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Adapting a Core-Idea Centered Undergraduate General Chemistry Curriculum for Use in High School

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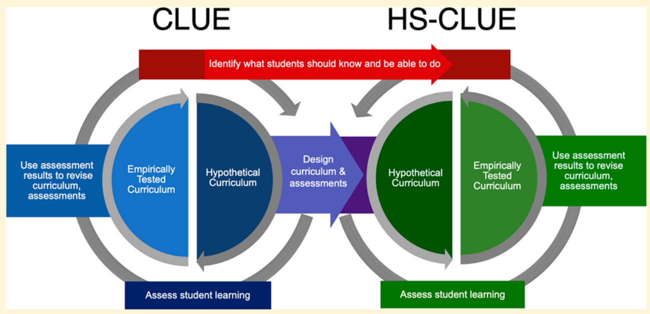
S *Supporting Information*

ABSTRACT: Connecting the behavior of invisible (to the naked eye) particles governed by the principles of quantum mechanics to the world we can see and touch requires a host of inferences, almost none of which can be extrapolated from experience. Molecular-level sensemaking thus relies upon intellectual resources that must be developed in large part by formal learning environments. Over a decade of research at the college-level indicates that centering instruction around scaffolded progressions of core ideas can help students cultivate, organize, and use their disciplinary knowledge to explain and model a range of phenomena. Informed by this literature, we have adapted a core-idea centered, evidence-based undergraduate general chemistry curriculum for use in high school. Our adaptation process, which was a collaborative effort between researchers and classroom teachers, is described in detail with emphasis on alignment between the Next Generation Science Standards and our materials. Efforts reported here represent a first-in-class model for high school curriculum development wherein conceptual progressions developed and validated at the college level form the basis for high school coursework.



KEYWORDS: *High School/Introductory Chemistry, Curriculum, Learning Theories*

■ INTRODUCTION

The *Next Generation Science Standards* (or NGSS)[1] and *A Framework for K-12 Science Education* (the Framework)[2] place substantial emphasis on students making sense of the world by building and critiquing explanatory models of observable phenomena. Answering questions about the natural world by developing, refining, and using scientific knowledge in communities is held up as much more representative of work in science than merely "knowing stuff".[3] In addition, sensemaking of this type can convey a host of productive messages to students about the utility of evidence-based models as well as the ability of all learners to engage in scientific discourse.[3,4] Unfortunately, while high-level overviews of STEM reform efforts have extolled the virtues of classroom focus on sensemaking, there are relatively few finely grained accounts of how students should be prepared to figure out and explain the cause for phenomena, how this might be assessed, or what the proper balance of "figuring out" versus "learning about" should be in a particular discipline, or at a particular point in a curriculum.

Different disciplines pose distinct challenges to the construction and critique of explanations for phenomena. Chemistry, at both the high school and college level, requires students to ground their reasoning in the behavior of invisible (to the naked eye) particles governed by the principles of quantum mechanics.[5] Connecting the weird world of atoms and molecules to the world we can see and touch requires students make a long chain of inferences, almost none of which can be intuited from macroscopic experience alone. For example, to explain why water so effectively mediates earth's temperature, students must consider the distribution of positive and negative charge on a water molecule as a function of individual bond dipoles and molecular shape, deduce the type and strength of intermolecular forces (IMFs) accessible to these molecules, and relate the strength of IMFs to the amount of energy required to disrupt attractions between populations of water molecules.[6] If any one of these inferences are problematic, students will be unable to make sense of why earth's temperature is moderated by large bodies of water, or why evaporation of sweat cools the body, and as a consequence will be reduced to memorizing facts about these particular phenomena.

Although literature studies exist describing strategies for improving a high school student's ability to relate atomic/molecular behavior to macroscopic phenomena,[7−9] no outcomes data has been published on the efficacy of *NGSS*-aligned, introductory chemistry curricula. This is extremely worrisome, as 19 states and the District of Columbia have

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adopted the NGSS and 20 more states model some aspect of their K−12 science standards after the Framework.[10] Widespread acceptance of the idea that STEM-enrolled students should use their knowledge to figure out aspects of the world around them has created an ideal climate for rethinking what high school chemistry should look like. However, as high-stakes tests are on the horizon in many states[11] and all signs point to *NGSS*-aligned curricula differing substantially from the status quo, there is an urgent need to efficiently craft and validate Standards-aligned learning environments. We have sought to help meet the immediate needs of high school chemistry teachers faced with restructuring their practice by developing an NGSS-aligned curricular framework for a two-semester introductory chemistry course. Our efforts toward the development of this framework were guided by five principles:

(1) Design of high school chemistry learning environments should be informed by modern theories of learning.
(2) High school chemistry learning environments should be structured by an integrated curriculum rather than a series of loosely associated modules.
(3) Curricular materials should be efficiently developed to meet the urgent needs of teachers across the country.
(4) Curricular materials should be developed in collaboration with practicing high school chemistry teachers.
(5) The curricular framework developed should be refined year-to-year in light of data from classroom enactments.

