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Organic Chemistry Students' Usage of Electrostatic Potential Maps Across an Unstructured and Structured Card Sort

Chloe K. Robinson^a, Melissa Weinrich^b, Scott E. Lewis^{a*}

^a University of South Florida, 4202 E. Fowler Ave., Tampa, Florida 33620

^b University of Northern Colorado, 501 W 20th St., Greeley, Colorado 80639

* Correspondence to: slewis@usf.edu

Abstract:

Electrostatic Potential Maps (EPM) have the potential to support organic chemistry students in seeing reaction mechanisms through the perspective of electrostatic attraction. Prior to any pedagogical changes, foundational knowledge on how students use EPMs in particular contexts would be needed to inform how to integrate EPMs into instruction. This study describes an exploration into how organic chemistry students use EPM's during two card sort tasks. Seventeen undergraduate organic chemistry students participated in an interview that included an open and closed card sort. The interviews were inductively coded to identify students' usage of EPMs, and usage change based on the open sort compared to the closed sort. Viewed from a resources framework, this study demonstrated how students' use of EPMs shifted depending on the task structure. Variations were observed both among students and within students between tasks in terms of whether EPMs were utilized and when utilized whether information from EPMs were used in isolation or integrated with other chemistry concepts. The results of this study imply that more formal integration of EPMs into instruction and assessment would be needed for students who did not use EPMs. Instruction that models and assesses translation of representations may begin activating a more integrated perspective of EPMs which could be productive for students who had an isolated use of EPMs. The introduction of EPMs independent of specific chemistry tasks (e.g. during a general introduction of molecular representations) could lead some students to focus only on explicit features of the EPM representation and not tie features of the representation to their existing chemical knowledge.

Background

Representations that explicitly depict molecular characteristics can assist students in interpreting molecular and chemical properties (Stowe and Esselman, 2022). A promising representation to promote interpreting chemical properties are Electrostatic Potential Maps (EPMs). EPMs use a color map to make electron density explicit. Studies have found EPMs aided students in determining polarity and miscibility (Sanger and Badger, 2001) or polarity in the context of chemical bonding (Tsaparlis, *et al.*, 2021). Placing EPMs advantages in contrast to other representations, Host et al. (2012), analyzed 17 chemistry students' using various representations including EPMs on the accuracy and time on task in assigning polarity

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3 to molecules depicted in these different representations. They found potential benefits
4 with EPMs to reduce cognitive complexity associated with correctly identifying molecular
5 polarity. In other studies focused on organic chemistry concepts, EPMs were found to
6 promote student attention to electron density, which aided students in making
7 conceptual connections between electron density and why species interact (Farheen, *et*
8 *al.*, 2024a). Nelson *et al.* (2024) interviewed 19 organic chemistry students as they
9 solved an elimination reaction using EPMs with and without a chemical formula to see
10 how students could reason with EPMs to explain potential chemical outcomes. It was
11 found that students used the EPMs to reason mechanistically, identify leaving groups,
12 and propose the start of a reaction mechanism. However, upon adding chemical
13 formula to the EPMs most students translated chemical formula to line-angle diagrams
14 and reasoned without reference to the EPMs. Therefore, despite their potential benefits,
15 students may elect to not use EPMs when more familiar molecular representations are
16 available. The goal of this study is to investigate how organic chemistry students'
17 utilization of EPMs are influenced by the type of problem given. In so doing, this work
18 can inform instruction on where students may experience benefits of EPMs when
19 problem solving.
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26 Several studies conclude EPMs are not taught as a traditional model for
27 examining the molecular behavior of chemicals or understanding the drive of electron
28 attraction behind molecular mechanisms. Hinze (2013) found that organic chemistry
29 textbooks regularly incorporated EPMs within them, but rarely include conceptual
30 support for interpreting EPMs nor practice problems involving EPMs. Without contextual
31 information and practicing opportunities for navigating these relatively novel
32 representations, EPMs may be ignored by students (Hinze, *et al.*, 2013). Popova and
33 Jones (2021) interviewed 13 chemistry instructors across the US about their teaching
34 and found that instructors tend to omit instructions necessary for students to
35 conceptually apply representational tools to chemical phenomena. The underutilization
36 of less common representations, such as EPMs, creates a learning environment in
37 which students prioritize more frequently utilized representations of chemical species
38 such as chemical formulas and line angle models.
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43 With the benefits of EPMs emphasized in the literature, using EPMs in courses
44 may be advantageous for student learning. Properly integrating this learning tool
45 requires understanding how students implement EPMs into their own thought
46 processes. Understanding where students begin with their representational
47 understanding and what information they extract from representations on their own is
48 important for teaching purposes, as visualizations are not automatically converted into
49 knowledge and students may not initially understand how to utilize a novel
50 representation (Rapp and Kurby, 2008). Additionally, Ainsworth (2006) argued learners
51 are faced with difficulties upon exposure to a novel representation because they must
52 encode and relate it to what it represents before accessing the benefits. As a result,
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3 many have argued that practice and chemical knowledge is required to support the use
4 of representations (Kozma and Russell, 1997; Schwonke, *et al.*, 2009; Hinze, *et al.*,
5 2013). However, students may be disinclined to use unfamiliar representations. For
6 example, in a study where students were tasked with identifying partial charges and
7 determining molecular attractions, 12 of 18 participants avoided EPMs due to
8 unfamiliarity, while students who adopted the EPMs had greater success with
9 answering problems (Hinze, *et al.*, 2013). The current study seeks to understand how
10 students use EPMs across distinct problem types, which can serve as a first step in
11 designing practice that would promote the use of EPMs when problem solving.
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16 **Card sort methodology**

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18 Card sort tasks involve providing students a set of cards that each contain topic-
19 specific information, such as molecular images, to understand students' conceptual
20 thinking pertaining to the topic (Krieter, *et al.*, 2016; Newman, *et al.*, 2023). Card sorts
21 have been adopted in chemistry education research, often to contrast novice and expert
22 thinking. Krieter and colleagues (2016) examined differences between experts and
23 novices' card sorts to differentiate conceptual thinking between these groups, finding
24 novices sorted based on surface level features while experts sorted based on chemistry
25 concepts. Galloway *et al.* (2018) compared undergraduates', graduates', and
26 professors' focal point when card sorting organic chemistry reactions, finding professors
27 focused on the reactivity of molecules. Similarly, Domin *et al.* (2008), conducted card
28 sorts using organic compounds at different time points finding students' focus on a
29 salient feature for sorting was not static, while the professors' focus was, indicating that
30 students reasoning with the compounds may be fluid over the course of a semester.
31 Other card sort studies within chemical education involve a variety of foci such as how
32 data for chemical education was collected during COVID-19 (Chatha and Bretz, 2020),
33 using card sorts to assess level coordination proficiency in chemistry (Irby, *et al.*, 2016),
34 and using card sorts as a classroom assignment (Ramsey, *et al.*, 2007). Combined, the
35 literature indicates that card sort tasks offer a fruitful venue for exploring student
36 thinking. Since this study seeks to explore how students use EPMs across distinct
37 problem types, this study is designed to contrast student performance on two distinct
38 card sort tasks. One task is unstructured (referred to as open-sort) where students sort
39 representations of molecules as they see fit, while the second task has a defined
40 chemical task (referred to as closed-sort). This approach has precedent in the research
41 literature. Robertson *et al.* (2020) conducted a card sort study on people's trust and
42 knowledge in self-driving cars using an open and closed card sort. With the closed-sort,
43 novice performance was more approximate to expert performance than the open-sort.
44 The authors credited the scaffolding present from the predetermined categories that
45 provided relevant cues and a framework to aid in knowledge organization.
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Theoretical Framework

