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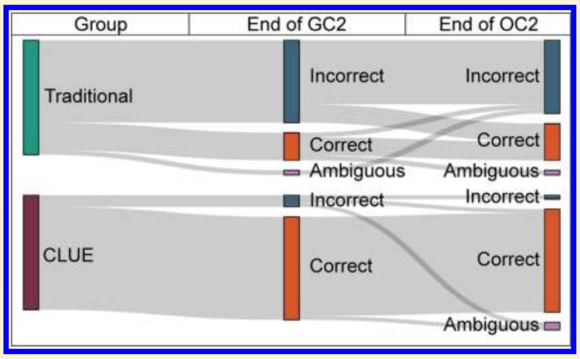
Are Noncovalent Interactions an Achilles Heel in Chemistry Education? A Comparison of Instructional Approaches

Leah C. Williams,[†] Sonia M. Underwood,[†] Michael W. Klymkowsky,[‡] and Melanie M. Cooper*[,†]

[†]Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, United States

[‡]Molecular, Cellular, and Developmental Biology, University of Colorado, Boulder, Boulder, Colorado 80309, United States

Supporting Information



ABSTRACT: Intermolecular forces (IMFs), or more broadly, noncovalent interactions either within or between molecules, are central to an understanding of a wide range of chemical and biological phenomena. In this study, we present a multiyear, multi-institutional, longitudinal comparison of how students enrolled in traditional general chemistry courses and those in a transformed general chemistry course (Chemistry, Life, the Universe and Everything, or CLUE) represent intermolecular forces in the context of small molecules. For multiple cohorts of students at two different universities, we found that students who participate in the CLUE curriculum were significantly more likely than those in a traditional curriculum to indicate (correctly) that intermolecular forces occur between, rather than within small molecules. In a longitudinal study, we followed the students from one cohort through the subsequent year of organic chemistry and found that the differences between the CLUE and traditional students persisted over the course of two years of chemistry instruction. In general, students who are enrolled in the transformed general chemistry curriculum have a more scientifically correct and more coherent understanding of IMFs. The finding that a majority of students leave general chemistry without a coherent understanding of the difference between covalent and noncovalent interactions must certainly impact their subsequent understanding of chemical and biological phenomena.

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

FEATURE: Chemical Education Research

■ INTRODUCTION

The noncovalent interactions, often referred to as intermolecular forces (IMFs), that occur between small molecules and within larger (macro) molecules are responsible for a wide range of phenomena. In the domain of chemistry, they provide the basis for understanding both the physical and chemical properties of a substance. In biological systems, noncovalent interactions determine the three-dimensional structure of macromolecules and the binding interactions between various molecules. Understanding how molecules interact is therefore critical to an understanding of a wide range of physical, chemical, and biological phenomena. In order for students to explain the difference between a phase change and a chemical change, the binding and dissociation of molecules to an enzyme or a transcription factor protein to a DNA molecule, or to understand why a particular macromolecule assumes the shape it does or how changes in its environment (e.g., temperature or solvent) influence its structure, students must develop and be able to apply an accurate appreciation of noncovalent interactions. Learning about how molecules interact is central to most chemistry courses and is usually presented under the umbrella term "intermolecular forces" with various types of IMFs being introduced; for example, hydrogen bonding, dipole−dipole interactions, and London dispersion forces are commonly discussed as examples of a similar phenomenon. The topic is equally important to learning biology, but different terminology is often used (except for hydrogen bonding); for example, biologists often speak of van der Waals forces and the hydrophobic effect rather than naming different types of forces.

We have previously shown that many students who perform well on traditional chemistry assessments have developed profound misunderstandings about the nature of IMFs.[1,2] In the context of small molecules, we found that the majority of students enrolled in a traditional general chemistry course constructed representations in which they showed IMFs acting within (rather than between) molecules. That is, most of these students represented a range of different IMFs as covalent rather than noncovalent interactions. We believe that one potential reason why this problem in understanding the essential point about IMFs has been under-reported for so

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long stems from the nature of the assessments used to probe student understanding. Most prior studies on student understanding of IMFs have used either multiple-choice instruments or students' written responses to prompts. For example, studies employing a 2-tier diagnostic multiple choice test found that around 30% of students had a problematic understanding of IMFs as forces within a molecule, rather than between.[3,4] Others have focused on hydrogen bonding interactions where they found problematic ideas particularly in relation to the idea that the O−H covalent bond is the hydrogen bond.[5,6] While student confusion about the nature of hydrogen bonding is understandable (the term hydrogen bond itself is misleading), there are few studies that explicitly examine other types of IMFs such as London dispersion forces (LDFs) and dipole−dipole interactions.[7,8]

In our studies we used the Intermolecular Forces Assessment (IMFA), an instrument that requires students to construct representations that show the location of various IMFs and to explain in words what they understand about each IMF.[2] The IMFA was administered to students using our online platform *beSocratic*, which allows us to collect, record, and analyze both student writing and drawings.[9,10] We found that at least 55% of each student cohort represented all IMFs that we asked about (hydrogen bonding, dipole−dipole, and London dispersion forces) as interactions within a single (small) molecule. We also found that much of what students wrote about IMFs was ambiguous as they often restated textbook definitions; indeed, without the student-generated drawings as further evidence, it would have been impossible to determine whether students understood IMFs as covalent or noncovalent interactions.

