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Student Understanding of Intermolecular Forces: A Multimodal Study

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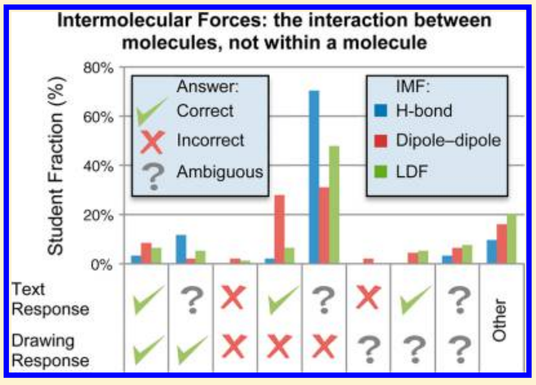
S *Supporting Information*

ABSTRACT: The ability to use representations of molecular structure to predict the macroscopic properties of a substance is central to the development of a robust understanding of chemistry. Intermolecular forces (IMFs) play an important role in this process because they provide a mechanism for how and why molecules interact. In this study, we investigate student thinking about IMFs (that is, hydrogen bonding, dipole−dipole interactions, and London dispersion forces) by asking general chemistry college students to both describe their understanding in writing and to draw representations of IMFs. Analysis of student drawings shows that most students in our study did not have a stable, coherent understanding of IMFs as interactions ***between*** molecules. At least 55% of the students in our study unambiguously represented each IMF an interaction or bond ***within a single molecule***, while only 10−30% of students represented each IMF as an interaction between molecules. Furthermore, the majority of students (59%) were not consistent in the way that they represented the different IMFs (as within or between). That is, their representations varied depending on the IMF. Student written descriptions of intermolecular forces were typically quite ambiguous, meaning that it was not possible to determine from the student description alone whether the student understood IMFs as bonds or interactions. It was only when the student's representation was consulted that we could determine whether a particular student had an appropriate understanding of IMFs. We believe that in situations where spatial information is crucial, free-form drawn representations are more likely to provide meaningful insight into student thinking.



KEYWORDS: *First-Year Undergraduate/General, Hydrogen Bonding, Chemical Education Research, Communication/Writing, Noncovalent Interactions*

FEATURE: Chemical Education Research

■ INTRODUCTION: THE IMPORTANCE OF INTERMOLECULAR FORCES

The study reported here is part of a series of studies on students' understanding of structure and property relationships.[1−5] Our goals for this research are to (i) investigate the difficulties that students have and (ii) develop assessment strategies for the steps involved in learning to use structures as models to predict and explain properties. Our ultimate goal is to use the data from these investigations to develop evidence-based approaches to teaching and learning that will improve understanding of this important construct. In this study, we focus on student understanding of intermolecular forces (IMFs), specifically hydrogen bonding, dipole−dipole interactions, and London dispersion forces (LDFs). As we have previously noted,[2] the pathway that connects a molecular structure to the properties of a substance requires a long chain of inferences. Ideally, a student should be able to construct and then use a structure (by understanding that the shape and electron distribution in the molecule determine molecular polarity) to make deductions about interactions between molecules (intermolecular forces) that govern both physical and chemical properties. Each of these tasks is difficult in itself[2] and connecting them to make predictions about properties is highly demanding for students. In essence, we are asking students to move from using Lewis structures as representations to using them as models with which they can predict and explain properties.[6] If this shift in perspective is not made explicit to students, then even the simple task of constructing the representation may become difficult for many students because they may not see the purpose of drawing structures. Students' knowledge of structure−property relationships is not conditionalized and is therefore often inert; that is, their knowledge is not useful for this purpose. For example, we have shown that even organic students struggle to construct Lewis structures[1] and have proposed that, while a rules-based approach to structure drawing provides a deceptively easy way to teach this skill, if students do not understand *why* they are learning to draw structures, then the tenets for meaningful learning[7,8] are not met and students do not connect and reinforce skills that do not seem relevant to them. This is supported by our findings that, even after organic chemistry, many students do not understand how to use Lewis structures to predict anything other than surface-level features of a molecule.[1,2] Many students have not

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progressed from the idea of a structure as a representation to the idea of a structure as a model.

In another study,[4] we interviewed students about how they used structural representations to predict properties. In this environment, where prompting and further elicitation of student ideas was possible, it became clear that, for many students, structure and properties were not explicitly connected. Typically, students tended to rely on heuristics and surface-level features of molecules to make predictions rather than using the sequence of inferences that they had been taught. In this study,[4] students usually did not use IMFs as a construct to help them reason about properties such as relative boiling points, even when specifically asked probing questions designed to elicit such ideas. Although some students used terms such as hydrogen bonding or London dispersion forces, few students used them in anything other than a rote fashion. Only two students invoked London dispersion forces to explain the difference in boiling point of methanol and ethanol, while most instead relied on rules such as "the more bonds the higher the boiling point", which was sometimes coupled with the idea that covalent bonds break during phase changes.[4] This finding supports the work of Talanquer and co-workers who have reported that heuristic reasoning is prevalent in a range of tasks such as identifying acids and bases[9] and predicting relative melting and boiling points and solubility.[10] Since many students did not seem to understand the need to incorporate IMFs into their reasoning about bulk properties of molecular species, we decided to investigate what students do understand about IMFs.