The resource framework discussed by Hammer (2006) asserts that the way students think about chemistry knowledge, and the conceptual resources activated by students when approaching chemistry problems, is highly dependent on the context of the situation. The term “resources” is a general term for more defined units of fine-grained knowledge that people use to construct ideas about a phenomenon (Hammer, *et al.*, 2006; Wood, *et al.*, 2014; Watts, *et al.*, 2021; Sheppard and Bauer, 2023; Rodriguez, 2024). Within this study, resources are understood as chemistry concepts that are activated and explained by the features students choose to focus on. These resources are activated by the representational features and other pieces of existing student knowledge. The explanations of these concepts were when students provided explicit evidence of conceptual understanding. The contextual dependence in this framework therefore implies that the processes to activate resources are not fixed (Hammer, *et al.*, 2006). Additionally, the activation of these resources is considered neither correct nor incorrect but instead provides a lens on students' development and construction of knowledge. In this study, students' utilization of representations is seen as evidence for how resources are activated, and students' utilization of resources across differing chemistry tasks serves as evidence for how the context informs the resources activated by those students regarding EPMs.

Rationale

The research literature shows potential for EPMs to aid students in problem-solving (Host, *et al.*, 2012; Tsaparlis, *et al.*, 2021), particularly when explaining chemical phenomenon (Farheen, *et al.*, 2024a; Nelsen, *et al.*, 2024). Students may be averse to utilizing EPMs if they are unfamiliar with this representation type (Hinze, *et al.*, 2013), and rely on more familiar representations (Nelsen, *et al.*, 2024). Chemistry instruction that takes advantage of the affordances offered by EPMs can be improved by knowing more about what students consider when deciding to use EPMs. More specifically, this study seeks to understand how students' considerations may be impacted by the chemical context in which EPMs are presented, since the task directs students to their own resources (prior knowledge and concepts) they consider relevant to the task. While the existing literature has highlighted how students use EPMs, those studies relied on structured tasks, with predefined outcomes of a given activity. As the resources framework expects students' utilization to change based on the task given, the exploration of how students use of EPMs change between unstructured and structured tasks broadens the picture on how students may use EPMs which can better serve instruction.

In this work, to examine how task changes influence students' considerations, this study investigated how students come to utilize EPMs as they move from an unstructured task (open-card sort) versus a structured task (closed-card sort). The

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3 open-card sort was designed to assess students' utility of EPMs when no explicit task is
4 given, while the closed-card sort task was designed to identify students' considerations
5 when working with an explicit goal in chemistry. These tasks may be analogous to
6 instruction presenting EPMs without a particular utilization (e.g. during an introductory
7 lesson on varying representations) versus introducing EPMs as a tool for working on a
8 particular problem type. Comparing student responses across these tasks can provide
9 guidance for introducing EPMs within instruction based on students' utility development.
10 Here utility refers to how students recognized, employ, and derive value from EPMs as
11 a representational tool for understanding and solving problems. It encompasses
12 whether EPMs are integrated with other chemical concepts and features or used in
13 isolation.
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19 **Research question**

20 This study is guided by the research question: How does organic chemistry students'
21 utilization of EPMs change when moving from an unstructured, open card sort task to a
22 structured, closed card sort task?
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25 **Methods**

26 **Research Settings**

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29 Students were recruited from those enrolled in organic chemistry 1 at two
30 research intensive universities, one in the midwestern and one in the southeastern
31 region of the United States. Seventeen students (8 from the southeastern university and
32 9 from the midwestern university) participated in a one-hour, in person interview. At
33 each setting, nucleophiles and electrophiles had been covered in the course prior to the
34 interviews. The course instruction regularly used line-angle representations. Each
35 interviewee was asked about the familiarity with EPMs at the start of the interview. Six
36 participants were unfamiliar with EPMs, six other participants expressed uncertainty in
37 whether they had seen EPMs previously, and five participants mentioned seeing EPMs
38 previously. Among those five, they described only a cursory use in class, as Clara
39 described "he probably flashed it up on the screen one time." Later tasks from the same
40 interviews have been analyzed and reported previously (Nelsen, *et al.*, 2024).
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47 **Ethical Considerations**

48 The study design was approved by the Institutional Review Board from the
49 midwestern university, with the southeastern university's comparable board recognizing
50 this oversight for the project. Recruitment for the study was conducted by research
51 team members who were not involved in teaching the classes to avoid potential
52 perceptions of coercion. Each student was informed ahead of the study that
53 participation entailed sitting for a one-hour interview and that participation was voluntary
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3 and each participant consented to be part of the study. Participants were paid \$25 upon
4 completion of the interview.
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7 **Study design**