These observations were surprising and disturbing given that they were generated by successful students enrolled in a well-designed traditional general chemistry course; these students averaged around the 75th percentile on the nationally normed ACS general chemistry examination.[11] If a majority of students do not have a clear understanding of the difference between IMFs and chemical bonds, it should not be surprising when we find that students believe that covalent bonds are broken during phase changes[1,5,6,12,13] or that they have trouble developing plausible reaction mechanisms.[14−17] Similarly, students who do not have a robust understanding of noncovalent interactions are unlikely to appreciate the properties of various biological structures, such as the behavior of lipid-based barrier membranes or the factors that influence binding interactions between molecules. Indeed, it has been reported that the most prevalent response to the question "What makes DNA a good place to store information?" is that "the hydrogen bonds that hold it together are very stable and difficult to break."[18]

■ DEVELOPING IMPROVED UNDERSTANDING IN A REFORMED CURRICULUM

We are using both research on student difficulties and theories of learning to design, implement, and assess evidence-based approaches to improve student learning.[1,19−22] One result of this process is the development of a new general chemistry curriculum, Chemistry, Life, the Universe and Everything (CLUE).[23] CLUE is based on a carefully scaffolded progression of the core ideas: structure, properties, forces, and energy. These core ideas are developed over a yearlong sequence and are connected explicitly to each other. CLUE students are asked to demonstrate their understanding using the online *beSocratic* system that allows us to ask students to explain phenomena and construct models by writing and drawing in response to prompts.[9,10] These exercises explicitly encourage students to combine their disciplinary knowledge with scientific practices[24] such as constructing explanations, arguments, and models. The *beSocratic* system records all student input and makes it available for replay and subsequent analysis. As reported previously,[20] a comparison between matched cohorts of CLUE and traditional students revealed that CLUE students were significantly better at drawing Lewis structures and were more likely to report that these structures could be used to predict both chemical and physical properties. That is, CLUE students were more likely to recognize that structural representations could be used to predict and explain properties than traditional students.

An obvious question then is whether courses based on the CLUE curriculum led to enhanced student understanding of key chemical concepts such as IMFs in the context of structure−property relationships. In this report, we compare students enrolled in CLUE to those enrolled in a more traditional general chemistry curriculum using the Intermolecular Forces Assessment (IMFA).[2] The IMFA prompts students to draw three molecules of ethanol and show the location of specific types of IMFs (hydrogen bonding, dipole−dipole and LDFs) that are typically taught in a general chemistry course. Students are also asked to explain what they understand about each type of IMF and to expand upon anything they cannot portray in their drawings.[2] We used these responses to address three research questions:

1. How do CLUE students' representations of IMFs compare to those of students enrolled in a traditional general chemistry course?
2. How do students at different institutions compare in their representations of IMFs?
3. How do CLUE and traditional students' representations of IMFs change over the course of the subsequent organic chemistry course?

■ METHODS

Student Population

The IMFA was administered at two universities. University 1 (Univ. 1) is a medium sized southeastern public research university with an average fall enrollment of 1600 students in first semester general chemistry (GC1). University 2 (Univ. 2) is a large midwestern public research university with an average fall enrollment of 3000 students in first semester general chemistry. The IMFA was administered to two matched cohorts of students (Cohort 1 and 2) enrolled in general chemistry at Univ. 1 and an additional cohort of students (Cohort 3) at Univ. 2. Students from Cohort 1 were followed through two years, from general chemistry through the second semester of organic chemistry (OC2). All the students included in this study consented to participate in this research by signing informed consent forms. Additional demographic information (sex and declared majors) for all three cohorts is provided in Supporting Information Tables S1, S4, and S7.