■ PRIOR WORK ON STUDENT UNDERSTANDING OF IMFS

The study described here is the first of a series of papers[11] designed to probe students' understanding of intermolecular forces and how students write about and construct representations of IMFs; that is, the interactions between separate molecules that govern the properties of those molecules such as boiling point and acid−base reactivity. Prior research involving IMFs has focused specifically on hydrogen bonding[12−14]—perhaps because of its importance in the properties of water and in biological systems—or more broadly on the general topic of IMFs.[15,16] Most of these studies have found that some students are (perhaps understandably) confused about the nature of the hydrogen bond. We should not be surprised when students have difficulties with the difference between covalent bonds and intermolecular forces, especially when they are exacerbated by the fact that an intermolecular force is named "bond". For example, Henderleiter and co-workers interviewed students about their understanding of hydrogen bonds and found that, of the 22 organic students, four of them indicated that the hydrogen bond was the covalent bond between an O and H in the same molecule.[12] Similarly, Peterson and co-workers, using a two-tier multiple choice diagnostic test, reported that 23% of grade 12 high school students indicated that intermolecular forces were the forces within a molecule.[15] Using this same diagnostic test, other researchers found that 35% of students in Singapore also displayed this idea.[16] While there are other well-documented problems with student understanding of hydrogen bonds (for example that any molecule containing hydrogen and oxygen can hydrogen bond[13]), it is the notion that an intermolecular force such as hydrogen bonding is actually a covalent bond that is most problematic.

If students believe that IMFs are interactions within molecules, this idea must affect their models of phase change. For example, if a student learns that water has a relatively high boiling point because the strong hydrogen bonds must be overcome, then we should not be too surprised when students' phase change models revolve around breaking actual covalent bonds.[4,12,13,17−19] Barker and Millar found that while the students they studied from age 16 through 18 improved in their understanding of hydrogen bonding over time, none of the students in the study invoked any other IMFs to explain trends in boiling point.[17] As discussed earlier, our own work has supported this finding and extends it to students at the college level in general and organic chemistry.[4] Schmidt and co-workers reported that upper secondary school students in Germany had great difficulty predicting boiling points of organic compounds and very few (15%) used appropriate reasoning when asked to explain their answer to a multiple-choice question.[13]

This paper describes an investigation into the external representations that students use to communicate about IMFs. Rather than hoping to prompt discussion of IMFs in a context with a phenomenon such as predicting relative boiling points (as we had done previously and which we now know is unlikely to happen[4]), we wanted to ask students specifically about their understanding of IMFs. As noted, earlier studies with IMFs have most often used forced-choice instruments.[13−16] Although it is impossible to "know" exactly what a student understands, it is important to use the best evidence available to draw conclusions.[20] For us, this means having students construct their own responses rather than restrict them to choosing an answer from a list. While multiple-choice items and diagnostic two-tier instruments are fast and reliable, it has been shown that students can answer these questions without recourse to appropriate scientific thinking.[21] For example, previous research has shown that students were able to rank the boiling points of a range of compounds without thinking about intermolecular forces[4,18] and instead used heuristics that may have led them to the correct answer but were scientifically flawed.

■ THEORETICAL PERSPECTIVE

The importance of multimodal learning, that is, providing both visual (pictures) and verbal (words) support for student learning, has long been emphasized. It has been proposed that instructional materials providing both words and pictorial representations are more effective because student understanding can be enhanced by the addition of nonverbal knowledge representations.[22] However, there is less research on how students use multimodal (pictorial and verbal) representations to explain and represent their understanding. It has been proposed that drawing can provide a "window into student thinking"[23] and there are a number of studies[23−28] that have investigated the effectiveness of drawing in support of learning in science. Drawing should be particularly helpful in identifying student ideas about spatial information; for example, understanding how they view the relative positions of molecules and the forces that act between them.

Similarly, having students write about their understanding can also provide useful insights into student thinking. Certainly both modalities require students to construct answers and thus make their ideas explicit. There are several studies that compare two groups of student responses: those who draw and those who write. For example, Gobert and Clement compared responses for student who drew diagrams or produced text summaries about plate tectonics.[29] Similarly, Akayagun and Jones looked at the ways that students wrote about or constructed representations of equilibrium systems.[30] Both studies found that the representations students constructed tended to emphasize different features

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than the written explanations. However, in neither study were students asked to both write and draw so it was not possible to compare a particular students textual explanations and drawings.

Our goals with this study were to investigate how both writing and drawing about IMFs can provide us with insight into how students understand this concept. Therefore, students were asked to both construct a representation of an IMF (i.e., draw three structures of ethanol to show how they interact) and discuss their understanding of that particular IMF in words. That is, we asked students to use more than one modality to answer questions about IMFs in hopes that it would provide us with a more nuanced picture of their understanding than either writing or drawing alone.

The study was designed to address three research questions:

RQ1: How do students represent IMFs in free-form drawings?

RQ2: How do students discuss and describe IMFs in open-ended written responses?

RQ3: How do students' written explanations compare to their drawn representations?

■ METHODS

Student Population

The participants in this study consisted of a subsample of students from a larger population of 1600 students enrolled in general chemistry at a mid-sized public southeastern research university (Cohort 1, Fall 2011−Spring 2012, $N = 94$). An additional cohort from the following year was included in this study for replication purposes (Cohort 2, Fall 2012−Spring 2013, $N = 160$). The freshman population at this university is approximately 48% female and 52% male with the majority of students, 84%, identifying as white. The average ACT score for incoming freshman ranges from 26 to 31 and the mean SAT score is 1246. While the general chemistry course at this university was traditional in content (i.e., taught using a commercially available text), the course had been revised to include a more conceptual approach and some sections of the courses employed reformed pedagogies such as the use of clickers and in-class group quizzes. Students also completed online homework assignments using a commercially available homework system (Mastering Chemistry[31]). The common examinations for these courses were exclusively multiple-choice and, at the end of a full academic year, the American Chemical Society (ACS) nationally normed general chemistry examination[32] was administered as the final exam. Students in this course typically score around the 75th percentile on the ACS general chemistry exam. All the students included in this study consented to participate in this research by signing informed consent forms. Demographic information for each cohort is provided in Supporting Information.

■ DEVELOPMENT OF THE INTERMOLECULAR FORCES ASSESSMENT (IMFA)

The Intermolecular Forces Assessment (IMFA) was designed to elicit students' understanding of IMFs by asking them a range of questions that probe the way students think about IMFs. It was developed based on responses from interviews with general chemistry and organic chemistry students where students discussed how they used structural representations to help them understand phase changes.[4] The representations that students constructed along with their verbal descriptions provided us with insight into how the students were thinking about these processes. Interim versions of the IMFA were piloted in student interviews and revised for clarity where necessary. The final version (Box 1) was administered to 68 students in a pilot study and was then used in the studies reported here.