These principles are grounded in both research literature and the values of the developer team. Principle 1 represents recognition that efforts to help students develop and use their knowledge must consider the character of that knowledge as well as how learning environments can support development of disciplinary expertise. Principle 2 is supported by a recent meta-analysis by Schunn and colleagues, which suggests that learning environments that are structured according to integrated curricula rather than stand-alone modules are more successful at improving student outcomes.[12] Principle 3 is an attempt by the development team to emphasize the urgency of this work: teachers needed evidence-based, NGSS-aligned high school chemistry curricula yesterday. Principle 4 foregrounds the developer team's commitment to incorporating teachers' perspectives into the design process in order that materials be grounded in the reality of high school classrooms.[13] Principle 5 is meant to indicate that our program is to be iterative and evidence-based, with curricular refinements to be guided by data from teachers' enactments.

Here we describe our efforts to develop a year-long, NGSS-aligned introductory high school chemistry course by adapting the conceptual progressions underpinning the undergraduate curriculum Chemistry, Life, the Universe, and Everything (or CLUE)[14] for use in high school. CLUE was designed to be a curriculum focused on helping students link topics to larger grain core ideas[15] as they grapple with explaining increasingly complex phenomena. "Core ideas" here are ideas foundational to a discipline that have significant explanatory power and underlie a great many disciplinary topics (e.g., "energy", "electrostatic and bonding interactions").[1,2,15] Explicitly foregrounding the connections between core ideas and topics is meant to support students in making the counterintuitive inferences that connect atomic/molecular behavior to events they can observe. By centering instruction around scaffolded progressions of core ideas, CLUE has supported students in making sense of a range of phenomena including atomic emission spectra,[16] phase changes,[17] and acid−base reactions.[18] This contribution is centered solely on the process used to adapt evidence-based undergraduate curricular materials for high school audiences to create a curricular activity system called High School Chemistry, Life, the Universe, and Everything (or HS-CLUE). A study examining the student outcomes of enacting these materials, via deployment and analysis of knowledge-in-use assessments, has been published in the *Journal* immediately following this piece.[19] Our adaptation process represents a new model for curriculum development in which progressions of core ideas are designed and validated in the undergraduate space, where faculty have substantial authority to refine materials and access student outcomes data, and subsequently adapt these for use in high school. This model is well-suited to our goals as it allows for efficient assembly of an integrated curricular framework which may be enacted, assessed, and iteratively refined. Interested readers may obtain access to curricular materials under development by contacting the corresponding author.

■ THEORETICAL BASIS FOR CORE-IDEA CENTERED CHEMISTRY INSTRUCTION

CLUE is conceptualized in a manner distinct from most other chemistry curricula. The course is embedded in four progressions of core ideas that are built up as students use their knowledge to predict, explain, and model more and more complex phenomena in terms of atomic/molecular behavior. The four large-grain core ideas that form the basis for CLUE are electrostatic and bonding interactions, change, and stability in chemical systems, atomic/molecular structure and properties, and energy (Figure 1). Connections between topics, as represented by the chapter headings of traditional texts, and larger grain ideas that permeate the whole of chemistry are made very explicit in CLUE, both by the actions of instructors and by the artifacts students are asked to generate. Phenomena

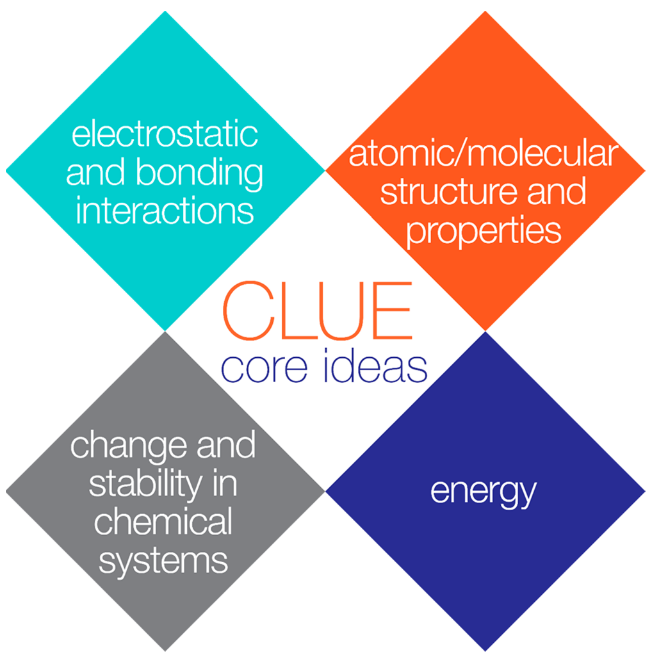

Figure 1. Core ideas underpinning the undergraduate general chemistry curriculum Chemistry, Life, the Universe, and Everything (or CLUE).