The coverage of IMFs in the traditional courses in both universities followed a similar path. In both universities, IMFs were explicitly introduced toward the end of the first semester, after bonding. At University 1, about five classroom periods were allocated to IMFs, while at University 2, one or two class periods were specifically allocated to IMFs. In CLUE, there is no specific section of the course where IMFs are treated separately. Rather, they are introduced early in the first

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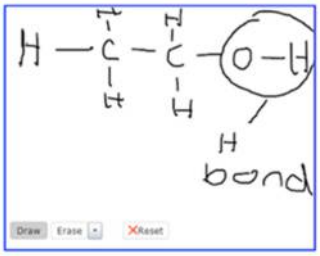
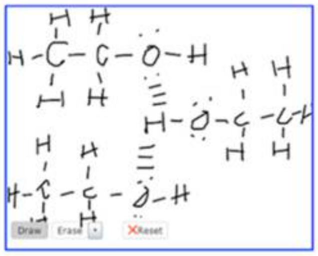
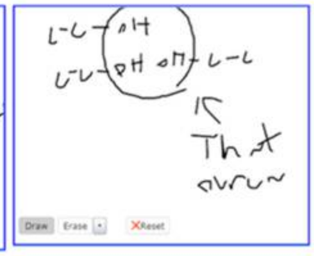
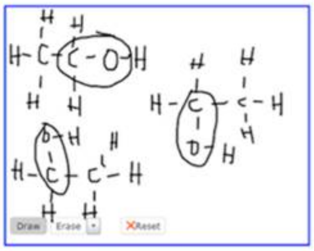
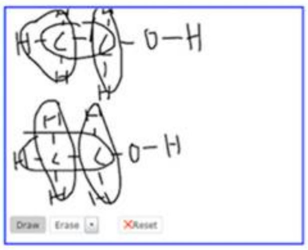
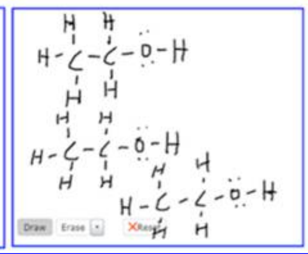
Table 1. Coding Examples for Student Drawings of Selected Types of Intermolecular Forces

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

semester in a very simple context, which is built upon over the course of the semester. IMFs are always discussed in the context of energy changes (e.g., during phase changes) and related to atomic and molecular structure. A more extensive discussion of the differences is provided in Supporting Information along with examples of CLUE materials that involve IMFs (Figures S1 and S2).

Study 1: A Comparison of CLUE and Traditional Students at University 1

The initial study with Cohort 1 and a replication study with Cohort 2 both followed a quasi-experimental control-treatment design.[25] CLUE students from each cohort were matched with students from the remaining population of around 1400 students who were enrolled in traditional sections of general chemistry, based on demographic information and SAT scores; responses of students in the two groups to precourse surveys and instruments were found to be equivalent (Tables S2–S3 and S5–S6 in Supporting Information). CLUE students in Cohorts 1 (N = 87) and 2 (N = 117) had different lecture instructors for the course, both of whom were familiar with the design and implementation of the CLUE curriculum. Traditional students in Cohorts 1 (N = 94) and 2 (N = 160) were chosen from classes taught by five different instructors.

IMFA responses were collected from Cohort 1 and Cohort 2 at the end of second semester general chemistry (GC2), to ensure that all CLUE and traditional students had been exposed to, and been assessed on, the topic of IMFs. Since there is an inherent conflict of interest when assessing the effects of a reform designed by the research team, it was important to separate, as much as possible, those involved in data collection and analysis from those involved in course delivery. Student responses were collected outside of the lecture setting as an assignment in the associated laboratory course. Students were provided with tablet PCs or iPads, since both devices allow for drawing with a stylus and typing written responses. Responses were recorded through *beSocratic*, which allows for free-form student input such as drawings, graphical representations, and text responses.[9,10] Students received credit (laboratory participation points) for attempting to complete the assessment. None of the lecture instructors were involved with data collection.

Study 2: A Comparison of CLUE and Traditional Students from Different Universities

Cohort 3 consists of CLUE (N = 187) and traditional (N = 239) students enrolled in GC2 at University 2. We do not have a matched control group to make statistical comparisons between instructional approaches, either for this cohort, or across cohorts. The demographic information for Cohort 3 (sex and declared majors) is provided in Table S7 of Supporting Information. However, we present the analysis of CLUE student responses in order to provide preliminary evidence of the impact of the curriculum at different institutions. We have also included the traditional student responses to address additional difficulties experienced by students. As with Cohorts 1 and 2, student responses for Cohort 3 were collected at the end of GC2, that is, after all students had been taught and tested on IMFs. Since students are not required to take the laboratory course concurrently with lecture at Univ. 2, the student responses were collected by research and teaching assistants during recitations using the *beSocratic* program on