Box 1. Items Included on the Intermolecular Forces Assessment

1. What is your current understanding of the term "intermolecular forces"?
2. List all types of intermolecular forces that you know of below and please define each.
3. Please give example(s) of a compound that would exhibit the intermolecular force(s) that you listed previously. Be sure to list the intermolecular force(s) that the compound is representing.

4−6. What is your current understanding of the terms hydrogen bonding, dipole−dipole interactions, and London dispersion forces?

7−9. Please draw and label a representation below that clearly indicates where the hydrogen bonding is present for **three** molecules of CH_3CH_2OH. In the box, please describe, in words, anything you were unable to adequately represent in your drawing. If you do not think this interaction is present, please write "not present".

Items 8 and 9 are similarly phrased and ask for representations of dipole−dipole and London dispersion forces, respectively. An example showing the question layout is included in Supporting Information.

The IMFA is designed to explore the how students think about and represent IMFs. Items 1−3 ask students for general examples and explanations of IMFs without any specific prompts. In this way, we are able to capture students' spontaneous responses without prompting them about a particular IMF. For example, students are asked to explain what they understand by the general term intermolecular forces, which IMFs they know about, and to provide an example of a substance that would exhibit those IMFs. In items 4−9, students are asked specifically about hydrogen bonding, dipole−dipole and London dispersion forces, both by explaining what they understand by these terms (items 4−6) as well as constructing drawings or representations (items 7−9) that would show the presence of specific IMFs (if present).

Note that students were explicitly asked to draw three molecules and the term **three** was bolded, since in early iterations of the IMFA many students drew only one molecule. Ethanol was selected as the target for these items because it is a relatively simple molecule that is capable of exhibiting hydrogen bonding, dipole−dipole, and London dispersion forces (LDFs). Students were asked to draw structures of ethanol, but were given structural cues (CH_3CH_2OH) so that most students in this study were able to construct a reasonable (recognizable) representation.

The IMFA was administered to both cohorts of students at the end of their second-semester of general chemistry (GC2) to ensure that all students had been exposed to, and tested on, the relevant material. The IMFA was administered outside of lecture in the laboratory setting (which students take concurrently with lecture). Students received participation points for at least attempting to complete the IMFA. None of the instructors for the course were involved in data collection or analysis process. Research and teaching assistants collected all

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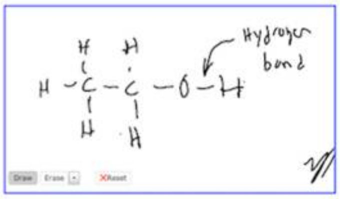
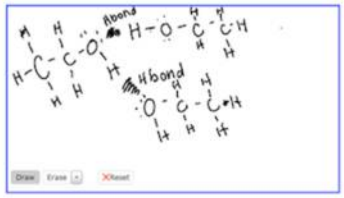
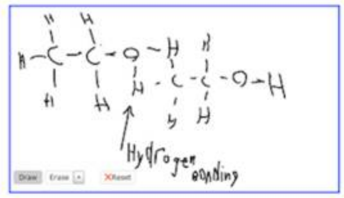
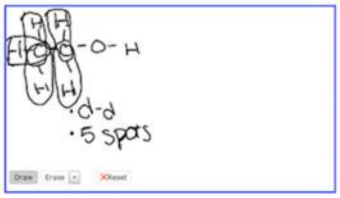
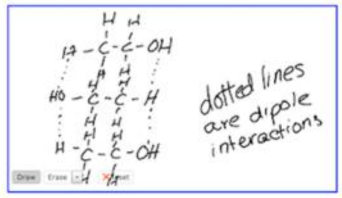
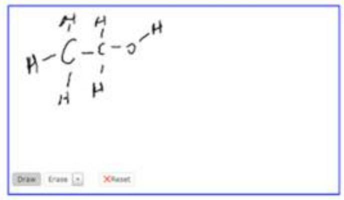
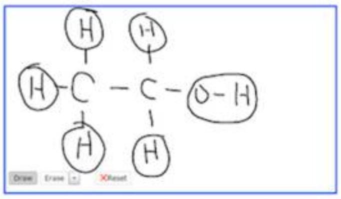
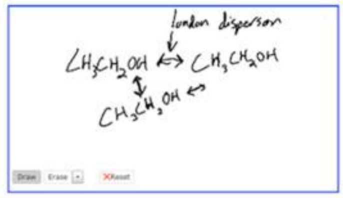
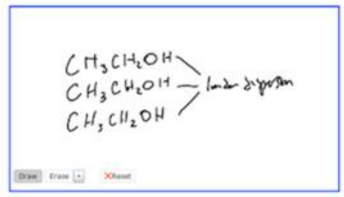
Table 1. Coding Examples for Student Drawings Demonstrating Understanding of Selected Types of Intermolecular Forces

IMF Type	Code for IMFA Response Drawings Characterizing IMF Locations: Within the Molecule	Between Molecules	Ambiguous
Hydrogen Bonding			
Dipole–Dipole Interactions			
London Dispersion Forces			

student responses on iPads and tablet PC's using the online software platform *beSocratic*, which allows collection of both free-form student drawing and text inputs.[33,34] That is, we asked students to both draw representations of IMFs and explain the IMFs in words. Using this system, we prevented students from returning to any prior items once they moved forward so that students were not able to alter their answers as they progressed through the assessment. In this study, we focus on the student responses to items 2 and 4–9. Drawings (items 7–9) from both Cohorts 1 and 2 were analyzed, and written responses (items 2, 4, 5, and 6) were analyzed for Cohort 1.