8 Semi-structured 1-hour interviews were conducted by one of three chemistry
9 graduate student researchers. The interview composed of six different tasks and this
10 study focused on the first and third. In the first task, students were given an open card
11 sort containing EPMs of different molecules as well as an EPM color code, in which
12 students could categorize the cards in any fashion of their choosing and were asked to
13 explain their reasoning (see Fig. 1 left side). Task 2 was the same task but instead
14 using cards of line-angle representations and is not discussed further in this study. In
15 task 3 students were given a closed card sort regarding six line-angle cards and six
16 EPM cards (see Fig. 1 right side), each EPM had a corresponding line-angle of the
17 identical molecule, but this pairing was not mentioned to students. Students were asked
18 to sort the cards based on nucleophilicity and electrophilicity. Task 1 and task 3 were
19 the focus of this study to analyze EPM utility across different structural formats.
20 Regarding each card sort task, various follow up questions were asked to probe
21 students thinking during their sorting to provide an indication of the utility of EPMs, such
22 as “What chemistry concepts were you considering while sorting?” and “what made you
23 sort the molecular representations this way?”
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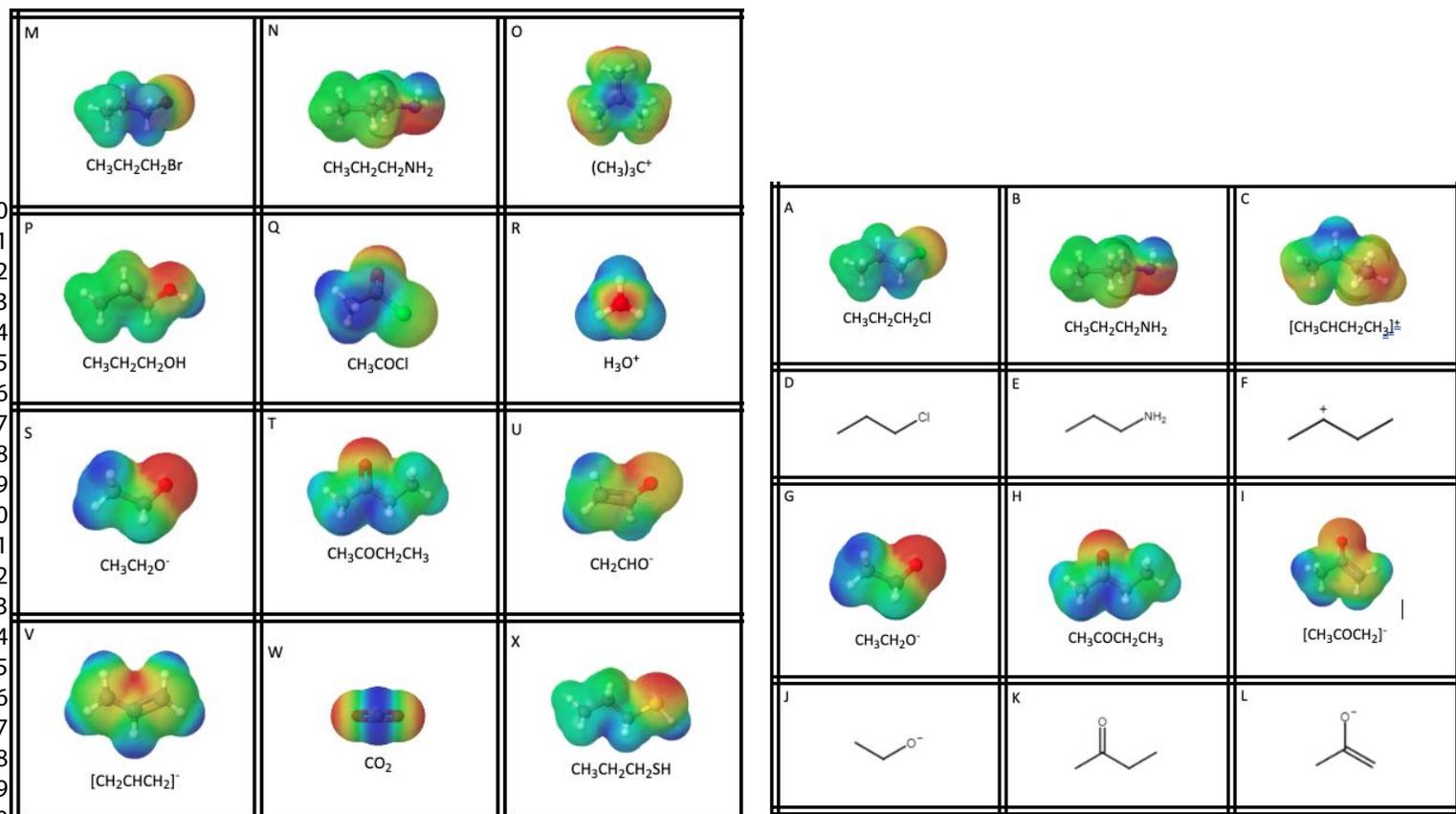


Figure 1 (Left) cards provided to participants in open card sort. Students were asked to sort any way they deemed appropriate. (Right) cards provided to students in closed card sort. Students were asked to sort based on nucleophilicity and electrophilicity.

Data analysis

Interviews were audio recorded and transcribed verbatim along with pictures taken of the sorted cards. The transcripts were read through various times to develop an understanding of the data. In the results section, presented quotes were edited for clarity by deletion of repeat or filler words (e.g. "like"), trailing sentences (e.g. "So with that in mind, that would make sense."), or minor, obvious misattributions (e.g. "EMPs" instead of "EPMs"). An inductive codebook was established from iterative processing with a focus on the participant's perceptions of the utility of EPMs. This codebook's reliability was then tested via interrater reliability between the first author and a graduate student specializing in chemistry education. After coding 7 of the 16 interviews, Cohen's Kappa was 0.944. This suggested a high reliability within the codes, and the first author coded the remaining transcripts. Review of the code assignments led to identifying various changes in students' use of EPM. To further confirm the ways that students were utilizing the EPMs, a second codebook was developed on the chemical concepts invoked with EPMs and with chemical formula. This followed an iterative process

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3 informed by interrater agreement, resulting in a final codebook that was applied
4 independently by the prior two raters and codes were assigned following consensus
5 coding. Both codebooks are presented in the appendix. Note was also taken over
6 whether students spontaneously identified the identical molecule pairings in Task 3 (see
7 Fig. 1 right side) as an indicator of students' readiness for translating representations.
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10 Groups were established from coding task 1 and 3 separately and grouping
11 participants with similar coding patterns. These groupings were then further defined
12 across the tasks from their EPM utility in task 1 and 3, highlighting the utility changes
13 from one task to another. After these groups were made, students' conceptual
14 understanding of the chemistry topics being discussed through the resources
15 perspective, was analyzed based on isolated and integrated reasoning, which further
16 characterized and distinguished the groups. Isolated reasoning describes problem
17 solving where the resources activated, namely the chemistry concepts, are explained by
18 explicit features of a representation independently of other representational features or
19 conceptual resources. Conversely, integrated reasoning describes problem solving
20 where the resources activated are done so by a combination of explicit features of
21 representations and chemistry conceptual knowledge to provide an explanation of
22 chemistry phenomenon.
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27 These reasoning types align with aspects of Schonborn and Anderson's visual
28 literacy framework (2010) in that three interdependent factors are required for
29 successful interpretation of a representation: the conceptual factor, the mode of
30 representation, and the reasoning or sensemaking factor. Specifically, isolated
31 reasoning consists of students incorporating a conceptual factor (resource)
32 independently from other existing factors such as reasoning and the mode of
33 representation, leading to unsuccessfully interpreting or implementing certain
34 representations. Integrated reasoning consists of incorporating a conceptual factor (a
35 resource) and the mode of representation together to incorporate the reasoning factor
36 for the existence of a chemical concept which ultimately leads to successful
37 interpretation and utility of representations (Schönborn and Anderson, 2010).
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43 **Results**

44 Four different groups of students were identified based on their change of utility
45 of EPMs from the open to the closed sort tasks (Figure 2). Each grouping was assigned
46 a letter (underlined in Figure 2) and pseudonyms for students from each group begin
47 with the same letter. Pseudonyms were not meant to convey presumed gender or any
48 other characteristics.
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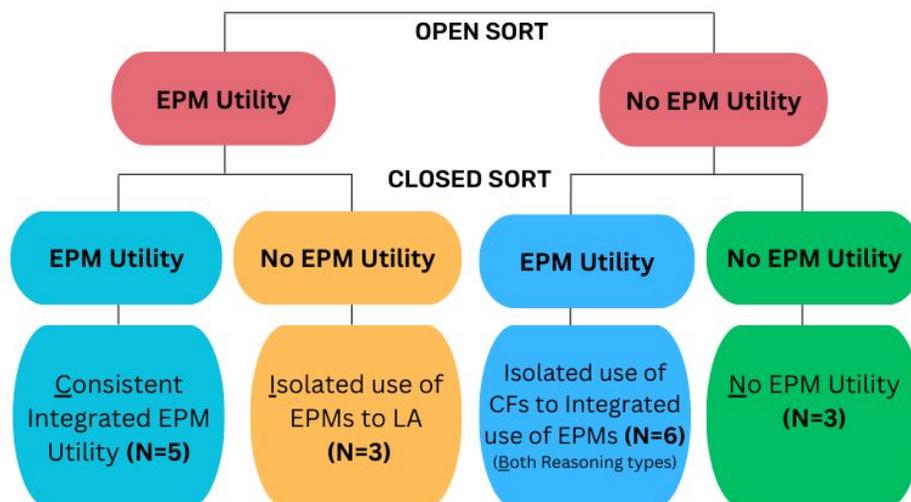


