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The Impact of Core-Idea Centered Instruction on High School Students' Understanding of Structure−Property Relationships

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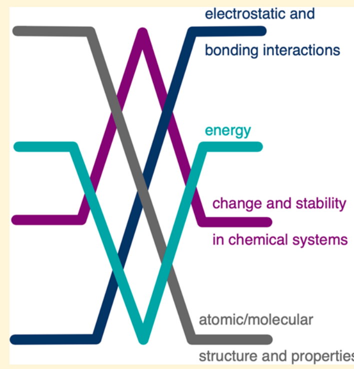
Supporting Information



ABSTRACT: Widespread adoption of the Next Generation Science Standards (NGSS) has created a need to carefully consider how chemistry curricula should support students in understanding the world in terms of atomic/molecular behavior. We argue that Standards-aligned coursework should be "core-ideas centered" due to evidence that curricula embedded in scaffolded progressions of core ideas can help students develop, organize, and use their knowledge to make molecular-level sense of phenomena. Our team of teachers and researchers has previously proposed a model for developing an integrated, core idea focused introductory chemistry curriculum by adapting the conceptual progressions underpinning the evidence-based undergraduate chemistry course Chemistry, Life, the Universe, and Everything (or CLUE). Here, we examine the efficacy this NGSS-aligned chemistry course (called High School CLUE or HS-CLUE) in helping students connect atomic/molecular structure to observable properties. This study made use of a cross-sectional approach to compare the responses of three student cohorts, each instructed according to a different curriculum, on a three-part structure−properties assessment. There is a positive association between enrollment in HS-CLUE and (1) viewing Lewis structures as models, (2) representing hydrogen bonds as "between" molecules, and (3) constructing scientifically accurate, molecular-level explanations for the difference in boiling point between two substances. These associations were primary drivers for the significant relationship between learning environment enrollment and student responses in the majority of instances examined. Our findings provide preliminary evidence that structuring high school chemistry instruction around validated progressions of core ideas supports students in relating atomic/molecular structure to properties.

KEYWORDS: *Chemical Education Research, High School/Introductory Chemistry, Curriculum, Learning Theories, Testing/Assessment*

FEATURE: Chemical Education Research

INTRODUCTION

Adoption of the Next Generation Science Standards[1] (the NGSS) by 19 states and the District of Columbia[2] has created a need to rethink what chemistry in high school could and should look like. Unlike prior standards,[3] which siloed content and "inquiry" into separate bins, the NGSS expect students to use knowledge anchored to large-grain "core ideas"[4] to predict, explain, and model phenomena. Accordingly, Performance Expectations (PEs) for these new standards integrate what students should know (that is, Disciplinary Core Ideas) and what they should do with that knowledge (expressed as Science and Engineering Practices), as well as provide lenses that precisely define how they should make sense of phenomena (Crosscutting Concepts). Supporting students in blending Disciplinary Core Ideas (DCIs), Science and Engineering Practices (SEPs), and Crosscutting Concepts (CCCs) throughout instruction should promote "3-Dimensional Learning" according to reform documents.[1,5]

In chemistry, expectations for 3-Dimensional Learning (as expressed by PEs) often require students to construct and revise explanatory accounts that connect atomic/molecular behavior to observable events. Tasks of this general type are extremely challenging due to the many counterintuitive inferences needed to relate interactions between invisible particles to the macroscopic world.[6] In the early 1980s, Alex Johnstone described these inferences as relating two "levels of thought": the "sub-micro-level" (involving the behavior of atoms and molecules) and the "macrolevel" (involving observable phenomena).[7] Johnstone was concerned that "multilevel thought" could easily overwhelm the processing capacity of novice learners if not built to gradually.[8] His concern has been echoed time and again, and in fact, much of the literature on student understanding of structure−properties relationships is dedicated to cataloging difficulties.[9−12] Thankfully, some scholars have moved beyond listing student struggles and have thought about how "multilevel thought"

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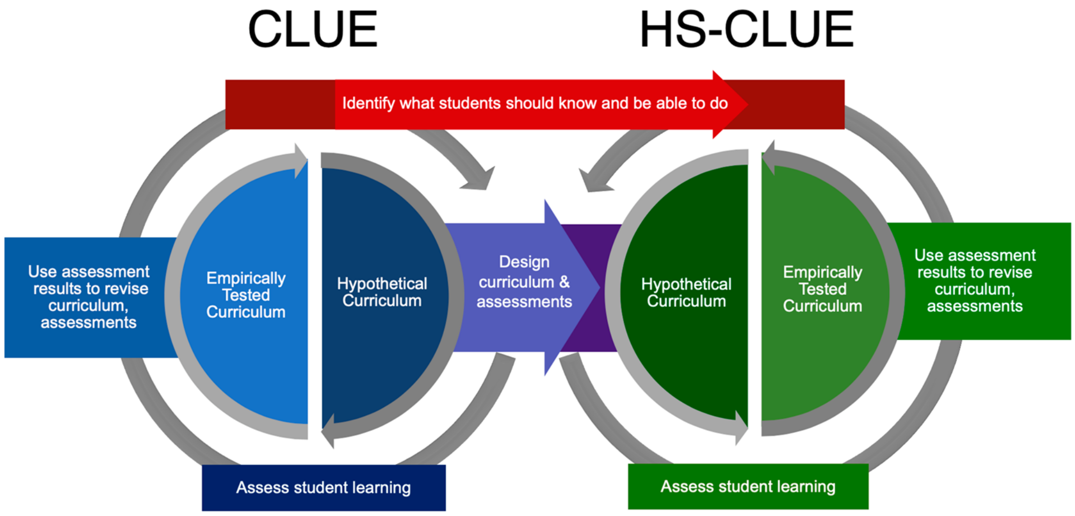

Figure 1. Linked design−research cycles that characterize adaptation of CLUE core-idea progressions for use in high school.[21]

might be supported. Meijer, Bulte, and Pilot have discussed the promise of constructing intermediate "mesolevels" on the path from atomic/molecular interactions to macroscopic events.[13] Levy, Wilensky, and Steiff have shown that exploring simulations depicting system properties as emerging from agent-level interactions improves student understanding of gas laws.[14−16] Cooper and colleagues demonstrated that embedding instruction in scaffolded conceptual progressions helps college students build the intellectual tools they need to relate structure to properties.[6,17,18] However, despite this scholarship, there is as yet no work examining the efficacy of NGSS-aligned high school chemistry curricula in helping students connect atomic/molecular behavior to observable phenomena. This is troubling as the NGSS were published six years ago and many states will soon be deploying standardized tests aimed at assessing 3-Dimensional learning.[19]

In an effort to meet the immediate needs of chemistry teachers across the country, we have developed a Standards-aligned, core-idea centered, introductory high school chemistry curriculum by adapting the conceptual progressions underpinning the undergraduate chemistry course Chemistry, Life, the Universe, and Everything (or CLUE).[20,21] We elected to base our efforts off of CLUE core-idea progressions due to evidence that core-idea centered chemistry instruction helps students develop, organize, and use their knowledge to construct particulate-level explanations for a range of phenomena (e.g., phase changes,[22] atomic emission spectra,[23] acid−base reactions[24,25]). Additionally, adaptation of existing resources allowed our team of teachers and researchers to efficiently assemble a "rough draft" NGSS-aligned high school chemistry curriculum suitable for enactment. Our general model for the development of high school CLUE (HS-CLUE) may be thought of as two linked design−research cycles (Figure 1). We have published a paper describing how we adapted CLUE learning objectives and curricular resources for use in high school, that is, the construction of the HS-CLUE "hypothetical curriculum".[21] Here, we turn attention to evaluation of the HS-CLUE enactment of one of our piloting teachers in pursuit of building an "empirically tested curriculum".

