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When All You Have Is a Covalent Model of Bonding, Every Substance Is a Molecule: A Longitudinal Study of Student Enactment of Covalent and Ionic Bonding Models

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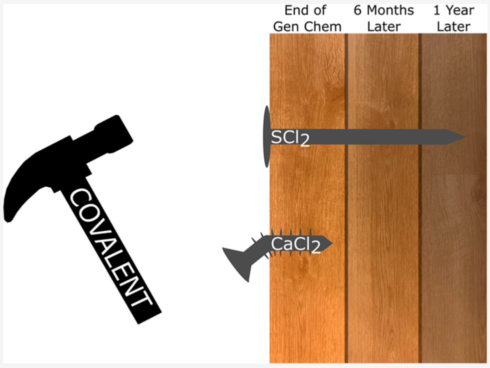
ABSTRACT: This longitudinal study examines the responses of students at two different institutions to creative exercises related to models of chemical bonding. Questions in the form of creative exercises required students to provide relevant, accurate, and distinct statements about two compounds for which they were provided only the formula and electronegativity values: SCl_2 and $CaCl_2$. Students responded to the questions at the end of general chemistry, six months later, and one year later. Their responses were analyzed qualitatively and quantitatively to explore patterns in application of bonding ideas and change over time. The data reveal extensive application of covalent bonding ideas to an ionic compound, regardless of whether a student identified the substance as ionic or not, and that this is consistent over a year out. Implications for instruction of bonding models in general chemistry (and beyond) are discussed.



KEYWORDS: *First-Year Undergraduate/General, Chemical Education Research, Rote Learning, Covalent Bonding, Ionic Bonding, VSEPR Theory*

INTRODUCTION

Student Ideas about Chemical Bonding

Chemical bonding is a foundational concept in chemistry. It is incorporated into introductory courses and continues to be built upon as students progress into more advanced chemistry and life science courses. Despite its importance for understanding structure, properties, interactions, and reactions, a significant body of research shows that students have numerous conceptual difficulties understanding bonding.[1−8] Diagnostic instruments have been developed to identify alternative conceptions and ascertain their prevalence in student populations.[7−11] Peterson et al.,[7] for example, found that students struggled with polar covalent bonding and disregarded the role of electronegativity. In examining students' mental models of molecules, Harrison and Treagust[12] identified misconceptions related to bond polarity, molecule shape, and overall molecule polarity. Nicoll[5] explored student ideas about electrons, bonding, electronegativity, and structure through semistructured interviews. She found evidence of incorrect understandings of electron behavior (e.g., electrons attract), inaccurate and vague understandings of electronegativity, and confusion in distinguishing between atom and molecule. Many of these misunderstandings remained even after instruction. Overarching patterns in student difficulties with and alternative conceptions of chemical bonding have also been summarized in various reviews.[13,14]

Students also exhibit difficulties making sense of how bonds form. Luxford and Bretz[4] found that students were capable of reciting definitions of bonding, but in practice could not explain how compounds were formed from atoms or ions. There is evidence of students thinking covalent bond formation involves the transfer of electrons[15−17] as well as that ionic bond formation involves the sharing of electrons.[5,18,19] In developing the Bonding Representations Inventory (BRI), Luxford and Bretz[20] also explored student conceptions of covalent and ionic bonding representations. They found a range of misconceptions related to periodic trends, electrostatic interactions, the octet rule, and surface features of representations. Almost four decades ago, Butts and Smith[21] explored student understanding of the structure of solids, finding that while some students could define ionic bonding, they evidently did not have a clear understanding of a three-dimensional lattice structure. Others were confused about the type and number of bonds in lattices, including believing the presence of both covalent and ionic bonds. Taber[16,17] found that students tended to explain bonding in

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terms of atoms “having”, “needing”, or “wanting” eight electrons “in order to be stable”. He proposed that the “octet rule” heuristic had come to be used by students as an explanatory framework for chemical bonding.[17,22] Studies in England, in university courses in Greece and Turkey, and in Croatia using a diagnostic instrument to elicit conceptions about bonding in NaCl provided evidence of students employing an alternative “molecular” conceptual framework to think about ionic bonding.[8,15,23]

The body of research has shown that while students gain some ability to use the language of bonding in their introductory chemistry courses, their ability to explain and distinguish between models of bonding is frequently disjointed. This suggests incomplete conceptualization, heuristic thinking, and rote memorization when it comes to chemical bonding.

Meaningful Learning

This work is guided by Ausubel’s Assumptive Learning Theory. In this theory, learning is placed on a continuum between rote and meaningful, with the end points differentiated by the degree to which the learning lends itself to concept retention.[24] Concepts that are learned by rote learning are characterized by limited retention, often being forgotten if the learner has made little to no effort to meaningfully incorporate the information into their existing knowledge structure. Meaningfully learned concepts are those that a learner has consciously chosen to associate and incorporate by anchoring them to relevant prior knowledge. In contrast to concepts learned by rote, material learned meaningfully can be remembered and transferred. In chemistry, meaningful learning will position students to build a coherent foundational knowledge structure upon which future knowledge can be developed, as well as to understand the relationships between disciplinary ideas and how they can provide explanations.[25]

To investigate the extent to which students exhibit meaningful learning regarding chemical bonding from their first encounter in general chemistry, we sought to follow students longitudinally over a year’s period. Meaningful learning of specific concepts in science education has rarely been studied from a longitudinal perspective.[26,27] This type of study will provide a valuable perspective on how successful common general chemistry curricula are in terms of supporting students in developing a strong understanding of chemical bonding.

We explored the following research questions:

RQ1: How do students who completed general chemistry employ covalent and ionic bonding ideas to describe ionic and covalent compounds?

RQ2: How does students’ use of ionic and covalent bonding ideas progress over 12 months from completing general chemistry?

RQ3: How do peer leaders, who are upper-level undergraduate students, employ covalent and ionic bonding ideas to describe ionic and covalent compounds?

■ METHODS

Context

This study was conducted at two doctoral, high-research activity public institutions, involving students enrolled in comparable second semester general chemistry courses (GCII) and peer instructional leaders associated with each course. The institutions differ considerably in student body size and demographic characteristics. The smaller institution has 15 000 full-time undergraduate students consisting of a student body that is 9% nonwhite and 55% female. The larger has 36 000 students with a student body that is 48% nonwhite and 60% female. IRB approval for this study was obtained at both institutions.

Both institutions used undergraduate students as peer instructional leaders. At the smaller institution, these leaders hold 80 min weekly sessions, scheduled separately from the class. During these sessions the peer leader works with students in general chemistry (first or second semester) as the students work in groups (of no more than 10) on a set of problems.[28] At the larger institution, peer leaders support student working teams during class periods such that all students participate. The sessions are 50 or 75 min once per week.

Data Collection

This study tracked a cohort of students over a year following the completion of general chemistry II. Participants were assessed at three time points: immediately at the end of general chemistry (May), six months later (November), and after one year (April of the following year). At the smaller institution, the first data collection occurred immediately preceding the final exam in general chemistry II, while at the larger institution, it occurred immediately following the final exam in general chemistry II. At both institutions, the final exam at the end of general chemistry II was a cumulative exam on general chemistry II content. Thirty students were recruited at the smaller institution and complete data sets (i.e., all three time points) exist for 27 (90% retention). Forty-five students were recruited at the larger institution and 31 complete data sets exist (69% retention). Total retention was 77% for a total of 58 participants, including 43 students who had just completed general chemistry and 15 upper-level undergraduate peer leaders. Students were recruited through an announcement distributed via their course management system. At the first data collection session, students were asked to provide their university email, a secondary email, and their phone number in order to contact them with information and reminders about the following sessions. After completion of each session, participants received a $30 gift card.

Students had 1 h to complete a seven-question survey. The only resource information provided was a periodic table. Due to the COVID-19 pandemic, data collection for the third time point occurred via online survey. Two questions in the survey explored concepts related to covalent and ionic bonding models. Each question was presented as a creative exercise (CE). Similar to concept maps, CEs are open-ended assessments that do not seek one specific correct answer. CEs start with a prompt and students are asked to provide as many statements as they can that are distinct, accurate, and relevant to the prompt.[29] This structure allows students to demonstrate whatever information and relationships they believe are related to the prompt, rather than assessing a pre- or narrowly defined objective.[30] Evidence regarding the validity of student responses to CEs used in assessments in general chemistry is discussed elsewhere.[30] The survey was structured this way to elicit what students believed in their own minds was sufficient to demonstrate their knowledge. In this way, CEs provide a snapshot of what students spontaneously believe is important when given minimal prompting. It was not a thorough examination of their understanding cued by more specific prompts or by an interviewer asking probing questions.