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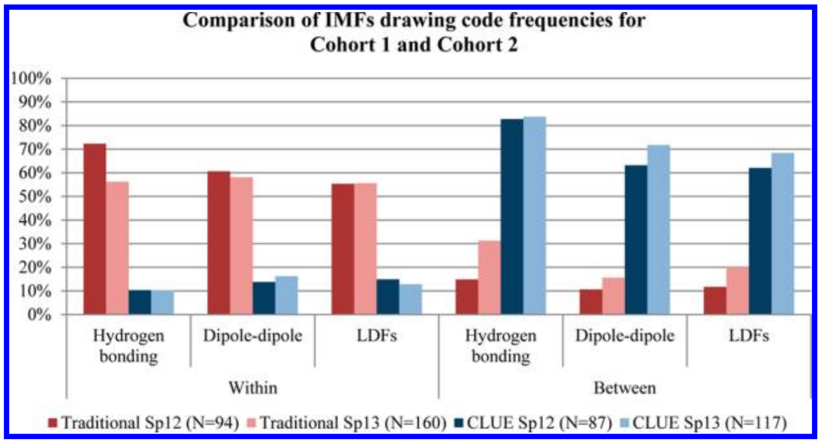

Figure 1. Comparison of code frequencies for students' representations of hydrogen bonding, dipole−dipole, and LDFs from Cohort 1 and Cohort 2.

iPads or tablet PCs. In this case, the teaching assistants leading recitation work closely with the lecturer for the course, meaning that the data collection at Univ. 2 is more closely tied to the lecture section and the course instructor. The CLUE instructor for Cohort 3 at Univ. 2 is the same instructor who taught CLUE Cohort 1 at Univ. 1.

Study 3: A Longitudinal Study of Students' Representations of IMFs

While the majority of our data from Univ. 1 was collected from students enrolled in general chemistry, we also followed students in Cohort 1 who continued on through both sequential semesters of organic chemistry (OC1 and OC2) in order to investigate how student representations of IMFs changed in subsequent courses. In this study, the IMFA was administered again at the end of OC2. Since most majors at Univ. 1 do not require students to take more than one year of chemistry, many students do not go on to enroll in organic chemistry; consequently, both CLUE and traditional groups were significantly smaller ($N = 30$ and $N = 25$, respectively) by the end of OC2. For this study, we compared the results for only this smaller subset of students who had completed *all* administrations of the IMFA.

Data Coding and Analysis

The studies discussed here focus on student drawings. As we have previously reported, most students' written responses to the prompts in the IMFA are ambiguous in regards to the location of IMFs.[2] Therefore, we chose to code the drawings only, which provided us with more useful information about where students believe IMFs are located. 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 κ of 1.0 for hydrogen bonding and dipole−dipole drawings, and a Cohen's κ of 0.96 for LDFs. The three major codes for each IMF are *between* (molecules), *within* (molecules), and *ambiguous* as shown in Table 1.

Other less prevalent codes included "within and between" for representations that clearly indicated an IMF as occurring both within a molecule as well as between molecules, "not present", "student does not know", and "always present" if the student wrote any of these items in the drawing space. For the purpose of clarity, we present only the "within molecules" and "between molecules" data for most of our analyses since these codes account for the majority of responses in our study.

■ RESULTS AND DISCUSSION

Study 1: Results and Discussion—University 1, Cohorts 1 and 2, GC2

As shown in Figure 1, there is a significant difference between the responses from CLUE students and those in the traditional general chemistry class for both Cohorts 1 and 2. That is, the results we found in the first year of data collection were replicated in year 2 with a different cohort of students. In general, the majority of CLUE students drew all types of IMFs as interactions **between** molecules, while the majority of traditional students drew IMFs **within** individual molecules. Specifically, 83% ($N = 72$) of CLUE students in Cohort 1 and 84% ($N = 98$) from Cohort 2 drew hydrogen bonds between molecules, while 15% ($N = 14$) of traditional students in Cohort 1 and 31% ($N = 50$) of traditional students in Cohort 2 indicated this as shown in Figure 1. Of the 72 Cohort 1 CLUE students who drew hydrogen bonding between molecules of ethanol, 96% ($N = 69$) correctly indicated the hydrogen bonding interaction between the oxygen of one molecule and the hydrogen covalently bonded to oxygen on another molecule. That is, not only did the majority of CLUE students correctly depict hydrogen bonding as occurring between molecules, but almost all of them provided what would be considered a correct representation of hydrogen bonding between appropriate elements on each molecule.