Figure 2: Four groups differing in EPM utility in Open & Closed Sort. EPM = Electrostatic Potential Map; LA = line-angle diagrams; CF = chemical formula

Consistent Integrated EPM Utility

Five students used the EPMs and the identities of atoms provided by the chemical formula to explain polarity in the open sort, through the concept of electron density. Specifically, these students described the electron density and/or polarity of molecules by evaluating the symmetricity and distribution of the colors in EPMs alongside atomic identities. Carter described why some molecules looked polar:

“The most polar would be [EPM of ethoxide], just due to the fact that it has this area of really high density, and then another end which has really low electron density. [...] And then [EPMs of propylamine & ethanol] are both similar in that regard. Yeah, they have four carbons each and then they each have three carbons and then some other more electronegative atom on one end.”

A similar result is seen with Clara when explaining her category,

“This [category] is less dense. And if it's super red on one end and super blue on the other, then it's probably a higher difference in electron density is probably more polar molecule [...] they all have a charged or partially charged part of the molecule like the nitrogens, the oxygens, and the bromines.”

This thought process of identifying polar molecules using the EPMs was also similar with Charlie, Caden, and Candice. Color can be shown to be integrated with the atomic identities to explain a region of polarity within a polar molecule through electron density, as in Candice's statement about propylamine, *“the [EPM of propylamine] has the nitrogen that's why it has the red spot there,”* shortly after discussing how nitrogen grabs electrons from carbon. These students were cued to polarity by the concentration of electron density as demonstrated by the integration of color distribution and the atomic identities contained within the chemical formula.

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3 Electronegativity and stability were also mentioned as additions to polarity. Carter
4 mentioned stability as a consideration for sorting, stating, *“electrostatic potential can*
5 *kind of show how different regions of areas that would readily bond to other things. And*
6 *so that’s kind of what I was thinking about. Like, which of these things would, is the*
7 *most readily reactive versus what is pretty stable. So [CH₂CHCH₂-] does have a little*
8 *section of higher electron density that is towards one of the edges, but it’s pretty*
9 *uniform.”* Charlie, Carter, and the other students integrated information from both the
10 chemical formula and EPMs to draw conclusions on various molecular properties, with
11 an overall focus on molecular polarity.
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15 When switching to the closed sort, these students continued to integrate the
16 colors to describe the electron density and relate to nucleophilicity, similarly to the
17 connection to polarity. For example, Candice explained nucleophilicity and nucleophilic
18 molecules similarly to how polarity was determined:
19

20 *“So, since the red regions have more electrons in them, a higher density, then*
21 *that would make that spot more nucleophilic.”*
22

23 The students focused on the color distribution and concentration to determine a
24 molecule as having nucleophilic characteristics. Caden discussed recognizing a
25 nucleophilic molecule from integrating both the line angles and the EPMs:
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27 *“Having them [LAs] all drawn out, it’s kind of easy to see where the lone pairs*
28 *would lie and then also with the colored images [EPMs], I think that generally if it*
29 *has more electron density in one area, it’s kind of a nucleophile too.”*
30

31 These students consistently made conceptual inferences based on the electron
32 distribution to indicate molecular behaviors. For students who integrated EPMs with
33 chemical concepts when explaining their open sort, the context change to closed-sort
34 did not impact their reasoning or utility of representational features. This suggests that
35 these five students may potentially utilize EPMs across varying contexts. Additionally,
36 everyone except Candice recognized that the closed sort molecules were duplicates of
37 one another. This is summarized by Clara who questioned, *“[EPM & LA of propylamine]*
38 *look the same. Yeah, it’s the same molecule. Okay, so the same strength of*
39 *nucleophilicity. Are these all the same? Okay.”* The recognition of molecular duplicates
40 among the line angle and EPMs demonstrates representational translation and may be
41 related to the employment of integrated reasoning. The use of EPMs integrated with
42 chemical formulas and line angles in both environments also suggests that these
43 students understand chemistry in a way that makes them open to implementing new
44 features from the EPMs with features from familiar representations to establish those
45 conceptual chemical explanations. The colors may serve as enrichment to students’
46 conceptual explanations and understanding when integrated with other explicit features
47 for electron density and therefore assist in explaining and understanding polarity and
48 nucleophilicity.
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Isolated Use of EPMs to Isolated Use of line-angles

Not all students who invoked EPMs in the open sort continued to utilize EPMs with the closed sort. Three students, Iris, lyla, and Ian, who heavily relied on the EPMs to guide their categories in the open sort, used EPMs less in the closed sort, instead relying on the line-angle representations independently. In the closed sort, EPMs were rarely or not at all used for support.

For these students, EPM colors were used in isolation from other representational features during the open sort to describe partial charges and polarity. Ian determined the polarity or lack thereof within a molecule from the color distribution alone:

“Based on where the red is on some of them, the red is really prevalent only on one side and some of them, they're spread out, which means they're non-polar.”

Ian used colors in isolation for determining polarity by focusing on the areas of color concentration, indicating a polar compound is one with a fair amount of red and a nonpolar compound is one with relatively even color distribution. The explanations of a polar molecule are limited to identification due to the isolated use of colors.

Iris focused on color intensity instead of color distribution and inferred charge intensity:

“I am thinking about the intensity of the charges. So, I sorted, based on having the most electrostatic potential, and there's a lot of green in here, and yellows, which are indicating there isn't a strong positive strong negative charge really at play. Of course, some of them have that little bit of intense color, but overall, there's a lot of those medium colors of orange, yellow, and green present, whereas in my left category, there are those strong vibrant blues and reds which indicate a strong positive and negative charge at play.”

Iris used colors to identify charges, but no other chemical properties or identities were used to justify the charge assignments. Similarly, lyla focused on the areas of color concentration, defining those areas as regions of charges of the molecules,

“With [EPM of propylamine, $\text{CH}_2\text{CHCH}_2^-$, & $(\text{CH}_3)_3\text{C}^+$], I saw more green, which I know is more neutral, so I put those in the middle.”

The colors serve as indicators for polarity or charge based on color presence or concentration alone, and thus EPMs were used with reasoning isolated from other chemical features and as a result, explicit explanations of chemistry concepts were not present. Unlike students who consistently used EPMs in an integrated way, students here chiefly utilized the EPMs for developing their categories, with little to no references to the chemical formula.