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Thus, we are not arguing that students' responses present a complete knowledge map.

The CE prompts in Figure 1 were deployed at each of the three time points. Less common substances were chosen (e.g., not water or sodium chloride) so that students would have to engage in some level of analysis and could not rely on rote recall. At the surface level, the target chemical substances in the prompts were chosen to have the same formula ratio and one element in common for more direct comparison. A formula ratio of 1:2 was chosen to allow for inferences regarding geometry and electron distribution. However, the implicit bonding model that describes each structure is different. The prompts intentionally refer to the substances differently ("molecule" vs "compound") to suggest that they should not be described the same way. For the same reason, electronegativity values were provided in the prompt.

Write down as many distinct factual statements as you can about a molecule of SCl_2. Please use complete sentences. You may also draw illustrations instead of verbal statements. Electronegativity values: S=2.5; Cl=3.0

Write down as many distinct factual statements as you can about the compound $CaCl_2$. Please use complete sentences. You may also draw illustrations instead of verbal statements. Electronegativity values: Ca=1.0; Cl=3.0

Figure 1. CE prompts about SCl_2 and $CaCl_2$. In the online assessment for time point three, these prompts were modified to allow upload of drawings.

Student Characteristics

The final grade distribution of the general chemistry students participating in this study tended to fall above the class average, with half attaining a B+ or better in General Chemistry II. This suggests that the students whose work is described here represent those with more proficiency in chemistry relative to students overall in the courses.

Peer leaders are recruited from among students with B or better outcomes in the previous year's class and participate in a training course. Across both institutions, peer leaders had a similar amount of experience prior to the beginning of the study. The two peer leaders at the smaller institution had two semesters of experience prior to the start of data collection and continued as leaders for the duration of the study. At the larger institution, eight peer leaders worked with General Chemistry I or General Chemistry II students during the academic year leading up to the first data collection and five peer leaders worked with General Chemistry II students in the semester between the first and second data collection.

Most participants at each institution, including the peer leaders, reported taking organic chemistry during the course of the study. Students who were not peer leaders also listed taking genetics, ecology, microbiology, and physics (two semesters) courses. Subsequent courses taken by peer leaders included physical chemistry or biochemistry, as well as life science courses like cellular biology, cellular metabolism, or physiology-related courses.

Analysis

Only those students with responses at all three time points were considered. Data were analyzed through a combination of inductive and deductive approaches. Initial analysis was inductive and qualitative, exploring nuances in how students described each substance and how those descriptions changed over time using a constant comparison approach.[31] For example, initial codes captured whether students determined formal charge, referred to electronegativities, or displayed particular features in drawn representations. These features were categorized according to overarching topic as well as according to chemical accuracy and the nature of the mistakes students made. This approach provided rich detail incorporated into the discussion of student responses; however, individual student responses for each CE prompt over time exhibited substantial unevenness at this finer level of detail such that discerning regularities or trends was difficult (e.g., a student calculating valence electron counts at the first and third time points, but not at the second). Conducting the survey online at the third time point due to the COVID-19 pandemic introduced another confounding factor, particularly as respondents provided fewer images.

To account for an individual's variability across time, two further approaches that drew on deductive and inductive strategies were taken to explore the data while maintaining alignment with the research questions. In particular, because the implicit bonding model used for each compound is different, we attended to whether students recognized SCl_2 as covalent and molecular, and $CaCl_2$ as ionic and in a lattice network, and the ways in which students described each substance or consequent properties at each of the three time points. One approach, which makes up the majority of the analysis, involved broadly classifying student responses by what bonding model they used. Each individual's SCl_2 and $CaCl_2$ responses were classified by two authors [KB, SL] as describing purely "covalent", purely "ionic", or "dissonant" (using or citing ionic and covalent bonding models within the same response). Criteria for classification are available in the Supporting Information (Table S1) and were developed by identifying characteristics canonically associated with each bonding model with consideration for the language and representations used by students in the current data set. In instances where insufficient information was provided to infer reliably a particular model (e.g., student made one statement about molar mass), the response was classified as "insufficient". Responses were coded separately, and initial agreement was satisfactory (Cohen's kappa = 0.84). Any differences were resolved by discussion. The number of individuals falling into each category (ionic, covalent, dissonant) at each time point was totaled. This summary allowed comparisons between the two CE prompts for individuals over time and for students who served as a peer leader or not. The potential impact of question order (SCl_2 vs $CaCl_2$ first) on the bonding model employed by students was also explored using another population of general chemistry students ($n = 73$) from the smaller institution. The prompt used in this follow-up study also employed the word "substance" to describe both compounds in an attempt to determine whether the term "molecule" in the longitudinal study cued thinking about covalent structure and bonding.

A second approach to account for individual variability over time was to examine the *differences* between the CE responses for each individual at each time point. Since participants

Table 1. Frequency of Bonding Model Applied to SCl_2 and $CaCl_2$ at the End of General Chemistry ($n = 43$)

Bonding Model	SCl_2 (%)	$CaCl_2$ (%)
Covalent	88	58
Ionic	2	5
Dissonant	7	33
Insufficient	2	5

responded to the two CE questions back-to-back (one about a covalent substance and the other about an ionic substance), the comparison between the responses at each moment in time offered a snapshot of whether and how each individual distinguished covalent from ionic bonding. Particular attention was given to the degree to which students walked the path from Lewis structure through evaluation of polarity and geometry, as well as whether this was done accurately (for SCl_2) or inappropriately (for $CaCl_2$).

Coding criteria for this second approach (Table S2) were developed by one researcher [CB], again by identifying the procedural steps canonically associated with constructing a Lewis structure but with consideration for what was and was not sufficient evidence given the language and representations used by students in the current data set. Another researcher [YW] applied the code definitions independently to the responses in two rounds. First, for five random students (10% of the population), the agreement in coding decisions was 95% (180 decisions). Differences were discussed and codes refined. For the second round, 12 more random students were selected. Agreement was again at 95% (432 decisions). Discussion led to further refinement of codes and a final check for consistency across the data set.

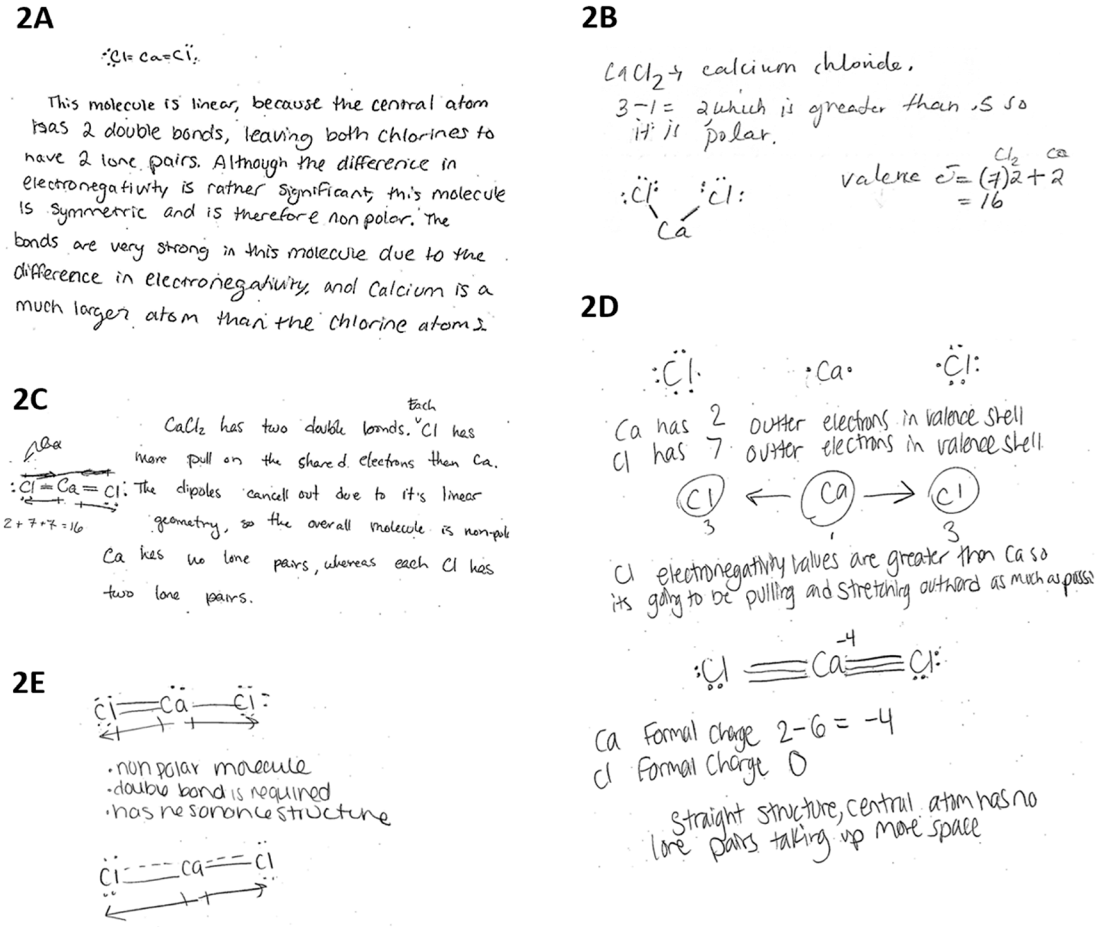
■ RESULTS

RQ1: How Do Students That Completed General Chemistry Employ Covalent and Ionic Bonding Ideas to Describe Ionic and Covalent Compounds?