This pattern, where CLUE students represented IMFs between molecules while traditional students indicated they correspond to bonds within a molecule, was not limited to hydrogen bonding as shown in Figure 1. In fact, for each of the three IMFs, at least 55% of the traditional students' representations from Cohorts 1 and 2 depicted all IMFs as a bond within a single ethanol molecule. At most only 31% ($N = 50$, Cohort 2) of traditional students ever provided a depiction of hydrogen bonding as located *between* molecules and even fewer represented dipole−dipole and LDFs as occurring between molecules, as shown below. Figure 1 shows the most common codes applied to student drawings; *all* code frequencies for all Cohort 1 and 2 responses as well as Chi-square analysis results for statistically significance differences are included in Supporting Information in Table S8.

The findings from Cohorts 1 and 2 for both CLUE and traditional students are very similar despite different instructors teaching CLUE each year and the fact that traditional students were chosen from sections taught by at least five different

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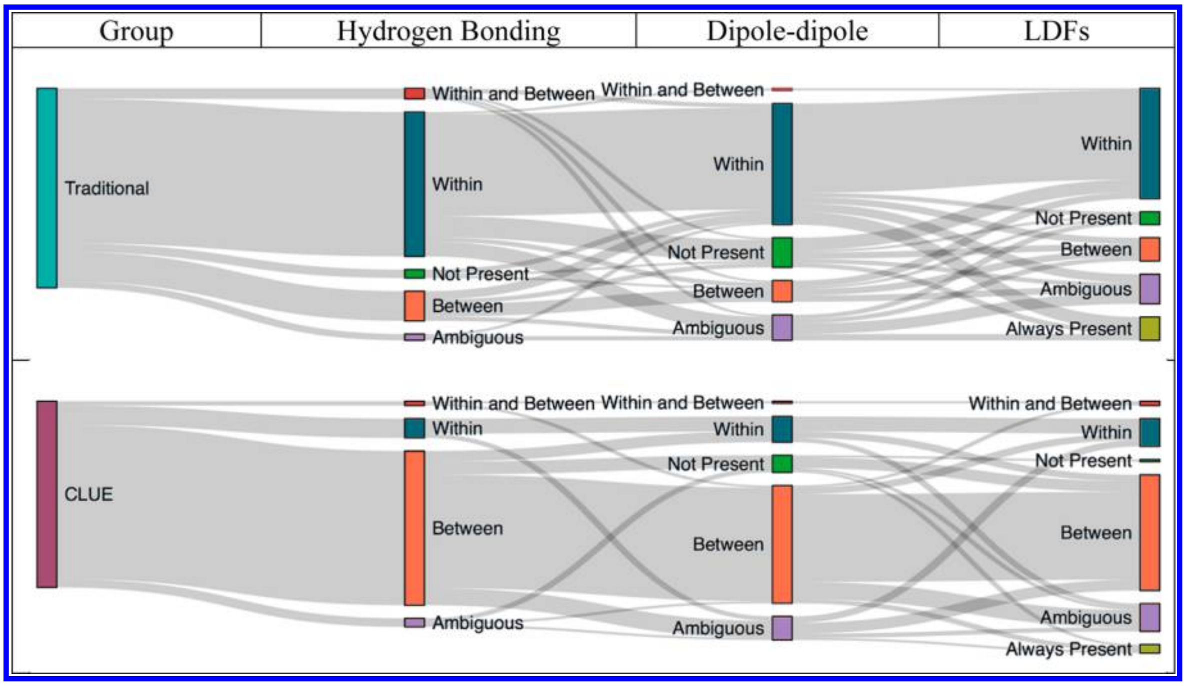

Figure 2. Flowchart showing how the code frequencies change for students in Cohort 1 across all three IMFs.

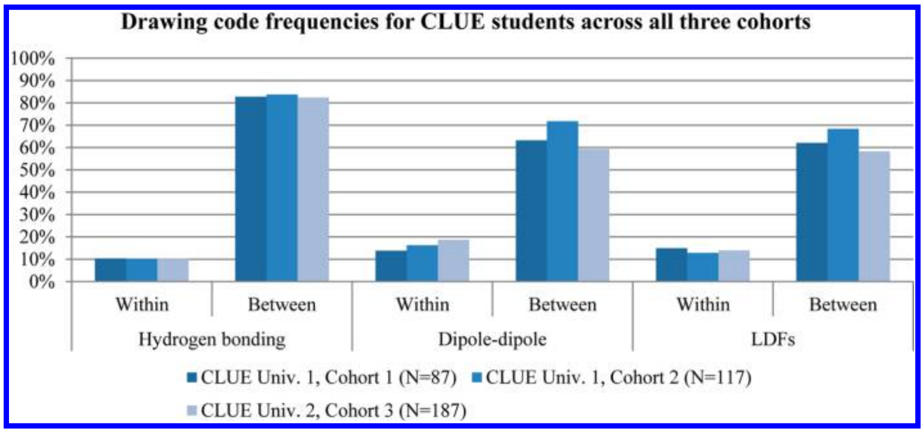

Figure 3. Code frequencies for CLUE students' drawings of all three IMFs from all three cohorts collected at two universities.

instructors. We believe that the persistent differences we see here are a result of the curriculum, not a function of student ability or the instructor.