Students who used isolated reasoning of colors in the open sort diminished their use of EPMs in the closed sort. Their approach to the nucleophilicity sorting relied on the isolated use of line angle features as a primary deciding factor while EPM usage

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3 was limited to assisting with memorized characteristics. Iris explicitly indicated a focus
4 on the line angle's *"potential charges and how much of an electrophile and nucleophile*
5 *these would be."* However, when analyzing propylamine said:

6 *"it looks overall to not be very nucleophilic or electrophilic with the EPMs just*
7 *because of that giant green spot with the CH₃, CH₂, CH₂. But in the NH₂*
8 *section, you can obviously see that the hydrogens and nitrogen are very different*
9 *with their charge potentials,"*

10 and concluded: *"It doesn't exactly match up the way I had expected."* Iris briefly referred
11 to EPMs when requiring support with regards to nucleophilic characteristics in
12 propylamine and decided to place that molecule in the "neither" category after
13 considering both representations. Specifically, Iris struggled with the identity of
14 propylamine concluding that *"CH chains are quite neutral"* and then seeing the EPM
15 have an area of high color contrast. While she considered both arguments, she did not
16 combine the two features together to conclude its electronic property. Instead, with two
17 conflicting ideas she did not move forward in making a decision with that molecule,
18 denoting it as neither an electrophile nor a nucleophile. Ian invoked a heuristic in
19 determining nucleophilicity and electrophilicity:

20 *"These are all I think nucleophiles: [ethoxide & CH₃COCH₂-] have a negative*
21 *charge so that makes them nucleophilic especially the [ethoxide] with the*
22 *negative charge on the O that makes it extremely nucleophilic and then [...] this*
23 *one [2-butanone] also has an O. So that's also like a nucleophilic."*

24 All students in this group used a heuristic of a negative charge indicating nucleophilicity
25 without considering features from other representations to explain why molecules were
26 nucleophilic or electrophilic. Ian concluded that the EPM's value had already been
27 exhausted as all the molecules provided were polar and his perception was that EPMs
28 did not provide more utility after that determination, based on the prior isolated use of
29 colors. He noted *"none of [the EPMs] were symmetrical in any way. There were charges*
30 *on them, and they were all polar molecules."* Abandonment of EPMs is equally seen
31 with lyla where although EPMs were initially used to guide the open sort, she instead
32 focused on atomic identities for electronegativity clues in the closed sort task:

33 *"Chlorine, I know is a good leaving group, so that would make [LA of 1-*
34 *chloropropane] more [of] a strong electrophile. And it would want to leave."*

35 This demonstrates that lyla knows chlorine is a good leaving group and the presence of
36 chlorine was taken from the representation, but there is no explicit indication of other
37 conceptual resources to conclude the leaving group properties of chlorine, indicating
38 isolated use of line-angle representations. Here, the EPMs were not utilized in the
39 closed sort. These students concluded nucleophilicity assignments from the chemical
40 formula and line angles, with EPMs used only when students expressed confusion with
41 assigning nucleophilicity to line-angle structures. Essentially, when the EPMs were
42 used, the colors served to be identifiers of polar molecules without explanation. The
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3 change from the open to closed sort showed these students picking features for
4 descriptions individually instead of in combination with other chemical properties, in
5 contrast with students who consistently utilized the EPMs. A tentative conclusion is that
6 students who invoke EPMs without chemical concepts may more readily abandon
7 EPMs when heuristics that use more familiar representations such as line-angle
8 diagrams are available. Further, only one student from this group, Ian, made explicit
9 note that the molecules of EPMs and line angles were duplicates, which suggests that
10 isolated reasoning of EPMs may also be indicative of eschewing representational
11 translations.
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16 ***Shift from Isolated Use of Chemical Formula to Integrated Use of EPMs (Both*** 17 ***Reasoning Types Activated)*** 18

19 Six students relied mainly on chemical formula in the open sort without explicit
20 establishment of a conceptual connection with the EPMs. These students cited
21 challenges in utilizing the EPMs during the open sort, as noted by Bailey:
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23 *"I did try to look at the electrostatic maps, but it wasn't working out. [...] Because*
24 *I feel like there's supposed to be a trend. But my placement of cards, there is not*
25 *any significant trend, so I just stuck to ionic, polar or non-polar."*
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27 and similarly with Beth:

28 *I didn't look much at the EPM, but I think it was mostly the one where it hindered*
29 *me the most in visual... looking at it would have been [EPM of an enolate] and*
30 *[EPM of an acyl chloride]. It was hard to see the EPM there."*
31

32 Beth attempted to use the EPM but found it difficult to visualize two of the molecules
33 that share similar structures. She did not make connections between the coloring
34 differences and therefore sorted primarily by the chemical formula in isolation from other
35 representational features. Brandon and Beau also explicitly stated that they did not see
36 a valuable connection among the molecules when looking at the EPMs. Within the open
37 sort, these students individually focused on negative or positive charges, atoms, or
38 functional groups inferred from the chemical formula of a molecule. For example, Bailey
39 explained her process of determining polarity:
40
41

42 *"Well, I know CO₂ is often nonpolar. For these ones, the CH₃-CH bonds there's a*
43 *lot of them and I think in one of the classes [an instructor] mentioned that just*
44 *because there's an oxygen in there doesn't make it polar."*
45
46

47 She used atoms of the chemical formula and heuristics to determine molecular polarity
48 but did not detail the cause of molecular polarity nor the properties that emerge from
49 polarity, unlike observations with the students who consistently integrated features.
50 Students in this group conveyed initial hesitation with EPMs and sorted by isolated, and
51 visually distinctive features from chemical formula such as the number of carbons,
52 structure, or the atom types. For example, Bryn sorted by charge:
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3 *“Now that we have charges – we have [EPM of CH₂CHO⁻] minus, [EPM of*
4 *ethoxide] minus, so [EPM of CH₂CHCH₂⁻] minus. So, this [group] is just a*
5 *negative.”*
6

7 These students did not integrate characteristics of the EPMs within their open sort. In
8 comparison to students who initially used isolated reasoning with EPM colors, it is
9 possible that the students discussed here did not feel a need for utilization of colors
10 when chemical formula and heuristics can be used to identify polarity or charges.

11
12 These students who relied on chemical formula in the open sort began
13 integrating the colors of EPMs with other features when sorting molecules on
14 nucleophilicity. Five of the six integrated the EPMs for categorizing molecular structures,
15 while Bryn categorized first with line angles and then integrated EPMs to support her
16 conclusions. These students focused on charges and atomic identities, in combination
17 with the EPM colors as an indication of electron density, to determine if molecules were
18 nucleophilic or electrophilic. Beau combined information from the charges of the
19 chemical formula and line angles with EPM colors:
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23 *“For [LA of 1-chloropropane], it doesn't have a positive charge, but I knew Cl was*
24 *a good leaving group and if Cl is going to leave then that third carbon would*
25 *become positive, and the same thing would go for [EPM of 1-chloropropane].*
26 *Because in the electric cloud, [...] saw the darker blue, which told me that would*
27 *lean towards the positive side more, so if that Cl did leave, it would be able to*
28 *react with the nucleophile.”*
29
30

31 The integration of the representations utilized allowed this student to determine that 1-
32 chloropropane could act as an electrophile. Similarly, Beth and Bailey integrated
33 charges, atomic identities, and colors of the EPM concurrently to draw conclusions
34 regarding electron density. For example, positive charges with dark blue hues were
35 used as an indication of low electron density that could participate in attracting
36 nucleophilic molecules. Becca relied primarily on structure of the chemical formula and
37 color intensity of the EPMs in determining nucleophiles and electrophiles:
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39