Responses were broadly classified as suggesting that students employed a purely covalent, purely ionic, or dissonant mixed model. Table 1 shows that at the end of general chemistry (hereafter Time Point 1, TP1), SCl_2 and $CaCl_2$ were both largely described using a covalent model: 88% and 58%, respectively. $CaCl_2$ was rarely described with language suggesting a purely ionic model (5%), with 33% of students using a mixture of aspects of covalent and ionic models in their responses. In a few instances, insufficient information was provided and the response was classified as insufficient.

As shown in Table 1, the majority of students enacted a covalent bonding model with $CaCl_2$ without mention of ionic bonding. Figure 2 shows five student responses to the $CaCl_2$ prompt.

In Figure 2, all five responses provided some form of a Lewis dot structure, placing dots on both calcium and chlorine in 2D and 2E but placing dots on only chlorine in 2A, 2B, and 2C. It was common for students to represent $CaCl_2$ with single (as in



This molecule is linear, because the central atom has 2 double bonds, leaving both chlorines to have 2 lone pairs. Although the difference in electronegativty is rather significant, this molecule is symmetric and is therefore non polar. The bonds are very strong in this molecule due to the difference in electronegativity, and Calcium is a much larger atom than the chlorine atoms.

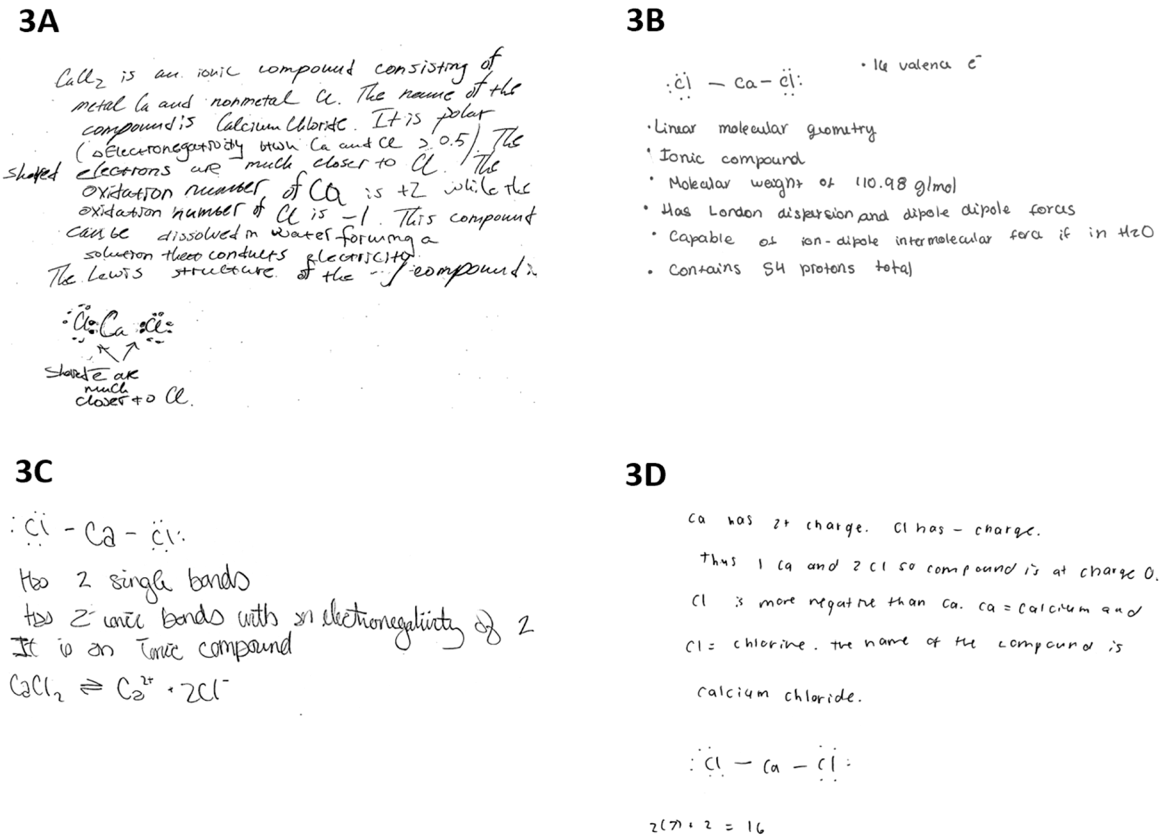
$CaCl_2$ → calcium chloride.
3 − 1 = 2 which is greater than .5 so it is polar.
valence e⁻ = (7)2 + 2 = 16

$CaCl_2$ has two double bonds. Each Cl has more pull on the shared electrons then Ca. The dipoles cancell out due to it's linear geometry, so the overall molecule is non-pol
Ca has no lone pairs, whereas each Cl has two lone pairs.

Ca has 2 outter electrons in valence shell
Cl has 7 outter electrons in valence shell
Cl electronegativity values are greater than Ca so its going to be pulling and stretching outward as much as possi
Ca Formal charge 2−6 = −4
Cl Formal Charge 0
Straight structure, central atom has no lone pairs taking up more space

- non polar molecule
- doubl bond is required
- has resonance structure

Figure 2. Variations in enacting covalent bonding with $CaCl_2$.



3A

CaCl₂ is an ionic compound consisting of metal Ca and nonmetal Cl. The name of the compound is Calcium Chloride. It is polar (ΔElectronegativity btwn Ca and Cl > 0.5). The shared electrons are much closer to Cl. The oxidation number of Ca is +2 while the oxidation number of Cl is −1. This compound can be dissolved in water forming a solution that conducts electricity. The Lewis structure of the compound is:

shared e are much closer to Cl.

3B

- 16 valence e⁻
- Linear molecular geometry
- Ionic compound
- Molecular weight of 110.98 g/mol
- Has London dispersion and dipole dipole forces
- Capable of ion-dipole intermolecular force if in H2O
- Contains 54 protons total

3C

Has 2 single bonds

Has 2 ionic bonds with an electronegativity of 2

It is an Ionic compound

$CaCl_2 \rightleftharpoons Ca^{2+} + 2Cl^-$

3D

Ca has 2+ charge. Cl has − charge.

thus 1 Ca and 2 Cl so compound is at charge 0.

Cl is more negative than Ca. Ca = Calcium and Cl = chlorine. the name of the compound is calcium chloride.

$2(7) + 2 = 16$

Figure 3. Variations in enacting a dissonant model with $CaCl_2$.