Our initial evaluation of HS-CLUE focused on assessing student understanding of relationships between atomic/molecular structure and observable properties. The connected inferences that relate assemblages of atoms to the world we can measure are vitally important if we ever hope for students to figure out observable, relatable phenomena in terms of atomic/molecular behavior. As the vast majority of high school students will never be chemists, appreciation of the tremendous power of particulate models of matter to explain aspects of everyday existence and macroscopic issues of import is perhaps the most meaningful contribution of chemistry to scientific literacy (as defined by Science for All Americans).[26] Additionally, structure−properties relationships are explicitly called out by NGSS performance expectations (e.g., HS-PS1-3, which reads "plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electric forces between particles"[1]). The following research question guided our study: How does structuring a chemistry curriculum around scaffolded progressions of core ideas affect high school students' ability to explain and model observable properties in terms of molecular-scale interactions and energy?

■ SUPPORTING STUDENT UNDERSTANDING OF STRUCTURE−PROPERTIES RELATIONSHIPS

Relating atomic/molecular behavior to observable phenomena requires students to make a large number of inferences, almost none of which are intuitively obvious. For example, to explain why a drop of ethanol feels cold on their hand, students must connect energy transfer from system to surroundings to the energy required to disrupt electrostatic forces between populations of ethanol molecules. That is, they must have a molecular-level view of phase changes anchored to the core ideas of "electrostatic and bonding interactions", "structure and properties", and "energy".[4] If we wanted students to discuss the structural origin of electrostatic forces between ethanol molecules, they would also be required to describe molecular charge distribution in terms of bond dipoles and molecular geometry. Virtually all of these inferences require explicit support for students to make molecular-level sense of why they feel colder when wet than when dry; staring at a liquid droplet does not evoke thoughts of electrostatic forces for most novices.

Strategies that have been successful in navigating the lived world of our experience tend not to map well onto scenarios at the atomic/molecular level. The intuited notion that more

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effort begets more result (called "Ohm's p-prim" by diSessa[27−29]) is useful when moving a refrigerator but can be less than helpful if inappropriately recruited to help explain why one substance boils at a higher temperature than another. For example, students might incorrectly claim that the molecule with more oxygens, more hydrogens, or more mass will always have the higher boiling point. Activation of intellectual resources like "Ohm's p-prim" in unproductive ways is often associated with construction of noncanonical molecular-level explanations.[30,31] We focus here on how students often coordinate small-grain knowledge elements in an unproductive way (rather than simply "getting a question wrong") to foreground our view that students possess a dynamic conceptual ecology, not coherent "wrong theories" of chemistry. In the context of a prompt, students may call on and connect a variety of "intellectual resources"[32−34] − including idea fragments intuited from experience, conceptual knowledge from coursework, and knowledge of procedures, to create a response that we as experts might categorize as "correct" or "incorrect". These individual resources are not "right" or "wrong" per se; rather, they can be woven together in more or less productive ways to address the task at hand. As learning environment designers, we should seek to help students develop and use appropriate resources to connect atomic/molecular behavior to phenomena of interest.

Chemistry, Life, the Universe, and Everything

There is evidence from research on college chemistry learning environments that making connections between topics and large-grain "core ideas" explicit helps students develop, organize, and appropriately use their intellectual resources.[6,17,18,20] Much of this research was done in the context of the transformed chemistry curriculum Chemistry, Life, the Universe, and Everything (or CLUE).[20] CLUE was conceptualized as embedded in four progressions of "core ideas" that underpin exploration of systems ranging from simple (e.g., two helium atoms approaching) to complex (e.g., endothermic dissolution of a salt in water). "Core ideas" underlie all topics in a discipline, have significant explanatory power, and can be taught at various levels of sophistication.[4,5] In CLUE, the core ideas woven together throughout the course are "electrostatic and bonding interactions", "atomic/molecular structure and properties", "energy", and "stability and change in chemical systems". Explicit emphasis on connections between topics and core ideas is believed to help students develop and organize their knowledge in order that it be appropriately cued when they encounter a new scenario to make sense of.[21] Thus, centering instruction on core ideas likely contributes to the ability of CLUE-enrolled students to offer sophisticated explanations for a range of phenomena including acid−base reactions,[24,25] atomic emission spectra,[23] and phase changes.[22]

The substantial success of CLUE in helping college students make molecular-level sense of phenomena motivated us to use CLUE core-idea progressions as the foundation for a high school chemistry course. During the summer of 2017, we assembled a team of teachers and researchers to adapt CLUE resources for high school audiences. Our adaptation process was guided by alignment between CLUE learning objectives and the physical science performance expectations (PEs) given by the NGSS for the 9−12 grade band. Materials were altered to be appropriate in scope for an introductory high school course while maintaining the integrity of the validated conceptual sequences. Starting with a well-developed, research-based curriculum enabled us to efficiently assemble a "rough draft" of HS-CLUE that consisted of the following: detailed teacher notes (specifying *Standards* alignment and day-by-day sequencing), annotated PowerPoint slides, a narrative text, and a series of assessment tasks. A detailed account of our curricular development program as well as the theoretical justification underpinning core-idea centered instruction has been published.[21]

Enacting HS-CLUE

Variations of the HS-CLUE "hypothetical curriculum" were enacted by four teacher developers during the 2017−2018 school year. Each teacher reported the details of their enactment in weekly logs administered via Qualtrics.[35,36] These logs asked teachers to reflect on their practice during the past week as well as what specific curricular resources were used and whether those resources were modified. If resources were modified, the log generated a question about what alterations were made and why they were made. Our focus in this piece is not on the heterogeneity of enactments, nor the drivers of that heterogeneity, but rather on the potential of HS-CLUE to promote student understanding of structure−properties relationships. Accordingly, our HS-CLUE data derives from the teacher (Ms. C) whose enactments best aligned with our hypothetical curriculum, as judged by her log responses.

■ METHODS

In assessing the impact of HS-CLUE on student understanding of structure−properties relationships, we examined (1) student perception of Lewis structures as models useful in explaining structure−property relationships, (2) student ability to draw representations of hydrogen bonding, and (3) student ability to explain the difference in boiling point between substances with the same molecular formula but different molecular structures. Each of these foci relate to one or more of the inferences needed to relate atomic-level structure to macroscopic properties. For instance, to explain and model the phenomenon of evaporative cooling, students must understand how the structure of a molecule is related to the electron distribution within that molecule, and in turn how unequal charge distribution affects the ways in which molecules interact with each other. They must be able to represent attractive interactions between molecules, vest those representations with meaning grounded in core ideas, and leverage their drawn model to explain the process of evaporation in terms of the energy required to disrupt the attractive interactions between molecules.

This study made use of a cross-sectional approach to compare aspects of how several different student cohorts understand structure−properties relationships. In general, cross-sectional studies make use of the same assessment prompts to gain insight into the understanding of students in different groups (in this case, three cohorts of high school students whose chemistry instruction is structured using different curricula).[37] By leveraging the same assessment prompts in three different contexts, we can gain insight into how different curricula might or might not support the development and flexible use of intellectual resources helpful in reasoning about structure−properties relationships.

The high school cohorts described in this study were instructed using three different curricula: HS-CLUE (discussed above), Modeling Instruction, and a traditionally structured

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Table 1. Demographics of Students in the Schools of the Participating Teachers[41−43]

School, by Teacher (Fall 2017)	Ethnicity of Students, %					Percentage of Students Who		
	White	Hispanic	Asian	African American	Two or More Races	Qualify for Reduced or Free Lunch	Met State Standards	Graduate
Ms. M's School	86.0	5.3	3.1	1.1	4.3	23	59	>95
Ms. C's School	51.6	3.3	35.5	8.2	1.3	5	73	>95
Mr. T's School	74.8	15.1	5.9	1.4	2.4	17	62	94
State Average	66.6	7.7	3.3	18.0	3.7	45	36	80

text. "Traditionally taught" students (taught by Mr. T) followed a sequence of topics that aligns closely with well-precedented norms established by Sienko and Plane in the late 1950s.[38] Accordingly, this course began with discussion of measurement followed by treatment of atomic structure, bonding, reactions (generally), solutions, and acid−base chemistry. "Modeling Instruction" chemistry (taught by Ms. M) is an outgrowth of research in physics education conducted at Arizona State University by David Hestenes. "Modeling chemistry" is structured around the evolution of atomic models with much of the course leveraging the Thomson model to explain phenomena.[39,40] More modern atomic models (such as the nuclear and Schrodinger models) are not discussed until relatively late in the semester. Although there is no published data attesting to the efficacy of "Modeling chemistry", there is a substantial community of educators who structure their coursework by its precepts.