■ DATA ANALYSIS: DRAWINGS (ITEMS 7–9)

The students' responses were analyzed using postanalysis tools in *beSocratic*.[33,34] The program records each student's drawing input step-by-step, allowing the researcher to replay a student's response at a later time. The coding feature in *beSocratic* was used to code and store important actions or features of the drawing. An open-coding, constant comparison approach was used to develop an analysis scheme for students' IMF drawings.[35,36] Three researchers (a graduate student, a postdoctoral researcher, and a faculty member) analyzed and discussed the set of codes created from the open-coding process and agreed that there were only a few, distinct ways that students represented IMFs. The major code categories that emerged for drawings of each type of IMF were: within, between, ambiguous, and not present. If a student clearly indicated that the IMF occurred within a molecule (i.e., circling or pointing to a particular covalent bond), the drawing was coded as "within", while a "between" molecules code meant that a student made an indication that the IMF was located between two molecules, typically by marking the space between ethanol molecules (see Table 1 for examples using drawings of hydrogen bonding).

If the location of an IMF was not clearly specified (i.e., within or between), the response was coded as "ambiguous". An explicit indication that the IMF was not present received a "not present" code. In rare cases, a student might indicate an IMF as both a bond within a molecule as well as occurring between molecules. These students received a "within and between" code. A code used only for the question about LDFs, "states always present" was added because some students, rather than providing a representation, described (in words) that LDFs are something that all substances are capable of or is always present for compounds. Some students indicated in words that they were unsure how to answer the question or represent the structures. A "Student DK" (does not know) code was added. Examples of the codes "within", "between", and "ambiguous" for dipole–dipole and LDFs are provided in Table 1.

It should be noted that the codes "within" or "between" do not indicate whether a student's representation of the IMF was completely correct. For example, a student might indicate that the hydrogen bonded to carbon in the ethanol molecule would hydrogen bond with the oxygen of another ethanol molecule. In this analysis, the student would receive a "between" code for their depiction, even though their representation of hydrogen bonding is incorrect. We did analyze the "correctness" of the students' representations of hydrogen bonding. However, analyzing drawings for correctness of dipole–dipole and LDFs was more challenging because students may represent charge distribution or fluctuating dipoles in many different ways, or not include indications of the role of charges at all. Even variations in structural representations, such as Lewis structures, condensed structures, or particulate representations can blur the lines between what can effectively be considered "correct" versus "incorrect". Therefore, we do not report "correct" for these two IMFs.

To determine the inter-rater reliability of the analyses, one of the authors and another graduate student coded a random sample of 30 student drawings for each IMF giving a Cohen's Kappa of 1.0 for hydrogen bonding and dipole–dipole drawings, and a Cohen's Kappa of 0.96 for LDFs.

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Table 2. Examples of Text Codes Applied to Cohort 1 Students' Responses for Each IMF

IMF	Pseudonym	Quote	Text Code
Hydrogen Bonding	Tracey	"When the hydrogen atom from a molecule that has a large difference in electronegativity (i.e., hydrogen and oxygen) is attracted to a negative portion of another molecule."	Between
	Lindsay	"The strongest types of intermolecular forces and a hydrogen atom must be bonded to another hydrogen, nitrogen, oxygen or floride [*sic*]."	Ambiguous
Dipole−Dipole	Adelaide	"Stronger than London dispersion forces and occurs between two polar molecules"	Between
	Laura	"Intermolecular force in which dipoles within the molecule are attracted to each other and hold the molecule together...stronger than LDFs"	Within
	Marta	"Exhibited when the compound it [*sic*] polar, Its the second strongest"	Ambiguous
LDFs	Ann	"Forces between all molecules that get stronger with increasing molecule size."	Between
	Rebel	"Are present in all molecules. Small attractive forces."	Ambiguous
	Casey	"The weakest that are found in every molecular bond"	Within

DATA ANALYSIS: TEXT RESPONSES (ITEMS 2, 4−6)

Student text responses collected from items 2, 4, 5, and 6 were analyzed using the coding scheme we developed from the students' drawings as a guide. The text responses for item 2 (where students were asked in general to identify types of IMFs) were combined with the specific items 4−6, since many students wrote more detailed responses in item 2 and simply referred to their prior responses in items 4−6. For this study, each text response was coded specifically for a discussion of the *location* of the IMFs. That is, the text was analyzed to see whether the student discussed IMFs as occurring "within" the molecule or "between" molecules and was coded as "ambiguous" if the location was not specified. Using a similar approach for both the students' drawings and explanations allowed us to investigate in what ways students' text responses corresponded to their drawn representations. Examples of text responses and the corresponding codes are shown in Table 2.

To determine the inter-rater reliability of the analyses, one of the authors and a graduate student coded a random sample of 40 student text responses for both hydrogen bonding and LDFs, initially resulting in a Cohen's Kappa of 0.87 and 0.58, respectively. Researchers further discussed the coding scheme for LDFs to clarify how to classify a response as "within" a molecule or "ambiguous". For example, the response "temporary dipoles in molecules create a weak force" was originally coded as "within" by one coder and "ambiguous" by the other. After discussion, we determined that, while the student did mention dipoles within the molecule, it was not apparent where the student considered the weak force to be located. If a response did not explicitly state that *LDFs* were located within a molecule, then it would not be coded as "within". Both sets of codes resulted in a Cohen's Kappa of 1.0 after negotiation between researchers to clarify any discrepancies. Two of the authors coded a random sample of 40 dipole−dipole responses giving a Cohen's kappa of 0.95.

RESULTS AND DISCUSSION

RQ1: How Do Students Represent IMFs in Free-Form Drawings?

The analysis of Cohort 1 students' drawings of hydrogen bonding, dipole−dipole, and LDFs (items 7−9) are shown in Figure 1. Of the 94 GC2 students who completed the IMFA, only 15% (N = 14) of students correctly indicated that hydrogen bonding occurs **between** separate molecules. Of these students, only nine were completely correct in showing the hydrogen bonding interaction between an H (bonded to an O) in one molecule and an O in another molecule.