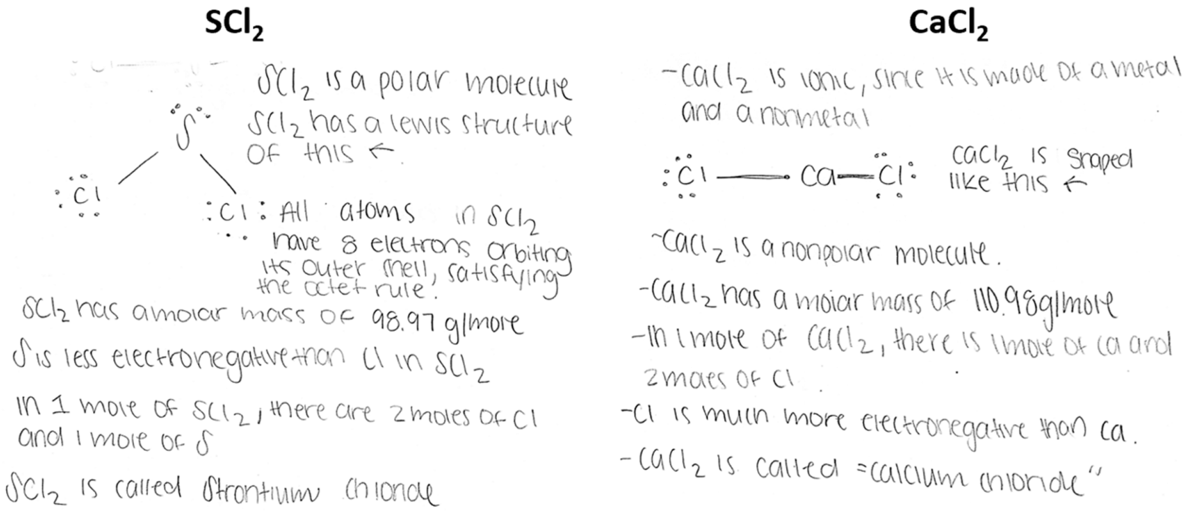
2B) or multiple bonds (2A, 2C−2E). $CaCl_2$ was drawn with single bonds by 31 students (72%) at least once over the three time points, and with one or two sets of multiple bonds by 19 students (44%). A frequent extension was an attempt to predict molecular geometry for the compound. The inference is that students were utilizing VSEPR theory, although not all students provided explicit evidence of this (as for example, 2C and 2D do by mentioning lone pairs being absent on Ca). 2A, 2C, and 2E each describe the molecule as linear or straight, while 2B presents a bent geometry, although the central atom has only two bonding groups. $CaCl_2$ was explicitly described as linear by 18 students at least once over the three time points (42%), while only 8 students (19%) explicitly predicted it had a bent geometry at least once.

All five of the responses in Figure 2 make predictions about polarity. The responses with explicit mention of a linear geometry (2A, 2C, and 2D) predicted a nonpolar compound. Similarly, 2E drew a linear geometry and predicted a nonpolar compound. 2B, with a bent geometry, predicted a polar compound. Considering all student responses, explicit predictions about polarity of $CaCl_2$ were evenly split, with 17 students (40%) describing it as nonpolar and 18 students (42%) describing it as polar at least once over the three time points. 2B and 2D each explicitly solve for differences in electronegativity to support their presentation for bond dipole. 2D also describes formal charge relying on the formula of valence electrons minus assigned electrons. Formal charge was rarely invoked in the responses and was occasionally presented as a formal charge of +2 for calcium and −1 for chlorine without explanation for why. 2E's original Lewis dot structure features one double bond and one single bond leading to an argument about invoking a resonance structure to explain electron distribution. Referring to resonance was rare but demonstrates students' firm commitment to continuing to apply a covalent model to this substance.

As demonstrated by the exemplar responses in Figure 2, respondents implemented a covalent bonding model beginning with a Lewis dot structure, followed by invocation of tenets of covalent bonding including VSEPR, assignment of dipole moments, and prediction of polar or nonpolar compounds. Additionally, but less frequently, respondents used formal charge or resonance to further describe the compound. In light of the multifaceted use of the covalent bonding model when describing an ionic compound, and that the responses represent students' answers to an open-ended prompt to describe an ionic compound, the evidence supports that students utilize a covalent bonding model as a default option in describing the structure and chemical properties of a compound.

About one-third (33%) of students employed a dissonant model when describing $CaCl_2$, mixing aspects of covalent and ionic bonding models. The four student responses in Figure 3 demonstrate various ways in which students applied covalent and ionic bonding ideas simultaneously to describe $CaCl_2$.

Of these dissonant responses, 3A−3C explicitly use the term "ionic" while 3D does not. However, prediction of a Lewis structure, geometry, and/or polarity occurred even when respondents did explicitly state the substance was "ionic." Like respondents who utilized a covalent bonding scheme, those with dissonant responses typically provided a Lewis dot structure for $CaCl_2$. All of the responses here feature single bonds; however, other dissonant responses represented $CaCl_2$



SCl_2 is a polar molecule

SCl_2 has a lewis structure of this ←

All atoms in SCl_2 have 8 electrons orbiting its outer shell, satisfying the octet rule!

SCl_2 has a molar mass of 98.97 g/more

S is less electronegative than Cl in SCl_2

In 1 more of SCl_2, there are 2 moles of Cl and 1 more of S

SCl_2 is called Strontium chlonde

-$CaCl_2$ is ionic, since it is made of a metal and a nonmetal

$CaCl_2$ is shaped like this ←

-$CaCl_2$ is a nonpolar molecule.

-$CaCl_2$ has a molar mass of 110.98 g/more

-In 1 more of $CaCl_2$, there is 1 more of Ca and 2 moles of Cl.

-Cl is much more electronegative than Ca.

-$CaCl_2$ is called "calcium chloride"

Figure 4. Comparison of one student's responses for SCl_2 and $CaCl_2$.

with double bonds. Dissonance was also apparent where $CaCl_2$ was drawn or referred to as being linear in structure (as in 3B) or bent, or that $CaCl_2$ was polar (3A). Both descriptions would commonly be used to describe a covalent substance, but not an ionic substance. More rarely, charges (3C, 3D) or oxidation states (3A) were assigned to the atoms. For 3D, the description of Ca as 2+ and Cl as −1 with a net charge of zero suggested the student was using ionic bonding ideas despite otherwise presenting $CaCl_2$ as a covalent compound.

Across responses classified as dissonant, the evidence suggests that students utilize covalent bonding ideas as a default framework even in instances where they explicitly state or imply that a substance is ionic. The default to covalent is particularly evident when comparing differences between an individual's responses to the SCl_2 and $CaCl_2$ prompts together. Figure 4 provides one such example. In this individual's response to SCl_2, they begin by constructing a Lewis dot structure and predicting that the compound is polar. They also calculate the molar mass, comment on the electronegativities of constituent atoms, state the ratio of atoms, and finally name the compound. Their SCl_2 response uses a covalent bonding scheme. Almost the same approach is followed in their $CaCl_2$ response, which is classified as dissonant. They first classify $CaCl_2$ as ionic given that it contains metal and nonmetal elements. Only eight students explicitly recognized and labeled elements as metals or nonmetals at least once when responding to either prompt. Then, as with SCl_2, they also provide a Lewis dot structure, predict that it is nonpolar, calculate the molar mass, comment on electronegativities, state the atomic ratio, and name the compound. The primary differences in the content of each response is the reference to the octet rule for SCl_2 and not $CaCl_2$, and a more explicit suggestion that $CaCl_2$ has a "shape" which suggests it is linear, whereas SCl_2 is presented as bent. Whether their $CaCl_2$ response was classified as covalent or dissonant, a side-by-side comparison of SCl_2 and $CaCl_2$ responses shows that many individuals drew similar structures and listed similar statements.

Additional perspective on the similarity between responses to the SCl_2 and $CaCl_2$ is provided in Table 2. Given the widespread application of covalent bonding ideas to both compounds, we explored the frequency with which respondents applied a Lewis/VSEPR approach to each compound. As part of coding, we identified four major steps to this approach, including the following: (1) predicting bonding or lone pair distribution; (2) accounting for bond polarity; (3) describing geometry; and (4) using geometry to determine the net polarity of the compound. Table 2 lists the percentages of students who attempted to follow this four-step Lewis procedure for SCl_2 and $CaCl_2$ at the end of general chemistry. Responses to $CaCl_2$ were coded as "attempting" each step rather than correctness because the application of the steps is inappropriate. Roughly 70% of students took the first step of applying Lewis dots to both substances. More than 50% of students continued through the first three steps. Tables 1 and 2 present a snapshot of the variation in how students employed bonding models to characterize each compound at the end of general chemistry (TP1).