Participants

A total of 240 students participated in this study. All participants were informed of the purpose of our investigation and given an opportunity to withdraw their data. All data submitted was deidentified in accordance with university Institutional Review Board requirements. Students were drawn from three public high schools in Michigan and were all enrolled in an introductory general chemistry course. Ms. M and Ms. C presided over courses open to all-comers, while Mr. T. presided over an honors introductory chemistry course. All course instructors possessed, at minimum, a bachelor's degree in chemistry and had taught for five or more years.

The three high school cohorts consisted of all students enrolled in Ms. C's and Mr. T.'s chemistry classes ($N = 96$ and 44, respectively) and a random sample of 100 students enrolled in Ms. M's chemistry classes. The demographic data for each of the three high schools from which our data were derived can be found in Table 1.[41] The percentage of students eligible for free or reduced lunch,[42] the percentage of students that met state standards, and the graduation rate for each high school population were compared to the state average[43] via a one-sample χ^2 test conducted using version 24 of *SPSS Statistics for Mac*.[44] Each of the high school contexts mentioned here have a significantly lower percentage of students who qualify for free or reduced lunch than the state average of 45% ($p < 0.001$ in all instances). Additionally, the percentage of students who met state standards in all three schools is significantly higher than the high school average of 36% for the state of Michigan ($p < 0.001$ in all instances). Finally, the percentage of students who graduate from the local school contexts of Ms. M, Ms. C, and Mr. T is significantly higher than the state average of 80% ($p < 0.001$ in all instances). The χ^2 values and effect sizes for each of these one-sample χ^2 tests can be found in Supporting Information Table S1. In sum, all three schools from which data were drawn may be considered relatively privileged contexts compared to what is typical in Michigan. For this reason, we judge comparisons among student responses derived from these contexts to be reasonable.

Instrument

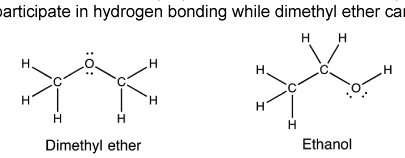
Several diagnostic prompts that were designed to examine the ability of the undergraduate CLUE curriculum to promote understanding of structure−property relationships were adapted for use in the high school classroom. Recall that we aimed to assess (1) whether students view Lewis structures as models, (2) whether students can reasonably represent intermolecular forces, and (3) students' ability to properly leverage core ideas when constructing a molecular-level explanation of the difference in boiling point between two substances. Our overall instrument is best considered a bundle of three individual items that each examine one of our assessment goals (Figure 2). Each of these items have been disclosed in prior publications, together with coding schemes capable of describing student responses. In the first of these, students were asked what information can be abstracted from a Lewis structure given appropriate chemistry knowledge (a survey known as the Implicit Information from Lewis

1. What information could you determine using a Lewis structure and any other chemistry knowledge you may have? (Mark all that may apply)

___ Polarity	___ Intermolecular forces
___ Element(s) present	___ Relative melting point
___ Reactivity	___ Geometry/shape
___ Type of bond(s)	___ Physical properties
___ Relative boiling point	___ Number of valence electrons
___ Number of bonds between particular atoms	___ Acidity/basicity
___ Bond angle	___ No information

2. Even though dimethyl ether and ethanol both have the same chemical formula (C_2H_6O) and molar mass (46 g/mol), you observe that dimethyl ether is a gas at room temperature, while ethanol is a liquid.

You hypothesize this difference in properties between the two compounds is because ethanol can participate in hydrogen bonding while dimethyl ether cannot.



Dimethyl ether   Ethanol

Please **draw** and **label** a representation below that clearly indicates where **hydrogen bonding** is present for **three** molecules of ethanol (CH_3CH_2OH).

3. Using the representation of hydrogen bonding you drew above, please explain **why** the ability of ethanol to form hydrogen bonds results in ethanol having a higher boiling point than dimethyl ether.

Figure 2. Three-part assessment given to three student cohorts to assess: (1) whether students view Lewis structures as models, (2) whether students can reasonably represent intermolecular forces, and (3) students' ability to properly leverage core ideas when constructing a molecular-level explanation of the difference in boiling point between two substances. Prompt spacing has been condensed from the item given to students.

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Structures Instrument or IILSI). The IILSI was developed by the Cooper group in 2012 and validated over the course of 3 years with over 8000 student responses.[45,46] It has been in use in various assessment contexts since then. Of principle interest for our purposes was whether students selected they could determine "relative melting point", "relative boiling point", and/or "physical properties" from a substance's Lewis structure and "any other chemistry knowledge" they had.

We argue that vesting a Lewis structure with chemical information sufficient to enable prediction of properties is, in essence, viewing a Lewis structure as a model. By "model" we mean here what Schwarz and colleagues characterize as a "scientific model". That is, "a scientific representation that abstracts and simplifies a system by focusing on key features to explain and predict scientific phenomena".[47] To an expert, Lewis structures define the connectivity of atoms in a molecule which, together with knowledge of the relative effective nuclear charges of these elements, enables inferences as to the charge distribution in that molecule. Predictions about relative macroscopic properties can be made from knowledge of the comparative strength of attractive interactions between molecules, which is a function of molecular charge distribution. It should be noted that there is no guarantee that students who say they can extract information on properties from Lewis structures actually can.

The second of our three prompts asked students to draw a representation of hydrogen bonding for three molecules of ethanol. This prompt was part of the Intermolecular Forces Assessment (or IMFA), an instrument in which students were asked to draw and subsequently explain a variety of intermolecular forces. Development and validation of the IMFA is reported elsewhere.[17] Asking students to draw the location of hydrogen bonding provides unambiguous evidence as to whether students understand that intermolecular forces are between (rather than within) molecules. Student text responses to, "What is your current understanding of the terms hydrogen bonding, dipole−dipole interactions, and London dispersion forces?" often fail to specify the location of IMFs.[17] Recognition that, in small molecules, IMFs are located between molecules (not within them) is a step toward providing particulate-level explanations of phase changes as IMFs, not covalent bonds, are disrupted when a substance transitions from solid, to liquid, to gas.

The third and final prompt asked students to explain why the ability of ethanol to form hydrogen bonds resulted in it having a higher boiling point than dimethyl ether. The development and validation of this task was reported by Underwood et al.[48] This item provides an opportunity for students to leverage their intellectual resources to provide a particulate-level explanation for a difference in properties. Ideally, students would mention both that the intermolecular interactions between ethanol molecules are stronger than those between dimethyl ether molecules and also that it takes more energy to disrupt stronger IMFs. Explicit and proper articulation of the role of energy in an explanation provides evidence that students have a core-idea-based notion of what "stronger interaction" means in a chemical system. Further, it may reflect students' recognition that energy is a core idea that is useful in making sense of phenomena across the whole of chemistry.