Comparing Student Responses Across the Three IMFs

Figure 1 depicts the percentage of students who received within or between codes for each IMF, but it does not show whether students are consistent in the way they represent IMFs. That is, a student could have drawn hydrogen bonding as occurring within a molecule, but provided ambiguous drawings for dipole−dipole and LDFs. We used Sankey diagrams,[26,27] which are a type of flow diagram, to visualize whether students' representations changed as they represented different IMFs. Figure 2 shows how the representations provided by each student changed (or did not change) between all three IMFs for both traditional and CLUE students in Cohort 1. The width of the pathways represents the number of students who took that path. Although the diagram can only show how students change between two consecutive IMFs, it does indicate that there is a lack of consistency for many students.

Ideally, we would have liked to find that all students had a consistent understanding of all three IMFs as interactions between ethanol molecules. In the traditional student population, only *one* student out of the entire sample (N= 94) consistently represented all three IMFs as occurring between molecules. Although at least 60% of CLUE students indicated that each IMF operates between molecules, the group of students who *consistently* received "between molecules" codes for all three IMFs representations was smaller (46%, N = 40). Only 6% (N = 5) of CLUE students consistently received within codes for all three IMFs representations, while a significant subset of traditional students consistently represent IMFs as interactions within a single molecule (38%, N = 36). A majority of traditional students (59%, N = 55) were inconsistent in their depictions of IMFs as examples of the same phenomenon (be it within or between). Similarly, even though a majority of CLUE students provided accurate and consistent representations for the location of each IMF as between molecules, many CLUE students (47%, N = 41) were still inconsistent from one IMF to another. All data for the consistency of CLUE and traditional students' responses across

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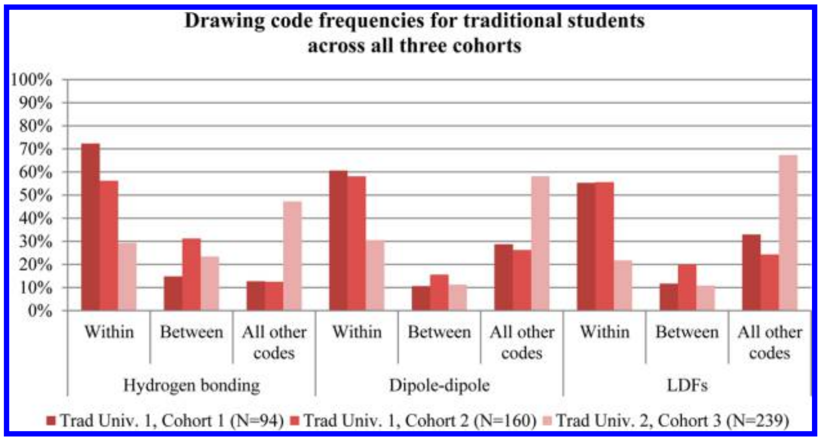

Figure 4. Code frequencies for traditional students' drawings of all three IMFs from all three cohorts collected at two universities.

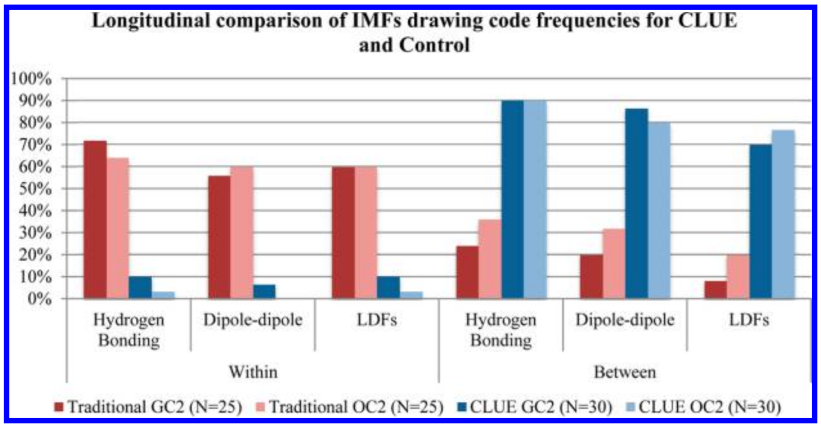

Figure 5. Longitudinal comparison of CLUE and traditional students' code frequencies for representations of hydrogen bonding, dipole–dipole, and LDFs from GC2 to OC2 (Cohort 1).

all three IMFs are provided in Supporting Information (Table S9).