Table 2. Percentage of Attempts, Correctly and Incorrectly Applied, at Procedural Steps of the Lewis/VSEPR Approach at the End of General Chemistry II for SCl_2 and $CaCl_2$ CEs (n = 43)

	SCl_2			$CaCl_2$
Step	Correct (%)	Incorrect (%)	No Attempt (%)	Attempted Application (%)
1. Predict bonding or lone pair distribution	65	21	14	77
2. Account for bond polarity	58	9	33	68
3. Describe geometry	53	14	33	58
4. Use geometry to judge net polarity	21	9	70	19

Question order was also examined to determine if it had any impact on students' tendency to apply covalent bonding ideas to $CaCl_2$. The CE prompts were provided to another group of general chemistry students (n = 73) from the smaller institution as part of their final exam. The exam was in-person and responses were hand-written. Approximately half (n = 32) received a version where the SCl_2 prompt was presented first in the exam booklet and the other half (n = 41) received a version with $CaCl_2$ first. It cannot be guaranteed that students completed them in this order. As shown in Table 3, there was essentially no difference in the percentage of students applying an ionic model to $CaCl_2$ (16% to 17%). However, the total percent of responses that included covalent ideas

Table 3. Frequency of Bonding Model Applied to SCl_2 and $CaCl_2$ Based on Order of Prompt during Exam (n = 73)

		SCl_2	$CaCl_2$
Prompt Order	Bonding Model	Percent Used Bonding Model (%)	Percent Used Bonding Model (%)
SCl_2 first (n = 32)	Covalent	66	25
	Ionic	0	16
	Dissonant	31	59
	Insufficient	3	0
$CaCl_2$ first (n = 41)	Covalent	73	5
	Ionic	0	17
	Dissonant	20	73
	Insufficient	7	5

(covalent and dissonant responses) was comparable when SCl_2 was encountered first (84%) versus when $CaCl_2$ was first (78%). Consequently, the data set is not likely influenced by an item order effect.

Furthermore, this item order experiment also included use of the same term "substance" as a modifier in the prompt instead of differentially "molecule" or "compound". The similarity of results suggests that students did not perceive this language difference as a cue to help distinguish covalent vs ionic behavior.

RQ2: How Does Students' Use of Ionic and Covalent Bonding Ideas Progress over 12 Months from Completing General Chemistry?

Responses over time were examined to explore how respondents' application of ionic and covalent bonding ideas changed from the end of general chemistry to six months and a year later (hereafter TP2 and TP3, respectively). The changes over time are visualized in the Sankey diagrams presented in Figure 5. For SCl_2, the majority of students employ a covalent model from TP1 to TP2 and then again from TP2 to TP3. A small number of students shift from covalent to ionic or dissonant and vice versa. For $CaCl_2$, student model enactment was considerably more inconsistent, as larger proportions of students began in different model classifications as well as shifted between classifications over time. Despite these shifts, the use of covalent or dissonant bonding models describes the majority of responses across each of the three time points. Figures 6 and 7 provide examples of the longitudinal trajectory of respondents who enacted covalent or dissonant bonding ideas to describe $CaCl_2$ at the end of GCII.

Figure 6 displays the responses of a student who consistently used a covalent bonding scheme to describe $CaCl_2$. At all three time points, a Lewis dot structure is provided. The structure at TP1 contains a pair of double bonds in contrast to the single bonds at TP2. At TP3 it is unclear whether the respondent intends to represent single bonds and/or bond dipoles. Dots are also placed on chlorine at TP1 and TP2 resulting in an octet for each, while only Ca was given dots at TP3. Each structure is presented as linear, although no specific geometry is stated. The electronegativity values for calcium and chlorine are written underneath the constituent atoms at every time point, and the structures at TP1 and TP2 include bond dipole arrows for all bonds. Compound polarity is predicted at TP1 and TP2 as polar. At TP1, the respondent states this is based on electronegativity values; at TP2 it is because the "arrows of electronegativity" face away from each other. The entire compound is described as "electronegative" at TP3.

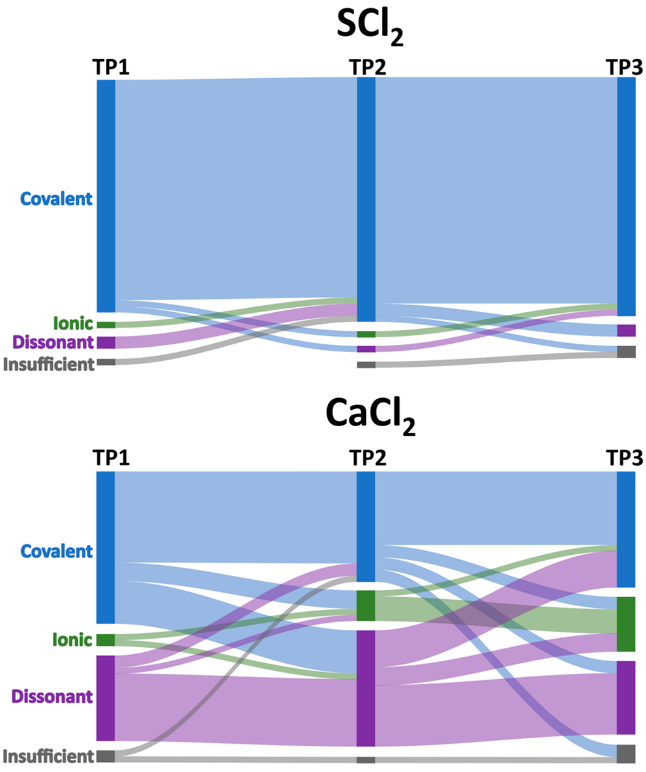
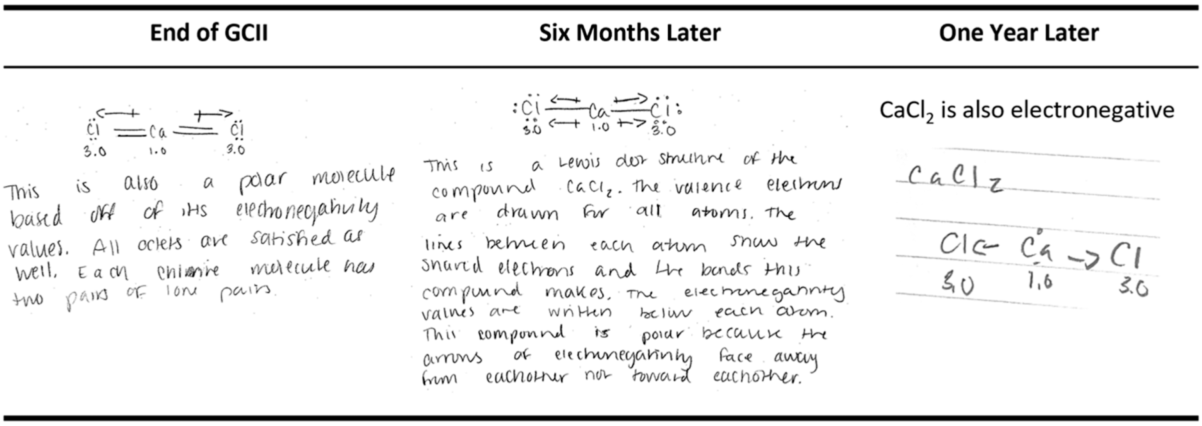


Figure 5. Proportion of students enacting each model from the end of general chemistry II (TP1) to six months (TP2) and one year later (TP3).

Respondents using a covalent bonding scheme commonly provided a Lewis dot structure and invoked other covalent bonding ideas, in a relatively consistent manner, longitudinally. A similar pattern existed for respondents classified as having a dissonant model. Figure 7 presents the responses of a student who consistently used a mix of ionic and covalent bonding ideas over time.

Lewis dot structures are provided at TP1 and TP2, with dots present on the chlorine atoms. Calcium and chlorine are presented with single bonds at TP1 and at TP2, although in the case of the latter the student did not use lines to represent the bonding. A Lewis dot is not provided at TP3 (possibly due to the online format), though the response states that octets are satisfied and both geometry and compound polarity are described. A linear molecular shape is assigned at all three time points. All three responses also suggest that there are bond dipole moments toward chlorine. While compound polarity is predicted as polar at TP1, dictated by the electronegativity values of chlorine, there is no mention of it at TP2 and it is seemingly mislabeled as "charge" at TP3. Charge is otherwise only mentioned at TP2, possibly referring to the presence of a negative charge on chlorine.