All student participants in this study were given our three-part assessment following instruction on the skill of "Lewis structure drawing" and discussion of intermolecular forces (IMFs). As the research team does not have detailed accounts of the enactments of Ms. M and Mr. T (e.g., classroom observations, weekly logs), we have no evidence as to whether either traditionally structured or Modeling courses supported students in linking IMFs to properties in a meaningful way. Accordingly, we do not make causal claims about how particular aspects of traditional and Modeling learning environments affect student responses to our assessment. Additionally, the duration between explicit discussion of IMFs and data collection differed among the three cohorts (Figure 3). HS-CLUE students were given the instrument at the end of their first semester of instruction (during the fall of 2017) and students taught according to the traditional and Modeling Chemistry curricula were given the assessment at the end of their second semester of instruction (during the spring of 2018). It should be noted that "discussion of intermolecular forces" almost certainly looked different in different courses. In Ms. C's enactment of HS-CLUE, IMFs were introduced early in the course and the forces and energy changes associated with them were built and elaborated throughout both semesters. In Ms. M's enactment of Modeling Chemistry, by contrast, students proceeded through much of the course with a model of the atom that does not include much detail about internal structure (i.e., the Thomson model).[40] The idea that atoms have a dense, positively charged nucleus and electrons in different energy levels was not introduced until the latter third of the course. Intermolecular forces resultant from distorted charge distributions in molecules were one of the last topics discussed. Mr. T introduced "types of IMFs" to his traditionally taught course in the first semester and did not revisit them to any great extent in the second semester. As assessment administration was somewhat removed from discussion of IMFs in Mr. T's class; the data reported here may underestimate the understanding of traditionally taught students. However, we would argue that attractive forces between molecules are integral to explaining many phenomena and should feature prominently in both semesters of general chemistry. As an example, "solutions" were one of the last topics taught in Mr. T's class, and it is not clear how to explain the enthalpic contributors to solubility without explicit invocation of IMFs. All high school cohorts completed the instrument tasks as a pencil-and-paper formative assessment.

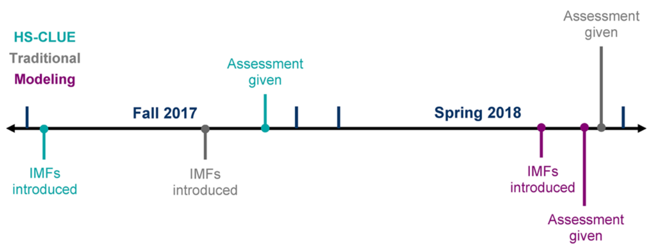

Figure 3. Timeline representing approximately when, in each learning environment, intermolecular forces (IMFs) were introduced and when our 3-part assessment was given. Note that this timeline captures only introduction of IMFs, not continued discussion of forces between molecules. HS-CLUE students returned to intermolecular forces throughout both semesters of the course.

Data Analysis

Analysis of student responses to our three-part instrument occurred separately for each individual item. Our threshold for significance in this study was a $p \leq 0.01$. For the first item

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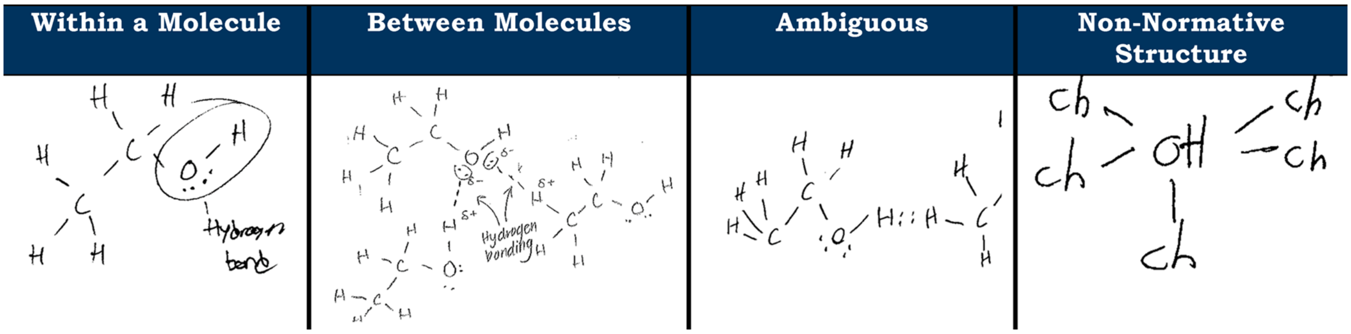

Figure 4. Student responses exemplifying each of the four major codes used to describe drawings of hydrogen bonding among ethanol molecules.

(derived from the IILSI), whether a student indicated they could determine "relative melting point", "relative boiling point", and/or "physical properties" from a Lewis structure was noted. Responses were examined as .pdfs scanned from the paper forms used by students. A series of Pearson's χ^2 tests were used to analyze the relationship between learning environment enrollment and IILSI statement selection. For results that showed a significant association, the strength of the relationship was calculated using Cramer's V and interpreted using guidelines published by Cohen.[49] According to these guidelines, a small effect would have a Cramer's V of 0.1. A medium effect would have a Cramer's V of 0.3, and a large effect would have a Cramer's V of 0.5.

Posthoc analysis of each χ^2 test which showed a significant association between variables was conducted in order to support inferences as to the driver(s) of that significance. This analysis involved comparing the standardized residual (calculated by SPSS[44]) for each cell of a contingency table to the critical value, which was 2.58 for this study. Standardized residuals provided a measure of how different the observed value was from the expected value for each cell.[50] The sign of these residuals indicated whether an observed value was greater than the expected value (in which case it was positive), or less than the expected value (in which case it was negative). The size of the standardized residual let us determine whether a particular cell was driving the significance observed for the overall χ^2 test; residuals that were greater in magnitude than the critical value were deemed primary drivers for the relationship.

Analysis of Student Hydrogen Bond Drawings

The second item, in which students were asked to represent hydrogen bonds present in ethanol molecules, was analyzed using a coding scheme adapted from Cooper et al.[17] Two authors (R.L.S. and R.L.M.) analyzed data from our three cohorts using Cooper et al.'s original coding scheme and discussed coding scheme ability to fully represent the data set. From this discussion, the need for a new code, "non-normative structure", was established. Thus, the four major categories within which student responses could fall were the following: within, between, ambiguous, and non-normative structure. A "within" code indicated that H-bonds were depicted as within a molecule (i.e., by circling a covalent bond). Student drawings coded as illustrating H-bonds "between" ethanol molecules were required to clearly show interactions between different molecules. If H-bond location was not clearly specified, a code of "ambiguous" was given. Relative to prior published work, few "ambiguous" codes were given for responses in our data set. Finally, students who were unable to draw a recognizable representation of ethanol were coded as depicting a "non-normative structure". Depictions of student responses corresponding to each of these categories can be found in Figure 4.

In addition to the four major codes discussed above, less common codes defined by the original Cooper et al. work were also used (albeit sparingly). Student drawings could be coded as "within and between" if hydrogen bonds were shown to be both within and also between molecules. Indication that no H-bonds were present was indicated by a "not present" code. Finally, students who expressed in words or drawings that they did not know how to answer the prompt were given a "student DK (does not know)" code.

Importantly, as in the original work, the codes "within" or "between" do not indicate canonical correctness but rather relative H-bond location. A student that indicates H-bonding as present between alkyl hydrogens on two ethanol molecules would thus be coded as depicting H-bonds "between" two molecules. Using drawings alone, it is very difficult to unambiguously determine correct intermolecular force depiction due in large part to different ways students indicate charge distribution.

To establish the reliability of the revised coding scheme, two of the authors (R.L.S. and R.L.M.) coded a random sample of 31% of the total data set (N = 75, 25 from each cohort). Cohort identifiers were removed from the data and replaced with generic names (e.g., "cohort A", "cohort B") to minimize bias. Agreement between the jointly coded responses merited a Cohen's Kappa of 0.87 (91% agreement). One author (R.L.M.) coded the remaining 69% of student hydrogen bonding drawings (N = 169). The presence of significant associations between student drawings of hydrogen bonds as "between" molecules and learning environment enrollment were determined via a χ^2 test. For significant associations, effect size was reported in terms of Cramer's V and interpreted using guidelines published by Cohen.[49] Post hoc analysis of the χ^2 test contingency table enabled us to determine what drove observed significance; each cell with a standardized residual greater in magnitude than 2.58 was deemed a primary driver of the significant relationship.