Study 2: Results and Discussion—University 2, Cohort 3, End of GC2

While we were able to successfully reproduce our initial findings of the impact of the CLUE curriculum on students' understanding of IMFs with a second cohort of students taught by a different instructor, it might be argued that the results are not generalizable since all of the responses collected from both CLUE and traditional students for the first study came from a single university. Therefore, we administered the IMFA to both CLUE and traditional students enrolled in GC2 at a second university (Univ. 2).

The CLUE GC2 students are quite consistent among the three cohorts as shown in Figure 3. Over 80% of students in all three cohorts received between codes for their representations of hydrogen bonding and between 58% and 72% of students in each cohort received between codes for their drawings of dipole–dipole and LDFs. It is notable that these responses are similar despite the differences in classroom environments and student demographics between Univ. 1 and Univ. 2. However, the traditional students in the three cohorts showed major differences. Figure 4 shows code frequencies for traditional students' responses at both Univ. 1 (as shown earlier) and Univ. 2. The percentage of students from Univ. 2 who drew IMFs between molecules was similar to that of traditional students from Univ. 1 (23%, N = 56). However, when compared to students from Univ. 1, far fewer students from Univ. 2 provided representations of IMFs within molecules. Instead, as can been seen from Figure 4, larger percentages of students at Univ. 2 received an "other" code, which here represents the "ambiguous", "not present", and "student does not know" codes. A larger percentage of students at Univ. 2 (24%, N = 57) had difficulty drawing the structure of ethanol in the context of hydrogen bonding interactions than that at Univ. 1 (13%, N = 12), which made it difficult to interpret some of their representations and to determine the intended location of each IMF. We cannot make statistical comparisons among the three cohorts of students for either curriculum since we do not have measures for student performance or prior achievement that are consistent across all three cohorts. Figure S3, in Supporting Information, shows an additional graph with the code frequencies for all "other" codes (Ambiguous, Not Present, and Student DK) for traditional students in each of the three cohorts.

Study 3: Longitudinal Study Results and Discussion—University 1, Cohort 1, GC2 through OC2

As noted in the NRC report on Discipline Based Education Research (DBER),[28] longitudinal studies of student learning are rare for many reasons. They can be expensive, time-consuming, and it is frequently impossible to track students over time because of the varying paths they take through their studies. We were able to follow a group of CLUE and traditional students from Cohort 1 through a full year of organic chemistry. Organic chemistry, however, is not required for all majors, and as might be expected, there was a significant reduction in our sample

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size. By the end of OC2, 25 traditional students and 30 CLUE students remained from the original Cohort 1; these students completed all administrations of the IMFA over the course of two years.

A comparison of the two groups showed that, even after a full year of organic chemistry, the majority of CLUE students continued to show IMFs between molecules and the traditional students still represented IMFs as occurring within molecules, as seen in Figure 5. That is, there was very little change in the students' representations of all three IMFs once the students left GC2. Statistical comparisons using Chi-square analysis between CLUE and traditional groups' IMFs drawings at each time point (the end of GC2 and again at the end of OC2) are provided in Table S10 of Supporting Information. The significant differences that were present at the end of GC2 were still significant after a full year of organic chemistry instruction with medium to large effect sizes. Figure 6 shows a Sankey diagram of Cohort 1 students' hydrogen bonding responses over time, and it is clear there is very little change in student responses after they leave GC2. Additional Sankey diagrams for students' representations of dipole−dipole and LDFs over time can be found in Supporting Information (Figures S4 and S5).

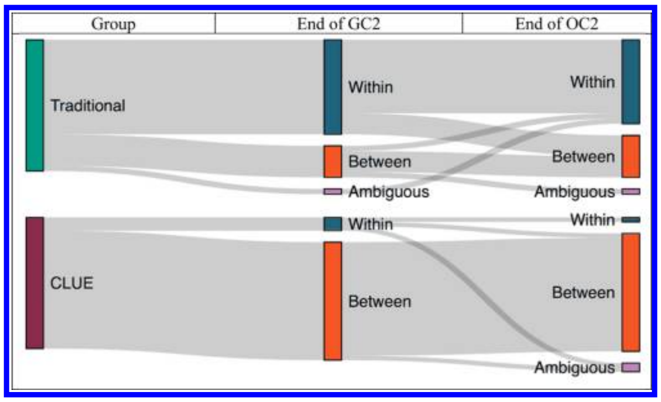

Figure 6. Sankey diagram showing how Cohort 1 CLUE and traditional students' representations of hydrogen bonding change between the end of GC2 and the end of OC2.

