chemical phenomena. Fostering students' proficiency at moving between macroscopic and submicroscopic domains may therefore be one of the more consequential investments chemistry instructors can make, as it serves as the foundation from which broader chemical thinking can develop.

Limitations

This highly exploratory study centered on a limited sample's interpretation of reaction outcomes across two task contexts. Consequently, several limitations must be acknowledged to contextualize the conclusions drawn from this work. One limitation is the specific nature of the macroscopic tasks. The study focused on students' conceptualizations of a single experiment within the organic chemistry curriculum, and thus, participants' usage of conceptual resources may vary with the theoretical constructs emphasized by an experiment type. Moreover, the macroscopic and submicroscopic-cued tasks did not directly align in reagent type or outcome. This intentional design choice was made to prevent students from focusing on the identic nature of the reagents, in an effort to ensure the impact of salient features would be more authentic to a real learning environment. Nevertheless, it may have introduced additional variability in how participants identified resources across the task types. Additionally, this study did not examine how the sequencing of macroscopic and submicroscopic-cued tasks may have influenced the conceptual resources students identified as relevant. Different patterns may have emerged if students had encountered the submicroscopic-cued tasks first, as prior studies indicate that representational ordering can impact what students attend to (Nelsen *et al.*, 2024a, 2024b). Furthermore, because the interview involved student observations of procedures from an experiment they had already completed, the potential exists for retrospective reasoning and *post hoc* rationalizations rather than real-time interpretations. Some instances of this were evident as participants referenced trying to recall their observations from when they previously conducted the experiment. While this approach ensured that students were familiar with the procedural aspects of the task, it also introduced occasional difficulty in disentangling memorized events from reasoning.

Conclusion

The pluralistic nature of chemistry presents a challenge to students, requiring conceptual flexibility across domains that present chemical information differently. This study focused on how students draw upon, adapt, and reconstruct their conceptual resources across a series of macroscopic and submicroscopic-cued tasks. Findings revealed that a reactivity framework grounded in memorization contributed significantly to the instability of conceptual resources across tasks, as learned associations carried meaning only within the conceptual domain in which they were formed. Furthermore, macroscopic observations played a major role in shaping how students interpreted and evaluated the underlying principles guiding reactions, even when they engaged with the same conceptual resources used in the submicroscopic cued tasks. Consequently, the identification of resource relevance across the submicroscopic and macroscopic domains is a more interpretive and domain-dependent process than previously acknowledged. Considering these findings, students may benefit from learning environments that jointly consider the submicroscopic and macroscopic domains, encouraging students to reason with submicroscopic principles and observable outcomes and to consider the driving forces of reactions, rather than mnemonic reagent-reactionary resources.

Conflicts of interest

Researcher SEL receives funding from the Royal Society of Chemistry. The Royal Society of Chemistry did not play a role in the data collection, data analysis or manuscript development.

Data availability

The transcript data are not publicly available as approval for this study did not include permission for sharing data publicly.

Supplementary information (SI) presenting codebook refinement and code and subcode assignments to each participant is available. See DOI: https://doi.org/10.1039/d5rp00439j.

Appendix

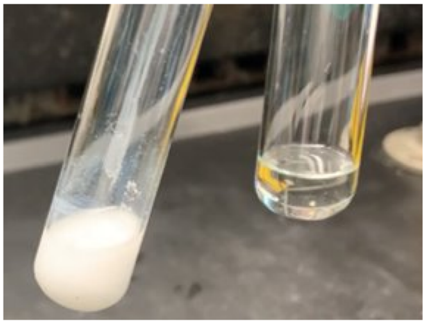
Interview protocol

Part I: in this first portion of the interview, you will be shown a video of an experiment conducting an organic chemistry reaction. Please watch the video and answer the questions when I pause the video. I may ask you follow up questions, but that does not mean you answered incorrectly, I am just attempting to better understand your answers.

(1) When the hydrochloric acid and *tert*-butyl alcohol are added to the separatory funnel and you begin to swirl, what is occurring at the molecular level

Still image from the video participants viewed

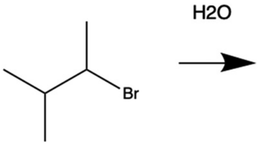
(2) Why do the contents in one test tube react at a faster rate than the other test tube?



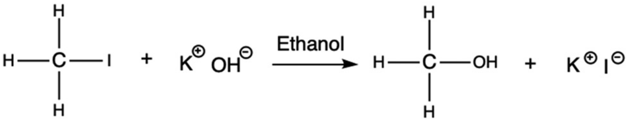
Still image from the video participants viewed

Part II: in this first portion of the interview, please answer the following questions. You can write any relevant information in the space provided if needed. Again, please express your thoughts audibly.

(1) For the reaction below, what would the major product(s) be? Draw the mechanism



(2) The following reaction is carried out. While some product forms, the reaction is extremely slow and has low yield. Identify any potential causes for this issue and how they may be fixed.



$$CH_3I + K^{\oplus}OH^{\ominus} \xrightarrow{\text{Ethanol}} CH_3OH + K^{\oplus}I^{\ominus}$$

Conceptual resource codebook

Parent codes	Description	Subcodes
Reactivity/ compatibility	Students frame reactions as dependent on reactivity or association between reagents	Acid base reactivity – student mentions the outcome of a reaction is dependent on the reactivity between acids and bases Association between reagent and action – Student describe that the outcome of a reaction is connected to a type of reagent (nucleophile, electrophile, base) and its specific behavior

		General reactivity – students describe that the outcome of a reaction is determined by reagent types and their reactivity; no deeper explanation is provided
Molecular stability	Students justify reactivity or product prediction using stability (applied to reagents and/or products).	Reagent stability – student explains that the reagent will not react due to its stability (*i.e.*, "it is happy on its own") Product stability – student identifies a major product based on its overall stability
Energy/ conditions	Students focus on how energetics/heat influence the progression of a reaction	Activation energy – student mentions activation energy as a determining factor as to whether a reaction will progress Heat requirement – student mentions that a major factor determining reaction outcome is the temperature or the heat
Reagent features	Students focus on specific features of nucleophiles, electrophiles, and solvents as determining factors for reaction outcomes	Charge – student emphasizes the charge or lone pairs in a reagent to determine its reactivity Nucleophile strength – student determines reaction outcome based on nucleophilic/ base strength Size/sterics – student emphasizes the size/ sterics of reagents as a determining factor for reaction outcome Solvent (protic *vs.* aprotic) – student identifies a solvent as polar protic or polar aprotic to determine reaction outcome
General principles of reaction type	Students generalize specific rules learned for substitution and elimination reaction	Product association – student product prediction is based on an association between product feature and type of reaction Rate generalization – students relate reaction speed to a particular type of reaction (Ex. SN1 is slower than SN2) Reagent association – participant describes that certain reagents are not good for certain reactions. (*i.e.* "Polar protic solvents are not good for SN2 reactions.") Step count – student associates the type of reaction occurring with the number of steps they determine the reaction to go through
Visible cue interpretation	Students rely on observable macroscopic changes (or absence) as evidence for whether and how a reaction occurred	Visual cue = reaction outcome – students determine reaction outcome on macroscopic observations Visual cue submicroscopic connection – student utilized macroscopic observations to inform submicroscopic predictions

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