Analysis of Student Boiling Point Explanations

The third and final item in our three-part instrument, in which students were asked to explain why ethanol's ability to hydrogen bond results in it having a higher boiling point than dimethyl ether, was analyzed using a coding scheme adapted from Underwood et al.[48] Data from scanned .pdfs was entered into an Excel spreadsheet that included both a cohort identifier and five-digit random ID for each student. For

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J. Chem. Educ. 2019, 96, 1327−1340

coding, the cohort identifier was hidden and the answers were sorted by random ID from lowest to highest value in order to randomly distribute responses from each cohort. Two authors (R.L.S. and R.L.M.) adapted the categories put forth by Underwood et al. and elaborated the coding scheme with exemplar student responses of each code. The fully elaborated coding scheme can be found in the Supporting Information. Once precisely defined, the five codes derived from work by Underwood et al. were capable of fully describing our data set.

The five codes used in this analysis, together with the code definition and an exemplar response, can be found in Table 2. If a student response indicated that they did not know the answer or they neglected to respond to the prompt, they received the code "student does not know/no response". If inaccurate or unrelated reasoning was used in a student's explanation, they received a "non-normative" code. Defining what constituted "inaccurate or unrelated reasoning" proved one of the signature challenges of coding scheme refinement. In particular, it was challenging to parse what students meant by "bond". Ultimately, if students used the word "bond" outside of the context of "hydrogen bonding", and provided no further evidence they meant IMFs, their responses were coded as non-normative. Given the large amount of data demonstrating that students often mean "covalent bonds" when they say "hydrogen bonds", it seems reasonable to assume the two are conflated when students refer to vaguely defined "bonds".[17,18] For example, we cannot know if students mean covalent bonds or IMFs when they say, "dimethyl ether bonds" in the statement: "hydrogen bonds are much stronger and require more energy to break than dimethyl ether bonds." It should be emphasized that coding explanations which vaguely mention bonds as "non-normative" rests on assumptions made by the developer team; we cannot be certain that "non-normative" accurately describes the reasoning underpinning all responses that were coded as such. It is possible that students offered vague or incomplete answers because they were unsure how much detail was appropriate to address the prompt.

The remaining three codes represent a hierarchy of reasonable responses. If students correctly mentioned hydrogen bonding in their explanation but did not invoke either the relative strength of intermolecular interactions between molecules of the two substances or energy, their response was coded as "H-bonding". Student responses that explained that the boiling point differential was due to the differing strength of IMFs but made no mention of energy were coded as "H-bonding + Strength of Interactions". Crucially, to merit this code, students had to use comparative language in their explanation. A student who wrote "hydrogen bonds are strong" would therefore not receive this code while a student that wrote, "hydrogen bonds are stronger than dipole−dipole interactions" would. Finally, if student explanations related the strength of interactions to the relative amount of energy required to disrupt those interactions, they were coded as "H-bonding + Strength of Interactions + Energy".

In order to determine inter-rater reliability, two authors (R.L.S. and R.L.M.) jointly coded approximately 31% of the data set (N = 75, 25 from each cohort). Neither coder had knowledge of the cohort from which any response was derived. The two coders agreed on the coding of 95% of these responses, with a Cohen's Kappa of 0.91. One author (R.L.M.) coded the remaining explanations (N = 169). The presence of significant association between learning environment enrollment and the distribution of codes characterizing student

Table 2. Codes Describing Student Boiling Point Explanations

Code	Definition	Example
Student Does Not Know/ No Response	Student expresses that they do not know the answer; they do not provide any reasoning.	*I do not know*
Non-normative	Student uses scientifically inaccurate or unrelated reasoning.	Because ethanol has space to bond oxygen with hydrogen
Hydrogen Bonding	Student explicitly mentions hydrogen bonding in their reasoning.	*Because Ethanol can form H-bonds where dimethyl ether cannot*
Hydrogen Bonding and Strength of Bonds/Interactions	Student explicitly mentions hydrogen bonding; student compares strength of intermolecular forces or bonds in their argument, ranking strengths or referring to bonds/interactions as being more difficult to break/interrupt.	*Hydrogen bonding is the strongest IMFA, meaning ethanol will have a harder time having molecules separated from each other meaning a high bp. Dimethyl ether can only have a weaker IMFA, thus lower bp*
Hydrogen Bonding, Strength of Bonds/Interactions and Energy	Student explicitly mentions hydrogen bonding and strength of bonds/interactions; student mentions energy in terms of it being higher/lower or more/less than another entity. Student may use the term "heat" instead of energy.	*Hydrogen bonds are a stronger attraction than dipole−dipole so they're harder to break and it takes more heat to break them*

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J. Chem. Educ. 2019, 96, 1327−1340

boiling point explanations was determined using a Pearson's χ^2 test. Effect size was reported in terms of Cramer's V and interpreted using guidelines published by Cohen.[49] Posthoc analysis was conducted on each cell of the χ^2 test contingency table to discern which cell(s) were driving significance.

■ FINDINGS

Association between Learning Environment Enrollment and Selection of Physical-Properties Relevant IILSI Statements

Examination of student responses on the Implicit Information from Lewis Structures Instrument (or IILSI) focused on whether students selected they could deduce information on "relative melting point", "relative boiling point", and/or "physical properties" from a substance's Lewis structure.[45] The percentage of students in each cohort who selected each of the physical-properties relevant IILSI responses is indicated in Figure 5.

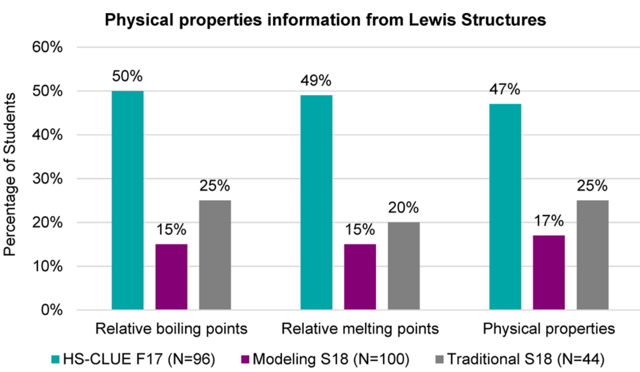

Figure 5. Percentage of students from three classroom cohorts that indicated they could determine relative boiling points, relative melting points, or physical properties from a substance's Lewis structure.

Approximately half of HS-CLUE-enrolled students indicated they could determine information on a substance's relative boiling point, relative melting point, and general physical properties from its Lewis structure. This is consistent with earlier reports in which approximately half of CLUE-enrolled undergraduates indicated the same.[6] Given the markedly lower percentage of Modeling-enrolled and traditionally taught students who selected that they could discern information on physical properties from a Lewis structure, it is perhaps unsurprising that there exists a significant association between learning environment enrollment and selection of a properties relevant IILSI statement. The relationship between learning environment enrollment and IILSI statement selection was significant for each statement (with a $p < 0.001$) and had a medium effect size (Table 3).

Posthoc analysis of the χ^2 tests examining association between learning environment enrollment and IILSI statement selection showed that, for all three tests, a main driver of significance was the positive association between enrolling in HS-CLUE and selecting an IILSI statement (Figure 6). For two of the three χ^2 tests, negative association between enrollment in a course taught according to the Modeling curriculum and selection of a physical-properties relevant IILSI statement was also a primary driver.

Table 3. Association between Learning Environment Enrollment and Selection of a Properties Relevant IILSI Statement

IILSI Statement	χ^2 Value	df	p-Value	Cramer's V
Relative boiling point	29.0	2	<0.001	0.35
Relative melting point	29.3	2	<0.001	0.35
Physical properties	21.4	2	<0.001	0.30

Association between Learning Environment Enrollment and Depictions of Hydrogen Bonds as "between" Molecules

Students' depictions of hydrogen bonding present among three molecules of ethanol were typically categorized as showing IMFs "between" molecules or "within" molecules, or as consisting of a non-normative structural representation that could not be interpreted. Figure 7 represents the percentage of students from each cohort whose drawings were coded with one of these three major codes.