Unlike the examples presented in Figure 3, the mentions of charge in Figure 7 do not necessarily suggest ionic bonding ideas. The respondent explicitly describes $CaCl_2$ as an ionic compound at all three time points. They also mention at TP1 and TP2 that calcium is a metal. At TP3, the electronegativity difference between calcium and chlorine is provided as the reason for the compound's classification as ionic. The presence of Lewis dot structures, assignment of geometry, and

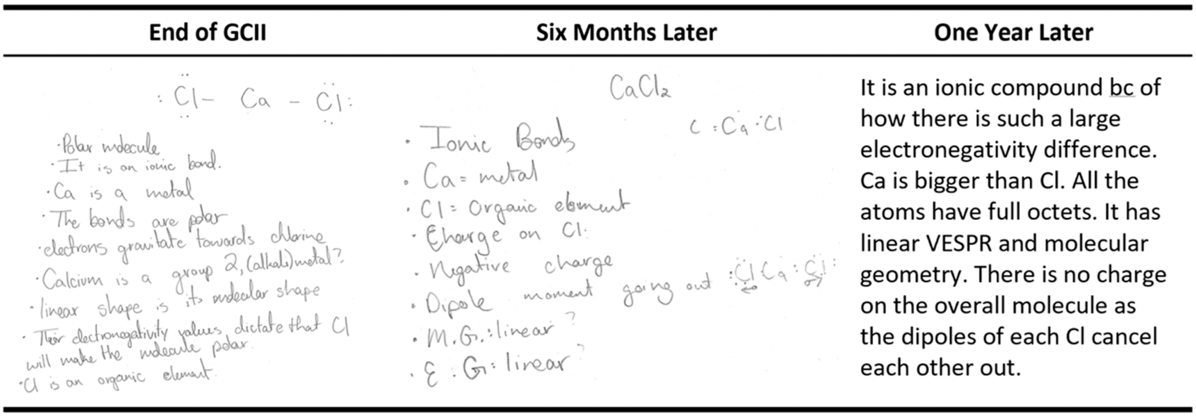


This is also a polar molecule based off of its electronegativity values. All octets are satisfied as well. Each chlorine molecule has two pairs of lone pairs.

This is a Lewis dot structure of the compound $CaCl_2$. The valence electrons are drawn for all atoms. The lines between each atom show the shared electrons and the bonds this compound makes. The electronegativity values are written below each atom. This compound is polar because the arrows of electronegativity face away from eachother nor toward eachother.

$CaCl_2$ is also electronegative

Figure 6. Consistent enactment (incorrectly) of a covalent model with $CaCl_2$ over time.



- Polar molecule
- It is an ionic bond.
- Ca is a metal
- The bonds are polar
- electrons gravitate towards chlorine
- Calcium is a group 2, (alkali) metal?
- linear shape is its molecular shape
- Their electronegativity values dictate that Cl will make the molecule polar.
- Cl is an organic element

- Ionic Bonds
- Ca = metal
- Cl = Organic element
- Charge on Cl
- Negative charge
- Dipole moment going out
- M.G.: linear ?
- E. G: linear ?

It is an ionic compound bc of how there is such a large electronegativity difference. Ca is bigger than Cl. All the atoms have full octets. It has linear VESPR and molecular geometry. There is no charge on the overall molecule as the dipoles of each Cl cancel each other out.

Figure 7. Consistent enactment of a dissonant model with $CaCl_2$ over time.

prediction of bond or compound polarity over time was typical among students enacting a dissonant bonding model.

To provide greater perspective on the application of covalent bonding ideas over time, Table 4 lists the frequencies with which respondents attempted to follow a four-step Lewis/VSEPR procedure for SCl_2 and $CaCl_2$ longitudinally.

In a situation where students are asked to spontaneously generate what they can say about the substances, the data show that the fraction of students using the Lewis/VSEPR approach is about the same whether the substance given is covalent or ionic (Table 4). This crude equivalence does not change over time. Most students over time display the Lewis approach and tend to express something about electron distribution and bond polarity. They are less likely to extend that to include compound geometry and overall polarity. The percentage of students expressing something about bonding or lone pair distribution is lower one year later, possibly due to the change in data collection modality (online survey).

Table 5 provides the specific percentages upon which Figure 5 is based to emphasize the disparity in model use. For SCl_2, between 88 and 93% of students enacted a covalent model (appropriately) at all time points. A covalent model choice for $CaCl_2$ displayed greater variation, dropping from 58% to 42% between the end of general chemistry and a year later, while use of an ionic model increased from 5% to 21%. The number of students employing a dissonant model started at one-third (33%, TP1), rose to 44% (TP2), and dropped after a year to 28% (TP3). There seems to be a small shift from employing covalent and dissonant models to ionic models over time.

Table 4. Percentage of Individuals Correctly and Incorrectly Attempting Procedural Steps of the Lewis/VSEPR Approach for SCl_2 and $CaCl_2$ CEs (n = 43) over Time[a]

		SCl_2		$CaCl_2$
Step	Time	Correct (%)	Incorrect (%)	Attempted Application (%)
1. Predict bonding or lone pair distribution	*T1*	65	21	77
	T2	70	16	63
	T3	44	12	35
2. Account for bond polarity	*T1*	58	9	67
	T2	72	0	67
	T3	72	2	58
3. Describe geometry	*T1*	53	14	56
	T2	47	16	44
	T3	33	21	33
4. Use geometry to judge net polarity	*T1*	21	9	19
	T2	19	9	16
	T3	21	12	12

[a] Remaining percentage represents no attempt made.

Of the 43 students, 28% (12 individuals) applied covalent bonding ideas consistently to $CaCl_2$ across all three time points. Twenty-one percent (n = 9) were consistently

Table 5. Frequency of Bonding Model Enacted for SCl_2 and $CaCl_2$ Longitudinally ($n = 43$)

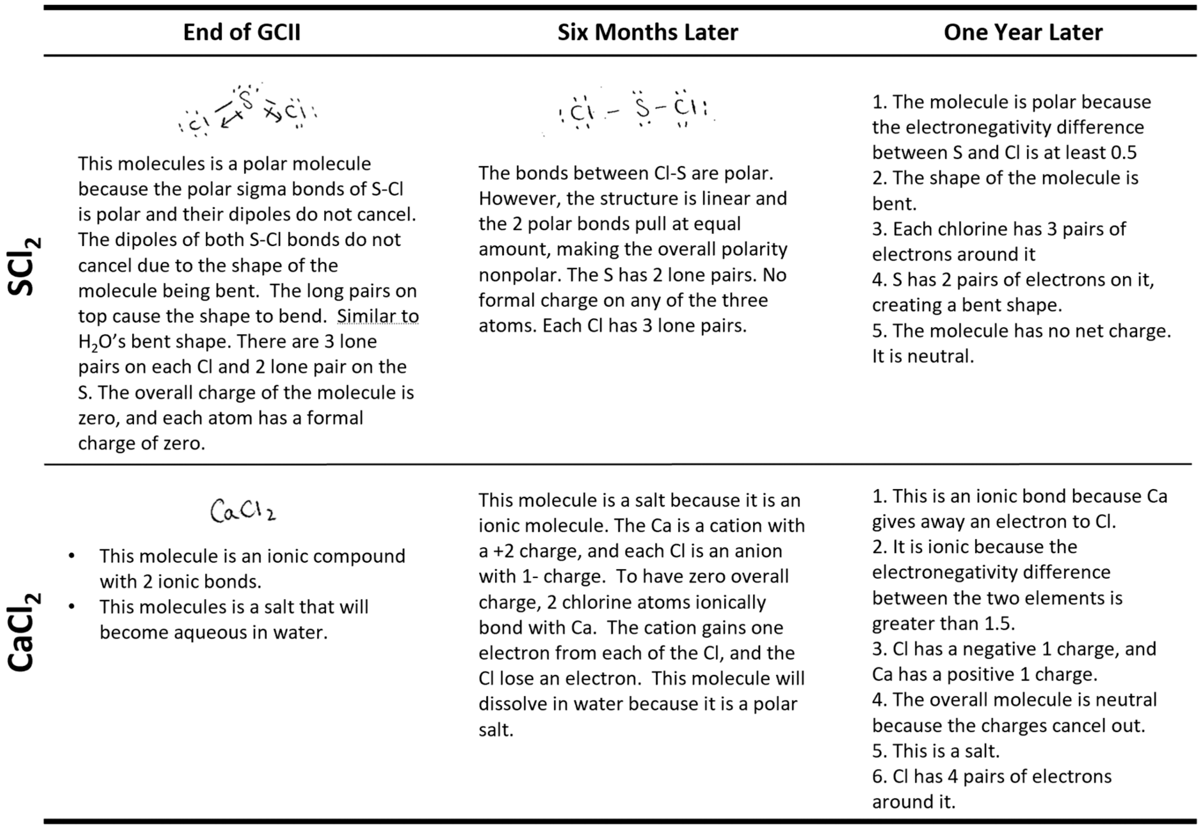
Bonding Model	Time	SCl_2 (%)	$CaCl_2$ (%)
Covalent	*T1*	88	58
	T2	93	42
	T3	91	42
Ionic	*T1*	2	5
	T2	2	12
	T3	0	21
Dissonant	*T1*	7	33
	T2	2	44
	T3	5	28
Insufficient	*T1*	2	5
	T2	2	2
	T3	5	9

dissonant, never moving to either just covalent or just ionic. Nineteen percent ($n = 8$) oscillated between covalent and dissonant models for $CaCl_2$ across time.