While the sample sizes are small, it seems clear that neither group's representations (CLUE or traditional) change much over a subsequent full year of organic chemistry. This is evidence that (i) the effects of the CLUE curriculum persist and (ii) that a traditional organic chemistry course does not contribute much to an improvement in students' understanding of IMFs. This is not particularly surprising since most organic faculty might reasonably expect to believe that students have already learned about IMFs in general chemistry. Our study implies that the understanding of IMFs that students develop in general chemistry is crucial, since it is unlikely to change after then.

■ CONCLUSIONS

Understanding the nature of IMFs is central to a robust understanding of structure−property relationships, not only in chemistry but also in a wide range of biological processes. We have shown that students in a transformed general chemistry curriculum (CLUE) are significantly more likely to represent the types of IMFs that they have been taught about in their chemistry courses as noncovalent interactions than similar students from traditionally sequenced courses. We ascribe this improvement to the structure and nature of the activities in the CLUE curriculum, which is designed so that ideas are linked and carefully scaffolded. Students are required to construct and revise answers to questions on a daily basis and to connect their understanding to what they have learned previously and to how that knowledge will be used. We note that the effects of instruction using the CLUE curriculum persist through an organic chemistry sequence (taught by different instructors). Moreover, traditional organic chemistry instruction does not lead students to significantly change their understanding of IMFs.

Together, these observations suggest the design of the traditional general chemistry courses does not explicitly or effectively connect the numerous steps required to link molecular structure to physical properties, a connection that involves an understanding of IMFs. This implies that students will be unable to generate plausible models of a wide range of molecular behaviors. If students do not understand how each of these ideas are connected, then they are unlikely to learn the material meaningfully and instead rely on heuristics and rules.[1,29−31] The CLUE curriculum supplies an example of how such ideas can be effectively developed in students.

Limitations

The limitations of this study are twofold. First, data from only two universities are presented here. It will be important to determine if a wider range of students display the same kinds of difficulties constructing representations of IMFs and whether the CLUE curriculum is as effective when more broadly disseminated. It is also unclear the extent to which students can put their understanding of IMFs to use; that is, can they use IMFs to predict relative melting and boiling points and to understand how molecules interact? These studies are ongoing and will be reported elsewhere.

Implications for Teaching

Our working model is that the results shown here stem directly from the use of the CLUE curriculum, in which the knowledge that students learn is explicitly connected to what they have already learned and to how that knowledge will be used. Students are routinely asked to construct models and explanations about how and why phenomena occur. In contrast, in many traditional approaches to teaching general chemistry, the material can be presented in disconnected chunks and students are often assessed on their ability to retrieve pieces of knowledge and solve routine exercises. In fact, we believe that the inability of many traditional students at Univ. 2 to construct reasonable drawings of individual molecules is a consequence of the fact that they were never asked to construct answers to prompts, but instead practiced multiple-choice questions that test fragments of knowledge.

In this study, it appears that students do not seem to change the way they think about IMFs once they leave general chemistry. Clearly, this is problematic for students' future studies in both chemistry and biology, where an understanding of IMFs (and, more broadly, noncovalent interactions) is assumed to be present. If the majority of students have (at best) an inconsistent understanding of IMFs, it is unlikely that they will be able to reason appropriately about a wide range of phenomena. We should also note that the fact that the magnitude of this problem has gone unrecognized for so long is perhaps a function of the move to forced-choice assessments,

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which appear to overestimate the depth of student understanding.[32]

It is also clear that although the interactions we studied in this research all fall under the broad term "non-covalent interactions", students do not recognize them as examples of similar phenomena. The names we give to these interactions also contribute to the confusion; hydrogen bonding, dipole−dipole interactions, and London dispersion forces are typically taught in general chemistry, while in biology, van der Waals forces are often discussed without explicit reference to what the differences or similarities are. Perhaps it is time to change the emphasis from a presentation of different kinds of historically named IMFs to the idea that there are covalent and noncovalent interactions between and within molecules and include discussions of the ways in which molecules and parts of molecules can interact without forming covalent bonds. Clearly, it is not feasible to change historical naming conventions, but the important distinction between bonds and interactions must be the "big idea" that students take away, rather than the ability to name individual kinds of interactions.

As a final note, we point out that many of the classes taught in this study use some form of active engagement pedagogy such as clickers, group quizzes, or class discussions. Our observations suggest that the ways the content of a course is structured and the ways that it is assessed are at least as important as the teaching strategy used.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00619.

Additional methods, results and discussion (PDF), DOCX

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: mmc@msu.edu.

Notes

The authors declare no competing financial interest.

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