40 *“For nucleophiles, I was more focusing on how strong the red region is in*
41 *comparison to the blue region. So, for [EPM of propylamine], it has a super*
42 *strong red region and a very short blue region, and the rest of the molecule is*
43 *green. So, I figured that would be a really, strong nucleophile [...] Like [EPM & LA*
44 *of 2-butanone] originally, I thought would be nucleophiles because if you have a*
45 *double bond connected to something, the double bond attacks and that's the*
46 *characteristic of a nucleophile.”*
47
48
49

50 Becca found utility in the EPMs, where color is related to electron density (mentioned
51 earlier in her interview) and then high electron density is connected to nucleophilicity,
52 and low to electrophilicity integrated with the structural feature of the line angles. Bryn
53 used the line angles and chemical formula first to assign nucleophilicity and then
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3 integrated the EPMS to provide evidence of other concepts, such as electronegativity, to
4 support the assignments:

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6 *"[...] The question is, which one's more electronegative? Because chlorine I*
7 *would guess... [...] If we look at the pictures, this is very red. Ok. So I'm going to*
8 *try to use that EPM to say that this [2-butanone] goes here [stronger than 1-*
9 *chloropropane]."*

10
11 She began to seek support by integrating the EPMS to assist in determining the levels of
12 electronegativity when using isolated atoms was not clear.

13
14 These students overcame their hesitancy in working with EPMS when the task
15 changed to the structured task. The contextual change from open sort to closed sort is
16 presumed to have prompted the students to integrate EPM with chemical concepts
17 when asked to predict nucleophilicity. This is also evidenced by four of the six students
18 in this group who explicitly acknowledged the molecules of EPMS were replicated as
19 line angle representations. Becca mentioned, *"See the more that I'm going through it,*
20 *the more that I'm realizing, that the line structures that you gave me are the exact same*
21 *as the ones with the potential maps."* These students' usage of the EPMS integrated
22 with chemical concepts mirrored the first group described, with recognition of duplicates
23 occurring more often when integrated reasoning was activated. However, these
24 students did not see the utility of EPMS within the open-sort task.
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30 **No EPM Utility**

31 Three students did not utilize EPMS throughout both tasks. Neena, Nolan, and
32 Naomi enacted an isolated use of the chemical formula. Neena explained:

33 *"I'm not really sure if I'll be able to, categorize them [EPMS] in an efficient manner*
34 *because I don't think that my understanding of the diagrams even provided in the*
35 *lecture notes are decent and we don't really need to use them in our tests or*
36 *homeworks."*
37
38

39 Similarly, Naomi's preference remained with the chemical formula representation also
40 citing unfamiliarity:

41 *"My teacher's mentioned [EPMS] in lecture basically. Usually, it's when he's*
42 *explaining things to us, concepts to us why they react a certain way, we don't*
43 *necessarily have to know it and understand it, at least not yet."*
44
45

46 Naomi seemed to similarly disregard the EPMS, not seeing them as necessary for
47 understanding the chemistry knowledge that has been encountered thus far. There is a
48 default to isolated use of the chemical formula in these students' sorting strategy, and
49 the utility remained throughout the two tasks. Students among this group typically did
50 not go further than listing the explicit features present in the chemical formula. Naomi
51 explained when describing the sort:
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3 *“My first group is ones that aren’t organic, so it doesn’t have carbons and*
4 *hydrogens so, one of them only has [...] hydrogen and oxygen, but it doesn’t*
5 *have a carbon.”*
6

7 This student identified explicit features, such as atomic identity, and used that in
8 isolation as the focus of the sort, without invoking other chemical properties. Nolan
9 similarly and predominately used the atoms of the chemical formula to determine
10 molecules as polar or nonpolar. He does not describe causes for polarity and instead,
11 discusses a heuristic for determining polarity through lone pair identification:
12

13 *“When you’re looking for example, ammonium or water, how to identify if the*
14 *molecules polar or not. If the central atom has no lone pairs and electrons*
15 *surrounding it are equal to each other then it’s non-polar. Okay. And if it violates*
16 *one of those restrictions, then it’s polar.”*
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18

19 These students disregarded the EPMs and instead isolated explicit features from the
20 chemical formula or used a heuristic without discussion of those concepts, as seen with
21 Nolan and polarity. These students approached the open-sort task similarly to the third
22 group in reliance on isolated features of chemical formula.
23

24 In the closed sort, these three students continued to avoid using the EPMs in
25 contrast to the third group. The discomfort expressed by Neena, Naomi, and Nolan
26 when utilizing the new learning tool, was attributed to inexperience and having a more
27 solid foundation for the other representations, as these students continued to sort based
28 off isolating explicit features in the line angle and chemical formula. Naomi stated,
29

30 *“I remember going over it [EPM & LA of 2-butanone], but I don’t remember which*
31 *one it was overall. I remember that - I think it’s a ketone on it - the oxygen is one*
32 *and then the carbon is one. But I don’t remember which one was more*
33 *electronegative.”*
34
35

36 This group can be summarized as those who did not utilize EPMs and made
37 conclusions about molecules based on isolating explicit features from the familiar
38 representations. Similarly to students who reasoned by isolating features with EPMs
39 and line angles, Nolan, Naomi, and Neena also did not recognize that the set of
40 molecules were duplicates, with Naomi and Nolan recognizing a subset. Specifically,
41 Nolan discovered three duplicate pairs and Naomi discovered one. This supports the
42 earlier suggestion that isolated reasoning of a representation may also be indicative of
43 eschewing representational translations.
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49 **Discussion**