Only one single respondent consistently treated $CaCl_2$ as ionic across all three time points (Figure 8). This case is illustrative as an extreme outlier. The SCl_2 responses demonstrate the amount of detail provided by this student when describing a covalent compound, determining geometry and polarity at each time point (although the conclusions about geometry and polarity change across time). The responses for $CaCl_2$ are noticeably different. At all three time points, the respondent indicates the compound is ionic or has ionic bonds and is a salt. At TP1 and TP2, water solubility is also noted. There is more detail at TP2, stating the charges on each ion and attempting to explain how an exchange of electrons leads to net overall charge of zero. However, they incorrectly describe calcium as gaining electrons from chlorine. At TP3, this is reversed in the first item on their list ("Ca gives away an electron to Cl") and they also incorrectly provide +1 as the charge for calcium. Describing a transfer of electrons is more sensible in the context of $CaCl_2$ and is often presented in school science as an initial model for ionic bonding, although this model has been described as not ideal.[8,16] Electronegativity and its relationship to compound classification are explicitly mentioned only at the final time point. Note that despite the consistent labeling of $CaCl_2$ as ionic and discussion of dissolution and ions, the student also employs the word "molecule" at all three time points when referring to $CaCl_2$.

RQ3: How Does Participation as an Instructional Peer Leader Influence How Students Employ Bonding Ideas to Describe Ionic and Covalent Compounds?

To explore whether additional or different learning opportunities might affect the ability to apply covalent and ionic bonding ideas more successfully, responses of students who served as peer leaders ($n = 15$) were also monitored over time. Table 6 lists the percentages of leaders who enacted each type of bonding model over time. It is helpful to recognize that three people represent 20 percentage points. Compared to the general chemistry respondents described above, leaders as a whole were more likely to implement both covalent and ionic models correctly and consistently. Nevertheless, a little more than half of the peer leaders were drawn to analyzing $CaCl_2$ incorrectly with either a dissonant or covalent perspective. Furthermore, leaders also provided inappropriate representations and predictions like the general chemistry students described previously. For example, eight leaders indicated



	End of GCII	Six Months Later	One Year Later
SCl_2	This molecules is a polar molecule because the polar sigma bonds of S-Cl is polar and their dipoles do not cancel. The dipoles of both S-Cl bonds do not cancel due to the shape of the molecule being bent. The long pairs on top cause the shape to bend. Similar to H_2O's bent shape. There are 3 lone pairs on each Cl and 2 lone pair on the S. The overall charge of the molecule is zero, and each atom has a formal charge of zero.	The bonds between Cl-S are polar. However, the structure is linear and the 2 polar bonds pull at equal amount, making the overall polarity nonpolar. The S has 2 lone pairs. No formal charge on any of the three atoms. Each Cl has 3 lone pairs.	1. The molecule is polar because the electronegativity difference between S and Cl is at least 0.5 2. The shape of the molecule is bent. 3. Each chlorine has 3 pairs of electrons around it 4. S has 2 pairs of electrons on it, creating a bent shape. 5. The molecule has no net charge. It is neutral.
$CaCl_2$	$CaCl_2$ - This molecule is an ionic compound with 2 ionic bonds. - This molecules is a salt that will become aqueous in water.	This molecule is a salt because it is an ionic molecule. The Ca is a cation with a +2 charge, and each Cl is an anion with 1- charge. To have zero overall charge, 2 chlorine atoms ionically bond with Ca. The cation gains one electron from each of the Cl, and the Cl lose an electron. This molecule will dissolve in water because it is a polar salt.	1. This is an ionic bond because Ca gives away an electron to Cl. 2. It is ionic because the electronegativity difference between the two elements is greater than 1.5. 3. Cl has a negative 1 charge, and Ca has a positive 1 charge. 4. The overall molecule is neutral because the charges cancel out. 5. This is a salt. 6. Cl has 4 pairs of electrons around it.

Figure 8. Comparison of one student's responses to the SCl_2 and $CaCl_2$ CEs over time. Responses have been transcribed verbatim for readability.

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Table 6. Frequency of Bonding Model Classification for Peer Leaders over Time ($n = 15$)

Bonding Model	Time	SCl_2 (%)	$CaCl_2$ (%)
Covalent	*T1*	100	20
	T2	87	20
	T3	93	0
Ionic	*T1*	0	40
	T2	0	40
	T3	0	47
Dissonant	*T1*	0	40
	T2	13	40
	T3	0	53
Insufficient	*T1*	0	0
	T2	0	0
	T3	7	0

$CaCl_2$ had single bonds, seven predicted it had a linear geometry, and five predicted it was nonpolar overall. Classifications did not change substantially over a year's time.

DISCUSSION

Broadly, students primarily enacted covalent ideas to describe SCl_2, an appropriate application of bonding model, but most responses for $CaCl_2$ were covalent or dissonant and thus inappropriately applied. These patterns held longitudinally with only a slight increase in purely ionic descriptions for $CaCl_2$ over time. Students were generally successful in recalling the procedural aspects of describing covalent structure, including electron position, bond polarity, geometry, and overall polarity. However, successful recall of the procedure did not always produce appropriate responses, with students incorrectly predicting properties or contradicting themselves. Particularly, application of the Lewis approach to $CaCl_2$ was widespread whether it was recognized as an ionic compound or not. The evidence here suggests that the change in compound formula from SCl_2 to $CaCl_2$ failed to cue a large portion of students. While different labels provided in the prompts ("molecule SCl_2" or "compound $CaCl_2$") for the longitudinal study could have cued students to the distinction, the results and follow-up study which used "substance" in both prompts suggest this went unnoticed. Students recalled information that should suggest that an ionic bonding model is appropriate (e.g., large electronegativity differences or the pairing of a metal and nonmetal), but this did not necessarily lead to classifying it as ionic. Even in instances where students recognized $CaCl_2$ as ionic, they often still treated it like a covalent compound by applying a molecular approach. Among responses classified as ionic, students would provide ion charges, describe $CaCl_2$ as a soluble salt, or reference the electronegativity difference. However, in comparison to the level of description provided for a covalent compound (e.g., structure, geometry, polarity), there was less breadth and depth in student descriptions of $CaCl_2$ even when identified as ionic. For both substances, student responses focused almost exclusively on structural features at the particulate level. One might expect that issues with depth or appropriate classification might be resolved over time and more course experience; however, Figure 5 and the exemplar responses in Figures 6−8 suggest that is not necessarily the case.

To the extent that this study's population of students is representative, many students do not leave general chemistry with a strong, functional conceptual understanding of ionic bonding. The consistent misapplication of covalent bonding ideas suggests that covalent bonding is a robust conceptual framework for students. This robustness is evident wherever students provide multiple statements invoking ionic bonding ideas for $CaCl_2$, but then draw lines between elements in their structures or count the bonds. Previous research has found that students in multiple countries and educational levels employ a "molecular" conceptual framework to think about ionic bonding.[8,15,23] Other studies have shown that students do not have the language to talk about ionic interactions and tend to rely on covalent language. For example, treating all substances as "molecules" and believing bonds to be "between" atoms linking them together.[32−34] The students in this study occasionally used language similarly. In Butts and Smith's[21] study of student understanding of the structure of solids, they noted that students saw no contradiction in referring to ionic bonding in sodium chloride while still talking about NaCl molecules. Students' limited vocabulary is corroborated by the data in this study: charge, electronegativity difference, and dissolution were the few commonly invoked ionic bonding ideas, but crystal lattices or electrostatic attractions were not mentioned.