Of the remaining students, 72% (N = 68) clearly represented hydrogen bonding as an O−H bond within a single molecule of ethanol. In fact, 54% (N = 51) of students drew only one molecule or none at all (even though they were explicitly asked to draw three molecules). All but three of the drawings coded as within clearly depicted the IMF as the covalent O−H bond within a molecule of ethanol. While the idea that the term "hydrogen bonding" refers to the covalent oxygen−hydrogen bond within the molecule has been previously documented, the extent of this error has not. As discussed earlier, previous studies have shown a much lower prevalence of this idea ranging from 23−35% of students.[12,15,16]

While it is quite understandable that students might be confused about the term "hydrogen bonding", since the term "bond" is misleading, we found that student confusion extended to representations of both dipole−dipole and LDFs as well. Again only a small number of students drew dipole−dipole (11%, N = 10) and LDFs (12%, N = 11) as interactions between molecules. As we saw with hydrogen bonding, the majority of students (61%, N = 57) in Cohort 1 drew dipole−dipole interactions as occurring within the ethanol molecule and as did 55% (N = 52) for LDFs. Students' depictions of dipole−dipole and LDFs were somewhat more varied than those for hydrogen bonding. For example, in Table 1 (within, dipole−dipole) all of the C−H bonds are depicted as dipole−dipole interactions. Representations of LDFs include circling individual atoms (such as hydrogen in Table 1 (within, LDFs)), lone pairs of electrons on oxygen atoms, or bonds. In fact, of the students in Cohort 1 who drew LDFs occurring within the molecule, seven students circled every bond in the ethanol molecule, which may be related to the idea that "every substance has LDFs".

The IMFA was also administered to a second cohort of general chemistry students (Cohort 2) in the following year, and the results are also shown in Figure 1. While there was a slight increase in the number of Cohort 2 students who drew representations of hydrogen bonding and LDFs occurring between molecules, again the majority of these students' representations for hydrogen bonding (56%, N = 90), for dipole−dipole (58%, N = 93), and for LDFs (56%, N = 89) clearly indicated that the IMFs were located within a single molecule. We attribute the slight improvement to the fact that the instructors in the courses were now aware of our results for Cohort 1 and had emphasized IMFs more than usual in the following year.

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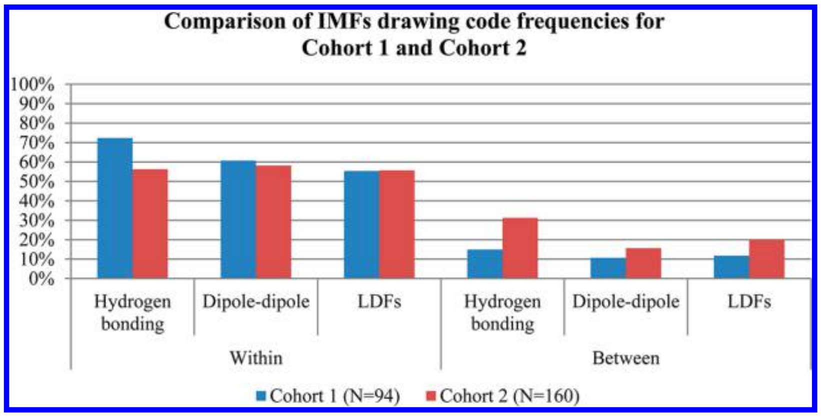

Figure 1. Code frequencies for students' representations of IMFs from Cohort 1 and Cohort 2.

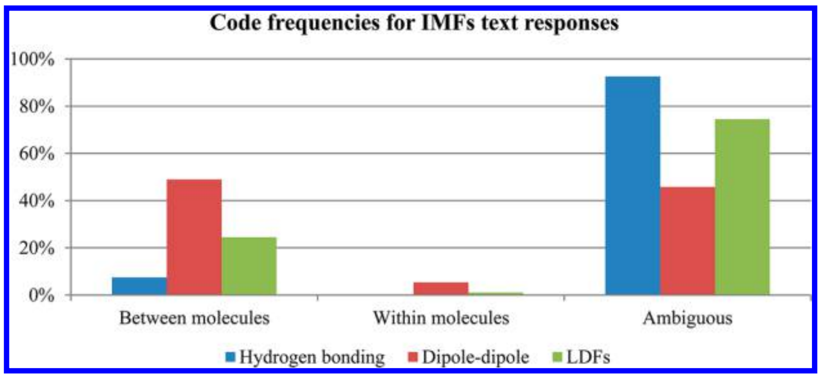

Figure 2. Code frequencies for students' representations of IMFs from Cohort 1 and Cohort 2.

RQ2: How Do Students Discuss and Describe IMFs in Open-Ended Written Responses?

Written responses about hydrogen bonding, dipole−dipole, and LDFs (items 2, 4−6) were analyzed for the students in Cohort 1 (N = 94), using a coding scheme similar to that for their drawings. Unlike the drawings where the location of IMFs, as either within a molecule or between molecules, was usually quite obvious, students' text responses were typically less explicit. Of the 94 students in Cohort 1, only 4% (N = 4) of students explicitly stated that IMFs occur between molecules for all three types of IMFs. Similarly only a few students stated explicitly that IMFs occur within a single molecule. Specifically, 5% (N = 5) of students stated that dipole−dipole occurred within a single molecule and only one student claimed that LDFs did the same. None of the students in Cohort 1 explicitly stated that hydrogen bonding occurs within a molecule. Indeed most students failed to make any reference to the location of IMFs at all, meaning that most responses received the ambiguous text code, as shown in Figure 2. It should be noted that an ambiguous code did not mean that a student's response was incorrect, but rather that it was missing a discussion of the location of the IMF.

Lindsay's ambiguous response for hydrogen bonding, shown in Table 2, is typical in that the elements involved and the strength of the IMF are discussed. Similarly, many students (for example, Rebel) provided ambiguous responses for LDFs. Not represented in Figure 2 are the 26% (N = 24) of students who explicitly stated in their written responses that LDFs are present for all molecules or always present. We suspect that this response may stem from students hearing their instructors talk about LDFs in a similar fashion. While it is true that all molecules are capable of interacting via LDFs, it is easy to imagine that students may understand this as a property of the molecule rather than of the interactions between molecules.