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51 Students’ changes in utilization of EPMs across the tasks are complex, as four
52 main variants: consistent integrated EPM use, isolated use of EPMs to line angles,
53 isolated use of chemical formula to integrated use of EPMs, and consistent no EPM
54 utility were observed. Therefore, neither context held a singular advantage in directing
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3 students toward EPM utilization. Nine of the seventeen participants changed their use
4 of EPMS as the context of the task changed, with three invoking EPMS mainly within the
5 open-sort and six using EPMS mainly within the closed sort. Twelve of the seventeen
6 students (all except those who consistently engaged with EPM) approached the open
7 sort with isolated reasoning when activating resources through focusing on explicit
8 properties, while six of those students began integrating EPMS with other chemistry
9 concepts during resource activation in the closed sort. The only observation of students
10 using EPM in an isolated framework was with the open-sort task, where those students
11 shifted away from EPM when engaging with the closed-sort task. The closed sort was
12 thus observed to be more conducive for students to integrate their chemistry knowledge
13 with the EPM representations.
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19 Past work has shown that when presented EPMS, students were more likely to
20 invoke electronic features (Farheen, *et al.*, 2024a; Farheen, *et al.*, 2024b; Nelsen, *et al.*,
21 2024) and causal reasoning when describing mechanisms (Farheen, *et al.*, 2024a;
22 Farheen, *et al.*, 2024b). However, it was also shown that when students had access to
23 information in addition to EPMS, students relied on more familiar representations such
24 as chemical formula (Nelsen, *et al.*, 2024). Past work relied on students' utilization of
25 EPMS within structured tasks, while the resources framework predicts that a change in
26 the task can change the resources activated by students. This study found that students
27 were more likely to utilize EPMS with the structured, closed-sort task and were more
28 likely to integrate EPMS with chemistry concepts in the structured task. With the open-
29 sort task, students were more likely to use EPMS in isolation with other chemistry
30 concepts. The use of chemistry concepts in isolation calls to question the meaningful
31 use of EPMS by students in this situation. The visual literacy framework describes
32 students who use a conceptual resource in isolation from other resources including the
33 representation presented are unsuccessful in accessing the benefits of representations
34 (Schönborn and Anderson, 2010).
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41 Promoting students' utilization of EPMS will become necessary to realize any
42 learning gains from using EPMS. The current study found that promoting students'
43 utilization may face a few distinct challenges. First, students from the "No EPM Utility"
44 group described both an unfamiliarity with EPMS and no need to learn EPMS within their
45 instruction as reasons for not utilizing EPMS. These challenges suggest that more
46 formal integration of EPMS into instruction and assessment would be needed to make
47 the case for utility of EPMS to some students. Second, students in the "Isolated use of
48 EPM" group relied only on explicit features of EPMS without bridging these features to
49 chemical concepts and activated resources and ultimately abandoned EPMS when
50 given a structured chemistry task. Hence, instruction that structurally models and
51 assesses translation of representations may begin activating a more integrated
52 perspective of EPMS which could be productive for these students. Such instruction
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3 could begin with students given EPMs and identifying possible atomic identities or
4 functional groups or identifying the corresponding line-angle or skeletal diagram rather
5 than providing students with EPMs as an optional tool. Each of these instructional
6 suggestions would require further testing. Ultimately, while eleven of the seventeen
7 spontaneously integrated EPMs with chemistry concepts when explaining their closed-
8 sort in this project, it suggests that such spontaneous integration cannot be relied on
9 from an instructional standpoint.
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13 Introducing EPMs within a defined chemistry task, such as ranking molecules on
14 nucleophilicity or identifying nucleophile sites on molecules, would appear to have
15 advantages over introducing EPMs without a defined chemistry task for some students.
16 This finding corresponds with a recent study evaluating tutorials designed to increase
17 students' levels of explaining an SN1 reaction using EPMs and line angle
18 representations that concluded further personalization of tutorials needs to occur to
19 properly support students' needs (Dood, *et al.*, 2020). Both the recent study in the
20 literature and this current work suggests meaningful variations in how students interpret
21 representations. The findings in the current study add to this by suggesting that more
22 students see relations between EPMs and information from other representations (e.g.
23 atomic identity) when they are engaging with EPMs in a defined task. The introduction
24 of EPMs independent of particular chemistry tasks (e.g. during a general introduction of
25 molecular representations) may lead some students to focus only on explicit features of
26 the EPM representation for resource activation rather than integrating features of the
27 representation to their existing chemical resources.
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33 The findings from this work also expand recent work in representational
34 competence as it applies to molecular representations. Representational competence
35 is a set of skills that allow a person to use single or multiple representations (Kozma
36 and Russell, 2005). One skill within representational competence is translation, or the
37 ability to make connections across different related representations (Ward, *et al.*, 2024).
38 Eleven of the seventeen students made explicit mention during their closed sort that the
39 molecules on the cards were duplicates. Eight of the eleven students who noted the
40 duplicates also adopted integrated reasoning between the EPM and chemical
41 properties. Conversely, three of the six students who did not explicitly note the
42 duplicates adopted integrated reasoning with the EPMs. These findings suggest that
43 training to promote translating between representations may be beneficial for students
44 to integrate representations with their chemistry resources; future research would be
45 needed to test this suggestion. Ward *et al.* (2024) found that representational
46 competence may be better described as correlations between skills of interpretation,
47 translation, and usage, instead of separately distinguished skills. Further they also
48 showed that among organic chemistry students, representational competence varied
49 and should not be assumed with instruction. The current project matches these findings
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3 as the ability to translate the EPMs (e.g. noting the duplication of molecules within the
4 closed sort) overlapped with the integration of EPMs in conjunction with chemistry
5 knowledge. This work expands Ward and colleagues (2024) findings to EPMs as this
6 representation was not explored in their work.
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10 **Conclusions**

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12 Analysis of the results of this study highlighted how the alternative features used
13 by students depends on context. Specifically, students integrating features of
14 representations tend to invoke utility of EPM features alongside other representations
15 for conceptual explanations and students were more apt to do this within the closed sort
16 task. The utility of EPMs, such as explaining polarity through the explicitness of colors,
17 does not necessarily indicate integration of features to prior knowledge and chemical
18 understanding. Students who use features in isolation result in recognition of concepts
19 through identifiable features, such as charges alone, to define concepts rather than
20 explain how they come to be. Further students who use EPM in isolation were more apt
21 to abandon EPM with the closed-sort or not use EPMs in either task.
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25 It can also be expected for some students to benefit from EPM utility when
26 features are integrated with other representational features. Eleven of the seventeen
27 participants found EPMs to be fruitful for integrating polarity or nucleophilicity with
28 chemistry concepts. Students using EPM features integrated with chemistry concepts
29 appear more likely to benefit from the use of EPMs, and the format of the context may
30 promote this integration. Additionally, 8 of the 11 students who integrated EPM features
31 into their reasoning also accurately recognized all the molecular duplicates, indicating
32 representational translation. Therefore, integrated reasoning may directly relate to the
33 ability to make connections across multiple representations and potentially improve
34 chemistry associated skills, offering an avenue for promoting integrated usage. This
35 study suggests that if students are to be trained in sensemaking of chemistry with
36 EPMs, establishing a context that requires a level of reliance on chemical principles
37 may encourage students to go from isolated utility to integrated utility in thought
38 processes, and therefore utilize EPMs in a beneficial way.
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44 **Limitations**

45 The 17 participants may not be representative of the entire undergraduate
46 organic chemistry population. It would be important to analyze a larger sample size to
47 see if the patterns found here hold. Additionally, all students who participated were
48 volunteers and, in this way, may not represent the undergraduate organic chemistry
49 population. Furthermore, while conclusions can be made regarding students'
50 understanding of science knowledge as well as their established reasoning methods,
51 their previous experiences that encompass those are assumed and difficult to decipher.
52 Additionally, student utilization was recorded via verbal explanations and gestures (ie:
53 pointing), and implicit considerations of representational features could not be included.
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3 However, within the interviews, clarification of student meaning was often achieved, and
4 thus provides reliability in these findings in addition to coding reliability. It is also crucial
5 to clarify that card sort tasks are just one kind of assessment, and future research is
6 needed to further analyze other potential EPM integration invoking environments to
7 promote students' learning through utility of EPMs. It would be informative for future
8 studies to further explore how EPMs were taught in classes for the two students who
9 indicated that they had seen EPMs in class before. This avenue was not explored within
10 this study as specific questions regarding the teaching of EPMs were not asked in the
11 interviews.
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16 **Data Availability Statement**

17 The transcript data are not publicly available as approval for this study did not
18 include permission for sharing data publicly. The EPMs were generated using the Jmol
19 software program through Gaussian which relied on partial charge calculations to
20 generate the gradients of colors for each molecule.
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24 **Conflict of Interest**

25 Researcher SEL receives funding from the Royal Society of Chemistry. The
26 Royal Society of Chemistry did not play a role in the data collection, data analysis or
27 presentation of the research results.
28
29

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39
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Appendix

Both Codebooks, presented below, were used for analysis in open and closed sort.