Around half of HS-CLUE and traditionally taught students depicted hydrogen bonds as between molecules of ethanol. However, the story was markedly different for Modeling-enrolled students, approximately 1/4 of whom could not draw recognizable Lewis structures. Additionally, over half of Modeling-enrolled students indicated that hydrogen bonds were "within" molecules of ethanol. A significant association was found between learning environment enrollment and drawing H-bonds as "between" molecules, $\chi^2(2) = 34.0$, $p < 0.001$, Cramer's V = 0.38. Posthoc analysis (Figure 8) showed that negative association between enrollment in the Modeling course and drawing hydrogen bonds as "between" molecules of ethanol was a primary driver of significance. Other associations that drove significance include positive association between HS-CLUE enrollment and drawing H-bonds as "between" molecules, and positive association between enrollment in a Modeling-based course and drawing H-bonds as "within" molecules. Enrollment in the traditionally structured course was also positively associated with drawing H-bonds as "between" molecules, though this association did not meet our criteria for "primary driver of significance".

Association between Learning Environment Enrollment and Distribution of Boiling Point Explanation Codes

Most student explanations of the boiling point differential between dimethyl ether and ethanol clustered under one of four codes: "Non-normative", "H-bonding", "H-bonding + Strength", and "H-bonding + Strength + Energy". The distribution of these four main codes for the explanations of each of the three student cohorts surveyed can be found in Figure 9. Very few students' responses were described by the "student doesn't know/no response" code (6 students total, 2 enrolled in the traditionally structured course and 4 taught according to Modeling Instruction). For the purposes of analyzing association between learning environment enrollment and student explanations, these students were combined with those who offered non-normative explanations in order to not violate an assumption of the χ^2 test.

The majority of HS-CLUE student explanations were coded as either "H-bonding + Strength" or "H-bonding + Strength + Energy", indicating that most HS-CLUE-enrolled students explicitly mentioned interaction strength when explaining boiling point differences between two substances. This contrasts starkly with the distribution of explanation codes for traditionally taught and Modeling-enrolled students. Most students taught according to these two curricula offered non-

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J. Chem. Educ. 2019, 96, 1327−1340

Curriculum	Relative boiling point		Relative melting point		Physical Properties	
	Selected	Not Selected	Selected	Not Selected	Selected	Not Selected
HS-CLUE	**3.4 Expected: 29.6 Observed: 48**	-2.3 Expected: 66.4 Observed: 48	**3.5 Expected: 28.4 Observed: 47**	-2.3 Expected: 67.6 Observed: 49	**2.9 Expected: 29.2 Observed: 45**	-1.9 Expected: 66.8 Observed: 51
Modeling	**-2.9 Expected: 30.8 Observed: 15**	1.9 Expected: 69.2 Observed: 85	**-2.7 Expected: 29.6 Observed: 15**	1.7 Expected: 70.4 Observed: 85	-2.4 Expected: 30.4 Observed: 17	1.6 Expected: 69.6 Observed: 83
Traditional	-0.7 Expected: 13.6 Observed: 11	0.5 Expected: 30.4 Observed: 33	-1.1 Expected: 13.0 Observed: 9	0.7 Expected: 31.0 Observed: 35	-0.7 Expected: 13.4 Observed: 11	0.4 Expected: 30.6 Observed: 33

Color key for standardized residual value (-3 to 3)

Figure 6. Contingency tables for the χ^2 tests examining association between learning environment enrollment and selection of each of the three properties relevant IILSI statements. In each cell, the standardized residual value is reported along with the observed and expected values. Standardized residuals larger than the critical value (±2.58) are in bold. To visualize the sign and magnitude of the standardized residuals, the cells are color coded from dark blue (most positive) to dark red (most negative).

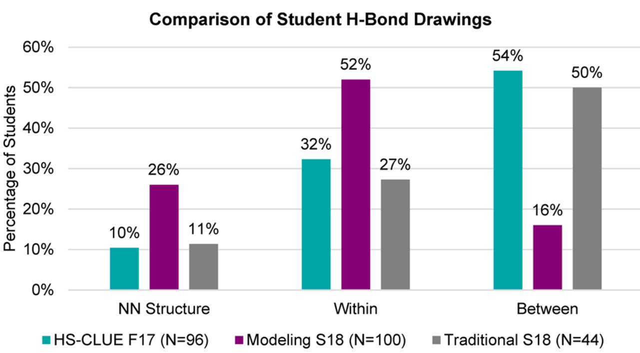

Figure 7. Percentage of students from each cohort who depicted hydrogen bonding among ethanol molecules as "between" molecules or "within" molecules, or who drew a "non-normative structure".

Curriculum	Hydrogen bonds drawn between ethanol molecules	
	Yes	No
HS-CLUE	**2.7 Expected: 36.0 Observed: 52**	-2.1 Expected: 60.0 Observed: 44
Modeling	**-3.5 Expected: 37.5 Observed: 16**	**2.7 Expected: 62.5 Observed: 84**
Traditional	1.4 Expected: 16.5 Observed: 22	-1.0 Expected: 27.5 Observed: 22

Color key for standardized residual value (-3 to 3)

Figure 8. Contingency table for the χ^2 test examining association between learning environment enrollment and drawing H-bonds as "between" molecules of ethanol. In each cell, the standardized residual value is reported along with the observed and expected values. Standardized residuals larger than the critical value (±2.58) are in bold. To visualize the sign and magnitude of the standardized residuals, the cells are color coded from dark blue (most positive) to dark red (most negative).

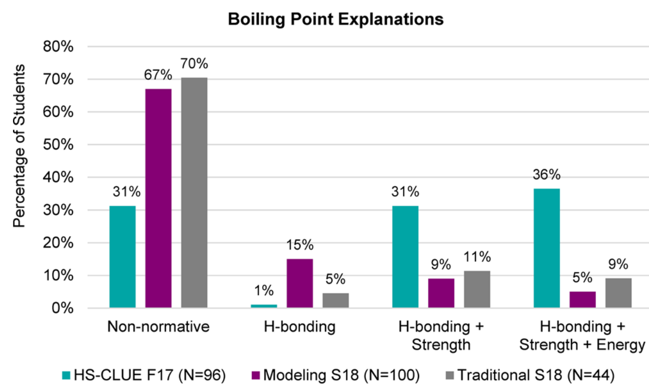

Figure 9. Percentage of students, from each of the three cohorts assessed, whose boiling point explanations merited codes of "non-normative", "H-bonding", "H-bonding + Strength", or "H-bonding + Strength + Energy".

Curriculum	Boiling Point Explanation Code			
	Non-normative/ None	H-bonding	H-bonding + Strength of Interactions	H-bonding + Strength of Interactions + Energy
HS-CLUE	**-3.2 Expected: 53.6 Observed: 30**	-2.3 Expected: 7.2 Observed: 1	**3.0 Expected: 17.6 Observed: 30**	**4.1 Expected: 17.6 Observed: 35**
Modeling	2.0 Expected: 55.8 Observed: 71	**2.7 Expected: 7.5 Observed: 15**	-2.2 Expected: 18.3 Observed: 9	**-3.1 Expected: 18.3 Observed: 5**
Traditional	1.7 Expected: 24.6 Observed: 33	-0.7 Expected: 3.3 Observed: 2	-1.1 Expected: 8.1 Observed: 5	-1.4 Expected: 8.1 Observed: 4

Color key for standardized residual value (-3 to 4)

Figure 10. Contingency table for the χ^2 test examining association between learning environment enrollment and the distribution of codes characterizing student boiling point explanations. In each cell, the standardized residual value is reported along with the observed and expected values. Standardized residuals larger than the critical value (±2.58) are in bold. To visualize the sign and magnitude of the standardized residuals, the cells are color coded from dark blue (most positive) to dark red (most negative).

normative boiling point explanations. A χ^2 test of this data set found a significant association between learning environment enrollment and distribution of boiling point explanation codes, $\chi^2(6) = 74.4$, $p < 0.001$, Cramer's V = 0.39. Posthoc analysis of the results of this test (Figure 10) showed that positive associations between enrollment in HS-CLUE and offering an explanation coded as "H-Bonding + Strength + Energy" or "H-Bonding + Strength" were primary drivers of significance. That is, the HS-CLUE-enrolled students explicitly invoked strength of interactions and energy in their explanations far more than