Interestingly, the written responses about dipole−dipole interactions did not follow the same pattern as those for hydrogen bonding and LDFs. A much larger group of Cohort 1 students (49%, N = 46) stated explicitly that dipole−dipole interactions occurred between molecules, shown in Figure 2. As discussed below, this is in contrast to the students' representations of dipole−dipole interactions where a majority of students drew structures showing dipole−dipole interactions *within* a particular molecule (Figure 1). While we do not know the reason why more students wrote about dipole−dipole interactions between molecules, like the responses for H-bonding and LDFs, the responses were somewhat superficial. It may be that the students had learned a definition of dipole−dipole that specifically included the idea that the interaction was between molecules.

One factor that made student written responses difficult to interpret was that students often appeared to use words without understanding their meaning. In addition to the term "intermolecular", students often used atom to mean molecule (or vice versa) and bond to mean IMF (or vice versa). For example, Rueben, as shown in Table 3, refers to a molecule of fluorine when discussing hydrogen bonding but he probably meant to describe an atom. This interchanging of atom and molecule has been in reported previously in work by Cokelez and Dumon.[37] The confusion between atom and molecule is fairly obvious here, but this mistake may not always be so clear. A student who confuses these terms might discuss an interaction between atoms but mean an interaction between molecules, an important distinction. Additionally, some students used the terms bond and interaction interchangeably. While a

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Table 3. Examples of Terminology Issues in Student Responses

Terminology Issue	IMF	Pseudonym	Quote	Text Code	Drawing Code
Atom vs Molecule	Hydrogen Bonding	Georgia	"hydrogen bonding- between a hydrogen atom on one molecule and either an oxygen, nitrogen, or fluorine of another atom"	Ambiguous	Between
		Rueben	"hydrogen bonds: a molecule of fluorine [*sic*], oxygen, or nitrogen bonded with a hydrogen"	Ambiguous	Within
		Regina	"Hydrogen bonds- an intermolecular force between a hydrogen atom and either an O or F molecule"	Ambiguous	Within
Bond vs Interaction	Dipole–Dipole	Thomas	Dipole–dipole is "a pretty weak bond between polar molecules."	Between	Within
		Ray	"Dipole–Dipole- bond between two molecules that is nonpolar"	Between	Ambiguous
	LDFs	Betty	LDFs are "A very weak bond that binds any two molecules, or parts of any two molecules, together."	Between	Ambiguous

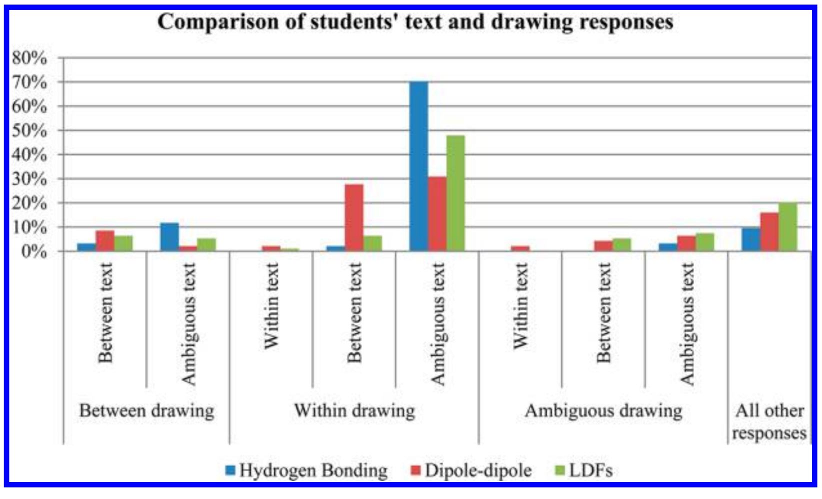

Figure 3. Comparison of Cohort 1 students' code frequencies for text and drawings of IMFs.

bond is a type of interaction, we usually do not refer to IMFs as bonds (except, of course, for hydrogen bonds!). Thomas, for example, discusses a bond between molecules but it is unclear whether he understands the difference between the terms bond and interaction and whether he is using the appropriate one in this scenario. Since student use of terminology can be imprecise, it can make it difficult to know what students mean from their writing alone, which often resulted in the students' text responses being considered ambiguous. Additional quotes from students where terminology becomes problematic are shown in Table 3.

RQ3: How Do Students' Written Explanations Compare to Their Drawn Representations?

Drawing and writing provide different approaches to eliciting student understanding and our use of similar codes for both modalities allowed us to compare the text and drawn responses. Most students constructed a drawing of an IMF showing its location explicitly within a single molecule, coupled with an ambiguous text description (for hydrogen bonding, 70%, N = 66; and LDFs, 48%, N = 45). Only 3% of students in Cohort 1 gave what would be considered an "ideal" answer for the location of hydrogen bonding by explicitly stating that hydrogen bonding occurred between molecules *and* drawing an interaction occurring between molecules. Comparisons of the major categories for drawing and written explanations are shown in Figure 3. We include here the "other" category, which also incorporates such answers as "not present" and "I don't know". (All combinations of text and drawing responses from students are provided in the Supporting Information.)

As discussed earlier most students were not specific about the location of IMFs in their written explanations; in fact, 93% (N = 87) of students' written responses for hydrogen bonding received an ambiguous code (Figure 2). It is only when we look at the drawings of hydrogen bonding that we can see what students are trying to explain. For example, Tobias and Maeby have similar explanations of hydrogen bonding, as shown in Table 4. It would be difficult to distinguish between their responses (knowing as we do that the term intermolecular is often misunderstood by students), without looking at their drawings, which show that Tobias understands hydrogen bonding as interactions between molecules, while Maeby does not.