Code	Description	Example
Prompted – EPM Utility	A prompt from interviewer that potentially causes a change in student's approach to sort where	(this ex would also be coded as <u>No use of EPMs</u>) Interviewer: "Were there any other chemistry concepts.

	EPMs are then used or student states that they used EPMs after prompt when use was not otherwise present	That you were thinking about? You mentioned earlier that EPMs would make you think about polarity. Did you think about polarity at all?" P13: "Well, they all look polar, so not really, since none of them were symmetrical in any way. There were charges on them and they were all polar molecules."
Unprompted – EPM Utility	Student begins to utilize the EPM on their own, not prompted by interviewer	(this ex would also be coded as <u>use of color to describe ED to relate to nucleophilicity</u>) "But then now looking at the electrostatic potential maps, and electron density. Yeah. Okay. So that, it's actually looking for... I'm trying to see or remember as well, just what...or see how these relate to each other as far as electrophilicity versus nucleophilicity goes, based on the electrostatic potential maps."
Prompted – No Utility	An explicit statement of students not using EPMs after being prompted by the interviewer	Interviewer: "Did that [colors] influence how you grouped them at all?" Interviewee: "I just...I think like in class we never really see the clouds as much, so I rely more heavily on the structure in the formula given, not the colors of the cloud around."

COMBINATORY Code	Sub-Code	Definition	Example
Atoms + Color	Electronegativity	Students make connections between atoms from CF and	"CO2 can have oxygen negative – red. And with the W, the carbon is very blue

1		colors to understand	because it's going to be very
2		electron	positive"
3		density/electronegativit	"Well, I can kind of make a
4		y in the molecules	connection to something
5			because like at the end of
6			the SH, its like popping up at
7			the separate atom, and then
8			here it's popping up at the Br
9			and then there's red at the H,
10			kind of showing which
11			molecule has more, not more
12			stability, but like in terms of
13			O and Br, it would be like
14			which atom is more
15			electronegative"
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23	Polarity	Students make	"Actually, this one does look,
24		connections between	the T card looks pretty
25		atoms from CF and	similar to these other ones
26		colors to understand	where it's mostly the greens
27		polarity of the	and blues and then the red
28		molecules	bit where the oxygen is. So
29			I'll put the T card in the polar
30			spot category."
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33			"M is an alkyl halide because
34			it has a chlorine bonded to it
35			then N has an amide group P
36			has an OH group meaning
37			that that's an alcohol and
38			then X has a sulfide group.
39			So they can be classified.
40			These can be classified as
41			polar, I would say because
42			there's like a, um, as a
43			diagram shows how like the
44			electron density is highest at
45			one pole and then the other
46			one it's green. How green
47			represents that there's not
48			much electron density."
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53	Stability	Students make	"So aside from looking at
54		connections between	charges, because not all of
55		atoms from CF and	them have charges, the
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		colors to understand stability of the molecules	charges kind of like help me, I guess picture and understand it [...] The less positive is, the more unstable its going to be”
	Reactivity	Students make connections between atoms from CF and colors to understand reactivity	“I knew Cl was a good leaving group and if Cl is going to leave then that third carbon would become positive, and the same thing would go for [EPM of 1-chloropropane]. Because in the electric cloud, [...] saw the darker blue, which told me that would lean towards the positive side more, so if that Cl did leave, it would be able to react with the nucleophile”
Charges + Color (students must indicate they are speaking of charges, default to atoms)	Electronegativity	Students make connections between charges from CF and colors to understand electron density/electronegativity in the molecules	“I am thinking about the intensity of the charges. So I sorted, based on having the most electrostatic potential, and there's a lot of green in here, and yellows, which are indicating there isn't a strong positive strong negative charge really at play.”
	Polarity	Students connect the colors and charges of CF to polarity	“Um, I looked at the charges first, but next I did look at the colors. And that's because that's how I really determined if they're polar or non-polar. So I think that without the colors, my categories would definitely be different.”
	Stability	Students connect the colors and charges to stability	N/A – this code was not applicable to the data
	Reactivity	Students connect the colors and charges to reactivity	“I would imagine if you look at this and look for example S&O's you can say oh probably S is more reactive

			than O just by the sake of having one like in shape as a spear. [...] it's a line in a ball and you can think that the line is going to be like more reactive into trying to touch something else instead of just having like a ball of concentrated red charge. That doesn't point in any given direction. It's just there."
<u>EPM Focused Code</u>		Definition	Example
Color	Electronegativity	Student uses color alone to identify the electronegative areas in the molecules	<p>"Let's see. And I also just and now that I know the difference, I think I know the difference. I could just differentiate by which ones seem to be more electronegative than the others based on the colors. So which ones exhibit more blue? Which ones exhibit more red?"</p> <p>"Well, I'm probably going to start to sort them by like where the electrons density is. Where it is more like centered and more like on the outside."</p>
	Polarity	Student uses color alone to describe the polarity of the molecules	"And it's it's leaving me right now. But you - I definitely know for a fact that if you're tipping more on one side than another, you definitely have a polar compound. And then if you see more of a mesh of colors, I want to assume that you're getting towards non polar and stability"

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			<p>“And then I'm like, the ones where it's more dense, like in the middle or the ones more on top, and then. less denser on the bottom because it's all like the polar regions. And then these, like it's not as polar because it's more like muddled.”</p>
	Partial Charges	Student uses color alone to describe the partial charges of the molecules	<p>“So I guess blue associates with positive. And as you get to red, which would be from green to yellow to red and that's why W is such a good reference, because you can see the clear cutness as you get to red, you're getting to partial negative and that's another thing. The partial charges, I think that's definitely related to this.”</p>
CF Focused Code		Definition	Example
Atoms		Student uses the atoms to describe sort without making conceptual connections	<p>“I think this is how I would sort. I don't know if this makes sense, but I did like X, N, P, T because they have like the carbon hydrogen chain, but then they have another molecule. These two don't have. R&W don't have a carbon hydrogen chain.”</p>
Charges		Student uses the charges to describe sort without making conceptual connections	<p>“Um, or negatively charged and positively charged species and then like neutral species. So there could be three ways of putting it which is again non-technical. So in that case, U, S, V these are negatively charged so they can be in one category. Okay? And then the positively charged are like O,</p>

		and then H3O, or actually, O and R and then everybody else's neutral and then among them, um, so there is again there could be like a very basic non-technical classifications form."
Polarity	Student describes polarity/electronegativity using only the CF	"For non-polar...from CO ₂ , it was more so the presence of the long chains of the CH stretch. And then for polar, it was a short chain of the CH stretch and then CO, which is pretty highly electronegative."
Structure	Student sorts based on pi bonds without making conceptual connections	"So kind of what's going through my head as I'm kind of looking at these three and going this one being a tertiary carbon and then this one doesn't because it has that pi bond"
Geometry	Student sorts by spatial arrangement without making conceptual connections	"And then S for me is kind of out there where I could put S I could kind of put S with R and O in terms of what it would look like in linear space. But it's a little bit different because R and O actually have that pyramid formation and this one doesn't."
Stability	Student determines stability using atoms in the CF or structure	"Negative charge, the more nucleophilic it is, the more willing it is to bond to that positive charge for the stability to become neutral."

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3 ***Data Availability Statement***
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5 The data are not publicly available as approval for this study did not include
6 permission for sharing data publicly.
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