It is possible that the curriculum experienced by students did not provide sufficient time or focus for developing a strong explanative model (e.g., for ionic bonding). In the data set here, there is evidence that students at one of the institutions exhibited use of covalent and dissonant models for $CaCl_2$ more frequently than at the other institution. Course assessments were inspected as an indirect indicator of curriculum focus. At the former institution the most explicit discussion of ionic and covalent bonding happened in General Chemistry I about six months before administration of the first survey. Students were assessed on ionic nomenclature, ionic compound solubility, and comparison of phase change points between ionic and covalent compounds. General Chemistry II, from which participants were recruited, started with a Lewis/VSEPR review leading into valence bond theory and hybridization. Through the second semester, ionic and covalent materials are incorporated into discussion of equilibrium, acid/base chemistry, kinetics, and thermodynamics. At the other institution, students were introduced and assessed on ionic nomenclature, solubility reactions involving ionic compounds, and the Born−Haber cycle in General Chemistry I. In General Chemistry II, properties of ionic compounds were emphasized in covering ion-dipole intermolecular forces, the Van't Hoff factor pertaining to colligative properties, and an equilibrium description of the solubility of ionic compounds. The greater attention to ionic behavior at the second institution may have led to fewer instances of applying a covalent model to $CaCl_2$, but the study design does not allow conclusive examination of this hypothesis. Others have also argued that chemistry instruction and textbooks present bonding in a way that leaves it widely open to interpretation,[35−37] and students ultimately have difficulty making appropriate and meaningful connections.[1,2,8]

A second perspective is that students have not generally been engaged in learning about bonding in a meaningful way. Meaningful learning requires the coordination and active linking of concepts from various contexts in a coherent and meaningful manner.[24] Taber[25] previously argued that instruction should help students view a subject as a set of linked concepts with explanatory power rather than isolated facts to be memorized. When students acquire facts and procedures without conceptual coherence, they fail to learn meaningfully. In considering this data, one may interpret that the students have a meaningful understanding of covalent bonding and do not have a meaningful understanding of ionic bonding. Indeed, analysis of the responses in this study suggest limited evidence that the students learned about ionic compounds in a meaningful way. Rather, many students applied the Lewis approach as a memorized heuristic: start with a chemical formula, allocate electrons to positions according to a set of rules, and interpret the consequences in terms of other heuristics regarding polarity and spatial positioning. This heuristic was seemingly applied to any compound offered. In contrast, there is no similar structural heuristic process that is typically offered in general chemistry for ionic substances. This is akin to mathematical algorithmic problem solving and is not new to chemical education: students have been shown to rely on memorized processes in various contexts.[38] While heuristics can be productive tools, research across STEM indicates heuristic reasoning triggered by surface features of problem-solving tasks is often the source of random or shallow student answers. This includes, for example, answers based on features first noticed or most explicit, using a single cue to make a choice or provide a plausible explanation (e.g., molecular polarity based only on bond polarity[39]), or using generalized patterns to draw conclusions before considering all variables involved.[40−42]

Additionally, it is surprising that these patterns remain generally the same longitudinally. After general chemistry, students do not completely "lose" their bonding ideas over the following year. Rather, and more importantly, students who leave general chemistry with incorrect or vague ideas seldom have them addressed and their understanding remains mostly unchanged. A year later most responses are not richer or more nuanced, which one would expect (and hope) of students who take additional chemistry or chemistry-adjacent science courses (Figures 6 and 7, for example). If anything, students' senses of "ionic" seem to fade over time. This indicates that students did not and have not found utility in ionic bonding, which suggests ionic bonding ideas were memorized rather than organized conceptually in a meaningful way. A previous case study of a single student focused on their developing understanding of chemical bonding over two years of college chemistry.[43] The study illustrated that a student can simultaneously hold and employ multiple explanatory principles about chemical bonding over many months across a variety of contexts, suggesting that conceptual development involves a gradual shift in preferred explanatory principle as a learner encounters new principles and examples where previous forms of explanation are unsuccessful or insufficient. In two years' time, the student failed to fully integrate some ideas related to chemical bonding and was further reluctant to abandon those explanatory principles perceived as successful. This and the results here argue for the necessity of longitudinal studies of conceptual development and greater awareness of how chemistry curriculum structures reinforce or weaken particular ideas and reasoning patterns from a meaningful learning perspective.

The 15 upper-level chemistry students, who were also peer leaders, were more likely to identify $CaCl_2$ as ionic; approximately double the frequency of the general chemistry students. They were also half as likely to apply purely covalent ideas to $CaCl_2$, but even so 40−50% of leaders provided responses classified as dissonant. Taken together this suggests that leaders were overall more likely than students completing general chemistry to recognize $CaCl_2$ as an ionic substance, but they still did not have clear models of ionic bonding. Students chosen to become peer leaders typically performed well in general chemistry (often a grade of "B" or better), which suggests this issue impacts students of all performance levels.

LIMITATIONS

As this was a voluntary research study, participants were not asked or expected to prepare by studying as they would for an exam and may have put in less effort. Lewis et al.[30] previously demonstrated stronger validity evidence for responses when CEs were given in class than if given as homework assignments. The current research context is more like the latter, although the investigation on ordering effect occurred within an exam with comparable results. It is also important to note that participants provided minimal explanation for their statements at all time points and the lack of elaboration obscures how much detail participants initially recalled and/or retained. This limits what claims can be made about the durability of the links participants make in response to the prompts.

Longitudinal data collection was impacted by the abrupt transition online due to the COVID-19 pandemic. Collecting data online resulted in a steep drop in participants providing drawings, from 95% of students providing at least one drawing at TP1 and TP2, to 33% at TP3. Peer leaders similarly went from 100% providing at least one drawing to 0% at TP3. Students' drawings provided significant insight into their ideas about intramolecular bonding and thus likely impacted classification. There is also the potential that participants used additional resources during the online administration; however, this does not bear out in a marked difference in the content and quality of responses.

It is interesting to note that language, sentence structure, and features in drawings remained the same or similar across several months for some students. This suggests the possibility of some amount of rote recall of previous responses to the same prompt. This has implications for any studies or assessments using repeated prompts to assess student knowledge longitudinally and bears investigation.

INSTRUCTIONAL IMPLICATIONS

Student responses in this study revealed a consistent misapplication of the covalent bonding model to ionic compounds, including the determination of the Lewis dot structure, molecular geometry, and polarity. In most general chemistry textbooks and courses, students are typically introduced to the idea of molecules early and considerable attention is spent developing a covalent bonding model. Given its explanatory ability for understanding chemical and physical properties, this attention can be readily justified. However, little textbook real estate, class time, or assessments are spent on differentiating molecules from other classes of substances.

Without attention to the limits of a covalent bonding model, students may apply covalent bonding ideas like Lewis structures and geometry to compounds where they are not applicable. Misapplication of the covalent model, for example by forcing it onto $CaCl_2$ (such as in Figures 3, 4, 6, and 7), also has the potential to establish this as a strategy for all compounds moving forward. Thus, failing to emphasize the limits of models may lead to not only misapplication of covalent bonding to noncovalent compounds, but also potentially to students' altering their mental model of covalent bonding in nonproductive or counterproductive ways when they attempt to fit their mental model of covalent bonding to noncovalent compounds.

One suggestion is purposeful discussion of the limits of models. For example, instructors could present a bonding model alongside examples of compounds where the model is and is not applicable. This would facilitate discussion about the model's limits and illustrate how these demarcations are made. When assessing molecular geometry, students can be instructed to first determine whether VSEPR is applicable to each compound and if it is appropriate to determine the molecular geometry. Assessments can then include items that require distinguishing among covalent, ionic, and metallic compounds, before assigning molecular geometry to the covalent compounds. Additionally, other assessment formats can highlight the limits of models. For example, the use of CEs across the curriculum of general chemistry have shown students overlooking the limits of models across multiple topics in chemistry,[44] and these responses give instructors an opportunity to give students feedback on their ideas or lead a whole class discussion on where a topic is applicable or not. Another approach is to offer practices and assessments that mix questions from the current and previous chapters to avoid presenting and assessing topics in a siloed fashion,[45] which provides few opportunities to determine if previously learned models are applicable in new contexts. We cannot comment directly on the effect of employing alternative curricular approaches (e.g., spiral curriculum, learning progressions) on developing students' explanatory models of chemical bonding, but the results here and those of previous studies[2,4,43] suggest future work should consider the impact of curriculum on students' use of bonding models.

A final important observation is that extensive application of covalent bonding ideas to an ionic compound remained a year out from the end of students' general chemistry instruction, even with intervening chemistry and biology courses. This suggests that students in subsequent contexts, like organic, analytical, or biochemistry, conceptualize ionic substances as ionic-in-name-only. To the extent that the students and instructional environments in this study are representative of general chemistry learners, it seems that our typical approaches to teaching ionic bonding make a faint impression, and certainly not a meaningful one.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00188.

Coding Criteria (Tables S1, S2) (PDF) (DOCX)

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Notes

The authors declare no competing financial interest.

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