Similarly for LDFs, the drawings provided more information than the writing. Consider, for example, Oscar and Rita in Table 5. Oscar described LDFs as "the simplest and weakest of the IMF" and Rita indicated that LDFs were "present in all molecules, but the one force in polar molecules. The weakest of the three". Again, upon viewing their drawings, it becomes clear that Oscar has an understanding of LDFs as interactions between separate molecules, while Rita does not.

Just as with hydrogen bonding and LDFs, few students (9%, N = 8) correctly described dipole–dipole as an interaction between molecules *and* provided an appropriate representation (Figure 3). Unlike hydrogen bonding and LDFs, however, 49% (N = 46) of students in Cohort 1 provided text responses for dipole–dipole that described the interaction as taking place *between* molecules (Figure 2). Despite this, 28% (N = 26) of Cohort 1 drew an explicit representation of dipole–dipole interactions as occurring *within* a molecule of ethanol while at the same time describing the interaction as occurring *between* molecules in their written response (Figure 3). For instance, Gene described dipole–dipole as an "intermolecular force formed between two dipole molecules that comes from different

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Table 4. Drawing and Text Comparisons for Tobias and Maeby

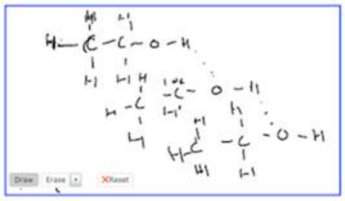
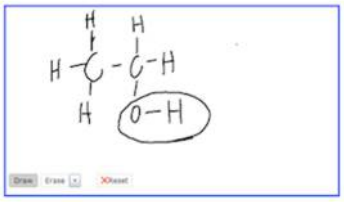
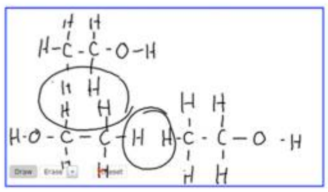
Pseudonym	Drawing	Quote
Tobias	 Between Molecules	**Hydrogen bonding** is "an intermolecular force between hydrogen and N O F. It is the strongest intermolecular force."
Maeby	 Within Molecules	**Hydrogen bonding** is "between hydrogen and oxygen, nitrogen, and fluorine"

Table 5. Drawing and Text Comparisons for Oscar and Rita

Pseudonym	Drawing	Quote
Oscar	 Between Molecules	**LDFs** are "the simplest and weakest of the IMF"
Rita	 Within Molecules	**LDFs** are "present in all molecules, but the one force in polar molecules. The weakest of the three"

electronegativities". Even so, his drawing, seen in Table 6, clearly shows dipole−dipole interactions as C−H bonds in one molecule of ethanol. Perhaps more important to note is that, while many students' written responses by themselves might be interpreted as correct, it is only when we consult the students' representations that we can see whether they understand the "intermolecular" part of intermolecular forces. By drawing, students are able to show us where they believe these interactions occur[23] and, as a result, show aspects of their understanding that are not captured in their written descriptions.

■ SUMMARY

The three main findings of this study follow.

First, drawings of IMFs collected in this study indicate that a majority of students draw representations showing that IMFs are located within a single molecule rather than between separate molecules (Figure 1). Although this finding is similar to previous studies in which students confuse IMFs and covalent bonds within a molecule,[12,15,16] the results presented here contrast with these prior studies where a much smaller percentage of the students (certainly less than a majority) exhibited this misunderstanding. There are several possible explanations for this finding; perhaps the most obvious is that these students have not been taught appropriately. However, these students are representative of a cohort who averaged around the 75th percentile on the ACS general chemistry examination. We also have some evidence[11] that while the student response is highly dependent on the learning environment, the finding that many students depict intermolecular forces as interactions within a molecule is not unusual for a traditionally sequenced general chemistry course.

Most of the previous reports on student understanding of IMFs rely on forced-choice assessments, in which some of the responses may not even address the particular problem of inter-versus intramolecular forces. For example, in Schmidt and colleagues' study of student understanding of IMFs,[13] several items were of the type "In which of the following compound(s) is hydrogen bonding likely to occur between the molecules?" which would, of course, preclude the idea that hydrogen bonding occurs within a molecule. Villafañe and colleagues developed a multiple-choice instrument using clusters of questions designed

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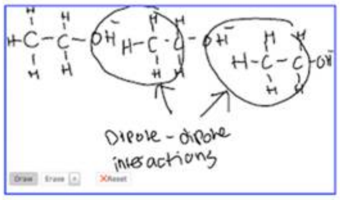
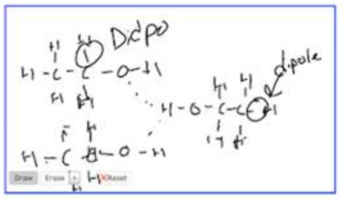
Table 6. Drawing and Text Comparisons for Trisha and Gene

Pseudonym	Drawing	Quote
Trisha	 Between Molecules	**Dipole–dipole** is "between molecules that have positive and negatively charged ends. The different ends are attracted to each other"
Gene	 Within Molecules	**Dipole-dipole** is an "intermolecular force formed between two dipole molecules that comes from different electronegativities"

to probe topics important to the development of students' understanding of biochemistry.[14] Their assessment included three items designed to address how students understand hydrogen bonding. It is significant that this cluster of items had the lowest Cronbach's alpha coefficient, 0.306, indicating a weak correlation between students' responses to the three items. Only 12% of the students in their study gave completely correct responses to all three items in the hydrogen bonding cluster.[21]

Second, in contrast to their drawings, students' writing about IMFs was more ambiguous (Figure 2). While most students' responses clearly indicated an attempt to discuss the IMF provided in the prompt, many were paraphrases of textbook definitions: for example, listing the elements involved in hydrogen bonding, or indicating that all molecules are capable of London dispersion forces. Very few students specifically indicated that intermolecular forces occur between molecules or discussed the origin of intermolecular forces as electrostatic interactions. While this may have been a consequence of the lack of specificity of the prompt, in this study it was not possible to determine from student writing whether students have an appropriate conception of IMFs.