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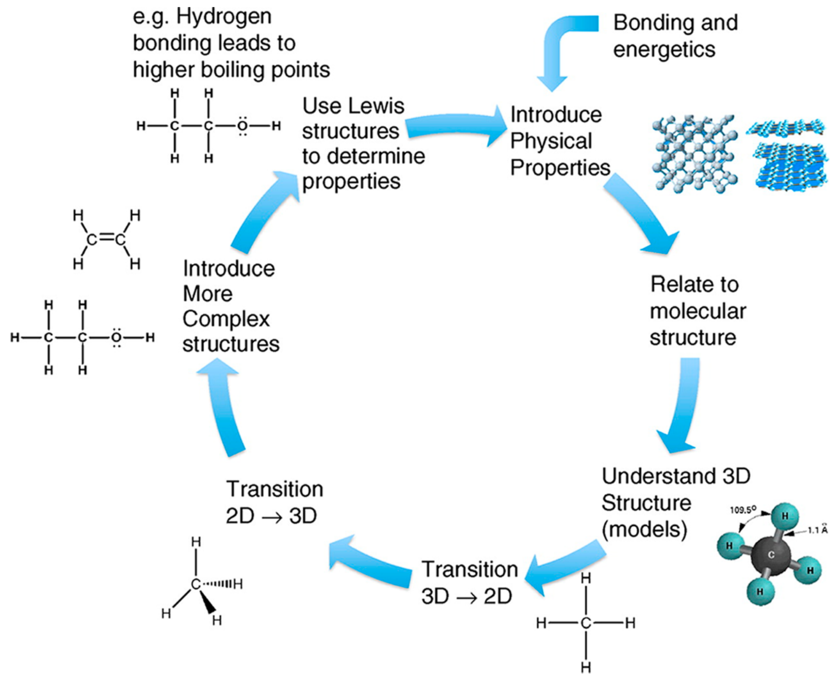

Figure 11. CLUE conceptual progression for relating molecular-level structure to properties. Reprinted with permission from ref 6. Copyright 2012 American Chemical Society.

would be expected by chance. This is quite encouraging as "energy" is one of the Disciplinary Core Ideas given by the NGSS for physical science. Integration of this core idea in the context of a Performance Expectation can be seen in HS-PS3-2, which specifically indicates that students should "Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motion of particles and energy associated with the relative position of particles." Three other cells in the contingency table also drove the significant relationship observed for the χ^2 test: negative association between enrollment in the Modeling course and constructing an explanation coded as "H-bonding + Strength + Energy", positive association between taking part in the Modeling course and writing an explanation coded as "H-bonding", and negative association between HS-CLUE enrollment and offering an explanation coded as "Non-Normative".

Relationship between Hydrogen Bond Drawings and Boiling Point Explanations

In order to evaluate whether explanation quality was linked to drawing hydrogen bonds between ethanol molecules, a χ^2 test was performed for each cohort. Specifically, association was examined between students' tendency to depict hydrogen bonds as between molecules and whether their explanation was coded using one of the three normative codes ("H-bonding", "H-bonding + Strength", "H-bonding + Strength + Energy"). For HS-CLUE, a significant association exists between constructing a reasonable boiling point explanation and drawing hydrogen bonds as between ethanol molecules, $\chi^2(1) = 13.3$, $p < 0.001$, Cramer's V = 0.37. No significant association was observed between the explanations and drawings of students enrolled in a traditionally structured curriculum ($p = 0.08$). Due to the low number of Modeling-enrolled students who offered normative explanations and also drew hydrogen bonds as between molecules, a χ^2 test would not be valid for this data set. However, a Fisher's exact test found no significant relationship between the drawings and explanations of Modeling-enrolled students ($p = 1.0$).

DISCUSSION AND CONCLUSIONS

Students' Views on Lewis Structures as Models Vested with Chemical Information Useful in Explaining Physical Properties

In and of itself, drawing a Lewis structure amounts to very little. Once the "rules of the game" are known, it is very possible to construct 2-dimensional "cartoons" for a whole range of structures without the slightest clue what the structures themselves mean. Past work by Cooper et al. has shown that college students often struggle to draw Lewis structures and, just as importantly, have no idea why they are drawing them in the first place.[51] This work concluded that students taught "Lewis structure drawing" as a disconnected skill tend to view it as following a set of obscure rules en route to something meaningless, a textbook example of "school science" at its worst. As there is no compelling reason to draw a Lewis structure apart from enabling the prediction of chemical and physical properties, it makes sense to situate "Lewis structure drawing" within a conceptual progression that builds toward relating molecular-level structure to macroscopic properties (Figure 11). Indeed, contextualizing structure drawing in this manner has enabled significant improvements in college students' ability to draw Lewis structures relative to a matched cohort of traditionally instructed students.[6] Further, significantly more CLUE-enrolled undergraduates reported an ability to intuit information on properties from Lewis structures than students taught traditionally.[46]

It is interesting that the percentage of HS-CLUE students who appear to view Lewis structures as models is approximately the same as the percentage of CLUE-enrolled undergraduates who previously reported this perspective.[6] Additionally, positive association between enrollment in HS-CLUE and indicating Lewis structures can be used as models

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drove significance in all three scenarios examined via χ^2 test. This finding supports the claim that CLUE conceptual progressions adapted for use in high school may provide a way to help students establish meaning in 2-dimensional molecular "cartoons". Negative associations between enrollment in a traditional or Modeling course and selecting a physical-properties relevant IILSI statement suggests that these curricula may not address "Lewis structures as models", even though such models play a central role in the NGSS. It is also possible that students enrolled in these classes were confused by the prompt. Indeed, several students in Mr. T's class were unsure what was meant by "any other chemistry knowledge you may have."

Students' Ability To Reasonably Represent Attractive Forces between Molecules

In order to provide a molecular-level explanation for phenomena such as evaporative cooling, students need to recognize that attractive electrostatic forces between molecules are disrupted when substances evaporate and that this disruption requires energy from the surroundings. However, the differences between IMFs and covalent bonds are subtle and difficult and must be explicitly constructed; otherwise, we should not be surprised when students offer explanations for boiling or evaporative cooling in which molecules are blown apart. Drawings of particular IMFs provide evidence that students appreciate that these forces are *between* rather than *within* molecules. Student definitions or descriptions of particular IMFs are often too vague to reliably discern whether they are referring to inter- or intramolecular forces.[17]

Students enrolled in HS-CLUE were more likely to draw hydrogen bonds as between molecules than would be predicted by chance. This positive association may indicate that the substantial emphasis HS-CLUE places upon forces between molecules has helped students construct a more accurate understanding of IMFs. Indeed, the relationship between taking part in HS-CLUE and drawing H-bonds between molecules was a primary driver for the significant association between learning environment enrollment and IMF drawings observed for our data set. Taking part in a traditionally structured learning environment was also positively associated with drawing hydrogen bonds as between molecules, though this association was not a primary driver of significance for the overall χ^2 test. A strong negative association between enrollment in a course structured according to Modeling Instruction and drawing hydrogen bonds as between molecules also drove significance. This is unsurprising as 78% of Modeling-enrolled students drew hydrogen bonds as within a molecule or constructed unintelligible structural representations (despite being given the Lewis structure in the prompt). The distribution of drawing codes noted for our Modeling-enrolled student cohort is consistent with earlier work that showed similar patterns of response among traditionally taught college students.[18] We should note that Modeling-enrolled students were instructed how to draw Lewis structures prior to assessment administration, and so their task performance cannot be attributed to unfamiliarity with the "rules of the game" for Lewis structure drawing. It should be mentioned that, from examination of this task alone, it is impossible to say whether appropriately depicting IMFs as interactions between ethanol molecules represents a deep understanding of electrostatic forces between molecules or whether it simply reflects practiced responses devoid of meaning. However, one might expect that students who understand what IMFs are are more likely to provide appropriate explanations about properties such as boiling points.

Explaining Observable Properties Using Molecular-Level Reasoning

HS-CLUE-enrolled students overwhelmingly centered their explanations about boiling point trends on the strength of interactions between molecules (67%), and 36% integrated both interactions and energy into their response. As a consequence of this, positive associations between enrollment in HS-CLUE and invocation of energy and/or strength of interactions in boiling point explanations were primary drivers of significance for our χ^2 test (see Figure 10). Given the emphasis the NGSS place upon energy as a disciplinary core idea in physical science coursework (and also as a Crosscutting Concept), we find this finding tremendously encouraging. We should like to see evidence that all students understand "strength" (of interactions or bonds) as a function of the amount of energy needed to disrupt electrostatic forces. In the absence of this evidence, it is impossible to know whether students appreciate the central importance of energy in discussions of bonding and IMFs.

That the majority of Modeling and traditionally taught students generated non-normative explanations (67% and 70%, respectively) indicates that they were unable to activate, coordinate, and use the necessary resources in the context of the question being asked. From this assessment alone, we cannot know whether they possess the requisite resources needed to relate structure to properties. However, we *can* say with some certainty that they could not call on them when asked in the manner of our third prompt. The significant association between learning environment enrollment and the distribution of codes for student boiling point explanations (as indicated by the p-value less than 0.001 and medium effect size) combined with a posthoc analysis of this relationship suggests that focusing a high school course explicitly on connecting and elaborating progressions of core ideas through engagement with contextualized SEPs may better prepare students for relating atomic/molecular behavior to properties than curricula centered on a particular SEP or well-precedented topical sequence. However, much more research is needed to firmly establish a causal link between curriculum adoption and student preparation for molecular-level sense-making.

As recognition that hydrogen bonds are interactions between molecules was a prerequisite to receiving any sort of normative code for a boiling point explanation, one might expect to see a relationship between the explanation code and whether students drew hydrogen bonds as between molecules. Indeed, such a connection exists among HS-CLUE students. This provides some evidence that depiction of IMFs was not perceived as a decontextualized skill by these students. In contrast, no relationship exists between Modeling and traditionally taught students' drawings and explanations, as judged by p-values for a χ^2 and Fisher's exact test ($p > 0.01$). This may indicate that many traditionally taught or Modeling-enrolled students who drew hydrogen bonds as between molecules were replicating memorized representations without a concomitant understanding of the consequences of such interactions (as evidenced by the low numbers of students who invoke energy arguments).

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We should note that not all of our cohort instructors believed their students should be able to construct models and explanations as called for in our three-part assessment. For example, Ms. M. reported that they "covered IMFs but did not have students draw and label IMFs between compounds... (IMF drawing) is something that is covered a lot more in AP chem." This is illustrative of a disconnect between teacher expectations and the sort of knowledge-in-use called for by the NGSS. The second and third parts of our assessment align closely with several performance expectations. For instance, HS-PS3-5 calls for development and use of "a model of two objects interacting through electric or magnetic fields", and HS-PS1-3 explicitly emphasizes the relationship between bulk-scale properties and "the strength of electric forces *between* particles" (emphasis added).[1] NGSS performance expectations are intended as goals for all students, and it is almost certain that many teachers will have to think carefully about their prior conceptions of what students should be able to do. Curriculum developers and researchers will need to work together with teachers to craft instructional environments that can support the ambitious vision detailed in the Framework in a manner accessible to everyone. Indeed, the study presented here serves as some evidence that high school students enrolled in an introductory chemistry are fully capable of linking structure to properties so long as such reasoning is a curricular focus.

Supporting Sensemaking in Chemistry

Students are making sense of a phenomenon when they draw on and use knowledge to build and refine explanations and/or models for that phenomenon. As is clearly evident from the legions of papers on student "misconceptions" in chemistry,[52−55] it is not possible to construct and critique molecular-level explanations or models for observable, engaging phenomena without having already developed robust and flexible command of a host of resources of different types. Further, these resources are very rarely intuitively obvious, and so their development and coordination must be fostered in large part by instruction. That is, they cannot be intuited by simply investigating a macroscopic phenomenon (even a very interesting one). If we are to have any hope of realizing the vision of the NGSS in the context of high school chemistry, we must carefully consider how to support students' development and use of the knowledge needed to make particulate-level sense of relatable scenarios.

We claim that grounding a curriculum first and foremost in slowly developed and interconnected progressions of core ideas is a potentially powerful means of equipping students to eventually predict, explain, and model the world they can see in terms of molecular behavior. This claim is grounded in nearly a decade of college-level curriculum development, analysis, and refinement.[17,18,20,22−24] Here we have provided preliminary evidence that, relative to students taught according to a traditional and transformed curriculum (Modeling Instruction), the HS-CLUE students assessed were better equipped for molecular-level sensemaking. Further studies examining HS-CLUE student use of knowledge in sensemaking will be reported in due course.

■ LIMITATIONS

As is the case with every study, the study described here has limitations that should be mentioned. First, our data were derived from students enrolled in one of three teacher's curricular enactments. Although we have some evidence that Ms. C's classes were aligned closely with communally developed HS-CLUE materials (via weekly logs), we can say nothing about how representative Ms. M's classes are of typical classes taught using Modeling Instruction. Likewise, we cannot say anything about how representative Mr. T's class is of "traditional instruction"; we can only note that his syllabus consisted of a sequence of topics that closely matches historic norms.[38] It is therefore not possible to generalize our results beyond the classes directly examined. Additionally, simply because particular intellectual resources were not activated in the context of a given set of prompts does not necessarily indicate that students lack facility with those resources. A more scaffolded prompt specifically asking students to link scientific principles to a claim by way of sound reasoning may have elicited better responses from some students. Some of the students surveyed may have been unfamiliar with the formatting of the questions presented. Indeed, many of Mr. T's students reported not understanding what was meant by "any other chemistry knowledge you may have", which is part of the IILSI. Further, as noted above, at least one of our enacting teachers did not believe her students should be able to relate structure to properties as called for in our assessment. As a consequence of this, her students may not have been adequately prepared to engage in the practice of "constructing explanations". From an analysis perspective, we assumed boiling point explanations that vaguely mentioned "bonds" represented conflation of IMFs and covalent bonds. While there is ample literature precedent for this conflation,[17,18] we cannot be certain that the student responses we described were, in fact, resultant from non-normative thinking; they may have simply been incomplete. Finally, as noted earlier, our instrument was not given at a consistent time: HS-CLUE students were assessed at the end of one semester of instruction while CLUE-, traditional-, and Modeling-enrolled students received their assessments after two semesters. Proximity to relevant instruction could therefore have impacted the data presented here.

■ IMPLICATIONS

Realizing the vision of the Next Generation Science Standards will require a dramatic departure from the status quo in high school chemistry. Rather than presentation of disaggregated facts and skills, coursework should be about helping students cultivate, organize, and use disciplinary knowledge to figure out mechanisms for phenomena and solve problems. Teachers' expectations of what teaching and learning in chemistry could and should look like may differ markedly from instructional practices capable of supporting molecular-level sensemaking. Many of the trappings of legacy chemistry curricula (such as solubility rules, electron configurations, and metal activity series) are not at all emphasized in the NGSS due to their tenuous linkage to core ideas and questionable utility. Most students enrolled in a high school chemistry course will not be chemists and have little use for memorized rules or orbital nomenclature.

It will require considerable research to discern how to effectively support all students in "understanding the world at a molecular-level". Cooper and colleagues' research program at the college level indicates that such understanding requires intentional, sustained curricular support which builds from simple systems to more complex and relatable scenarios. This is due to the fact that students entering a chemistry class have very few experiences or knowledge fragments that can be

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J. Chem. Educ. 2019, 96, 1327−1340

mapped productively onto atomic/molecular behavior. High school students, too, must construct particulate models and explanations almost entirely from formal, instructionally introduced knowledge. Our work here indicates that curricula which are shown to support college students in predicting, explaining and/or modeling phenomena in terms of atomic/molecular behavior can, if appropriately adapted, support similar understanding at the high school level.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00111.

Elaborated coding schemes for hydrogen bond drawings and boiling point explanations and statistical analysis of school demographic measures (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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