Third, comparison of student writing and drawing indicates that drawings are much easier to categorize. For the most part, students' written descriptions were ambiguous, while their drawings were not (Figure 3). In fact, we provided some examples within this paper that show student discussions may have been considered "correct" but were paired with a representation that would be incorrect: for instance, Maeby's response in Table 4 or Gene's in Table 6. We believe that student-constructed representations can provide more insight into student understanding, particularly with respect to spatial information such as the location of IMFs.

CONCLUSIONS

It is clear from inspection of student drawings that many students have problematic ideas about intermolecular forces. For each IMF, more than half of the students in both cohorts drew representations that explicitly showed an interaction within a molecule, yet student written descriptions were often much more ambiguous or, in the case of dipole–dipole, contradictory. The fact that the majority of students drew pictures indicating each IMF as interactions within a molecule leads us to believe that, like many other concepts, student understanding of IMFs is highly problematic, fractured, and unstable.[4,38−40] Depending on the nature of the prompt, we may elicit differing and often contradictory ideas. Because of this, we must be particularly careful not to draw conclusions from single assessment items. Clearly it is important to provide students with opportunities to construct responses in multiple formats and to help them reconcile differences between their responses.

IMPLICATIONS FOR TEACHING AND FUTURE WORK

The fact that a majority of students can emerge from a general chemistry course without a consistent understanding that intermolecular forces operate between molecules is highly problematic. Intermolecular forces mediate much of chemistry, from the temperature at which phase changes occur, to solubility and reactivity. The well documented "misconception" that covalent bonds break when a phase change occurs[4,12,13,17−19] becomes more understandable in light of this finding. As we have previously noted, determining which IMFs are present within the bulk substance are part of a long sequence of ideas and skills that students must construct for themselves before they can understand structure–property relationships. Clearly, one approach to helping students might be to emphasize the teaching of IMFs more in general chemistry courses. Inspection of a number of popular texts, including the one used by students in this study (*General Chemistry: Atoms First* by McMurray and Fay[41]) shows that the topic of IMFs is clearly explicated with well-designed and clear representations. However, knowledge is not transferred intact (either from a text or in a lecture), but is instead constructed by the student.[42,43] Clear exposition and repetition of important ideas are not sufficient to produce a robust and useful understanding. In fact, in many general chemistry courses the topic of IMFs is often separated both from the prior knowledge that is needed to understand it (i.e., molecular structure, shape, and polarity) and from the material for which IMFs are needed to understand a concept (e.g., solubility and phase changes). That is, the teaching of IMFs does not meet the tenets for meaningful learning in that prior knowledge, instruction, and the purpose of that knowledge must be explicitly connected.[7,42] Knowledge must be contextualized before it

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becomes useful.[44] While this study looked at IMFs using small molecules as our substrate, we must also bear in mind that noncovalent interactions mediate much of biological chemistry from protein folding to enzyme substrate interactions.

It is our contention that, to develop a robust understanding, the curriculum must be restructured to emphasize the connections between important ideas and that students must be given opportunities to reflect on and make their thinking visible.[45] That is, students must have the opportunity to construct and revise representations, models, and explanations that allow them to predict and explain phenomena. Otherwise, it becomes too easy to assume that students have learned important concepts because they can choose the correct answer on an examination. Indeed one might wonder why the extent of this problem has gone unrecognized for so long. It may well be that our increasing reliance on homework using online course management systems and multiple-choice tests has contributed to the problem. If students are not ever asked to write and draw, to reflect, to explain, and to revise their ideas, but instead are only assessed by which item they choose on a test or randomly generated homework, it is unlikely that they will develop a robust and coherent understanding of core concepts. This is not to say that multiple-choice items are never useful (indeed they are almost unavoidable in large enrollment courses), but that students must also be given many opportunities to construct answers for themselves as they learn.

One further note, some authors have recommended that intermolecular forces such as hydrogen bonding or London dispersion forces be considered as bonds[46] and there is a compelling argument that bonds and intermolecular forces be considered part of a continuum of interactions between atoms. However, it is crucial that students also understand the differences. That is, when an IMF is overcome, the result is typically not a new chemical substance but rather a phase change (or in the case of large molecules a change in conformation or shape). When bonds are broken, new chemical substances are produced with different properties and arrangements of atoms. These differences, while quite apparent to the expert, are clearly not so obvious to students. It is our contention that students who do not have a firm grasp on the forces that act both within and between molecules will be unable to make sense of phase changes, solution formations, and chemical reactions. While experts may point out that the word "intermolecular" actually defines where the forces act, it has been well documented, both in this study and in other reports, that students have difficulty using terminology appropriately.[37,47]

Our future work on helping students understand and use IMFs focuses on two areas. The first is investigating how changes in learning environment affect the ways that students represent and understand intermolecular forces. In a follow-up paper in this series,[11] we present a comparison between matched cohorts of students from traditional and transformed courses. We also are collecting data from a wider range of institutions and instructional settings. The second area of research is to develop more nuanced approaches to eliciting the ways in which students think about IMFs and their role in bulk properties of matter, including designing scaffolded prompts to elicit student beliefs about how IMFs are formed and how they are linked to properties. We believe that a major goal of chemistry education is to help students develop causal, mechanistic explanations of phenomena, and understanding IMFs is crucial to this goal.

LIMITATIONS OF THE STUDY

The IMFA was designed to require students to first write about their understanding of IMFs and then construct representations of those IMFs. We did not ask students to justify or explain their drawings and what they intended to show. Because of this, we had to infer students' intentions from their drawings alone.

The study reported here was performed at one institution and it might be argued that the institutional setting was such that the results are not applicable to other institutions. However, in future papers we will be reporting similar studies from multiple institutions and with multiple types of courses, and we have reason to believe that the data presented here are not a "worst case scenario".

ASSOCIATED CONTENT

Supporting Information

Student demographic information for each cohort; an example question from the IMFA; all combinations of student text and drawing responses. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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