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considered throughout the curriculum progress from very simple (e.g., two helium atoms approaching) to more complex (e.g., phase changes, exothermic dissolution of a salt, acid–base reactions) in order to support students in developing, organizing, and using their knowledge in sensemaking. To understand why centering instruction around progressively elaborated core ideas helps equip students for molecular-level sensemaking, we must attend to the character of expert vs novice knowledge as well as how we believe learning in chemistry occurs.

Expert vs Novice Knowledge

Experts perceive their area of expertise as rich with linkages between related topics and between topics and larger grain size core ideas.[5,20] Command of productive connections between ideas allows experts to hone in on the salient features of a new scenario and call to mind the knowledge, skills, and heuristics that will allow for construction of a reasonable explanation or model of that scenario. In the language of *How People Learn*, expert knowledge is organized, contextualized, and useful.[20] The highly organized nature of expert knowledge also enables those with expertise to process information much more efficiently than novices. They can consider, store, and retrieve chunks of knowledge that consist of networks of interrelated facts, skills, and heuristics.[5,20] As an example, an expert viewing a reaction mechanism drawn using bond-line representations and curved arrow formalism might call to mind the electron distributions of reacting species, alternate reaction pathways that might compete with the mechanism drawn, and potential energy changes that occur in the forward and reverse direction of the depicted process. Each of these foci could enable construction of productive predictions, explanations, and/or models of the phenomenon represented by the mechanism examined.

By contrast, novices perceive a domain as fragmented into many discrete pieces that are not clearly connected to one another or to core ideas. A processable information chunk to a novice consists of one of these discrete pieces rather than a network of interrelated ideas, as is the case for experts. A novice viewing a curved arrow mechanism might perceive shapes, letters, and arrows as discrete chunks with little connection to disciplinary knowledge (or to each other). As the capacity of one's working memory to process information is very limited,[21−24] the information richness of one's chunks" is directly related to one's ability to efficiently make sense of complex scenarios. Thus, experts can much more efficiently predict, explain, or model new phenomena than novices. Focus on connections between topics and core ideas during instruction is an attempt to model expert-like organization of ideas for students and thereby foster development of more interconnected and useful knowledge. Implicit in this instructional strategy is the notion that "expert knowledge" is not a monolithic "correct" framework to be transferred whole cloth but rather a dynamic conceptual ecology composed of more finely grained knowledge elements themselves connected to one or more core ideas.

Character of Concepts in Chemistry

There is very little evidence that novice chemistry students have a self-consistent, theory-like "wrong" understanding of the discipline. Indeed, most modern conceptual change theorists view "misconceptions" as concrete manifestations of more complex cognitive structures rather than simply flawed "central concepts" to be replaced.[5] Studies by Taber and Cooper support the notion that students reason by connecting up smaller grain ideas, heuristics, and skills on the spot rather than drawing from a "wrong theory".[25,26] For example, Cooper noted that students tended to reason inconsistently across several very similar tasks, indicating that small-grain knowledge elements that make up students' conceptual ecologies are often not stably linked but are rather activated in the context of a prompt.[26] As a consequence of students' fragmented knowledge, prompts that an expert perceives to be very similar, as they differ in context but address the same concept, can elicit wildly different answers.

We contend that students' knowledge of chemistry should be thought of as a dynamic collection of intellectual resources,[27−29] including intuited fragments generalized from experience, ideas about the nature and appropriate use of knowledge, conceptual knowledge from coursework, and procedural knowledge, that may be woven together in more or less productive ways to accomplish a given task (e.g., explaining the difference between physical properties of substances). Learning environments in chemistry should support the development of appropriate resources and help students realize when and how resources should be connected in particular contexts. It is our working hypothesis that explicitly tying topics to core ideas while considering progressively more complex systems helps students develop and organize their intellectual "toolkit" in order that they might ultimately explain macroscopic phenomena in terms of atomic/molecular behavior. If productive connections between resources are not explicit during instruction from a student's perspective, then many will fall back on patterns of thinking that seem intuitively useful but are not helpful in connecting particulate and macroscopic levels.[25,26] As both high school and college chemistry students often enter a chemistry course with a fragmented understanding of the discipline, we believe centering high school curricula around core idea sequences will lead to improved outcomes analogous to those observed for college students enrolled in CLUE.

■ ADAPTING CLUE FOR HIGH SCHOOL

Why Adapt a Whole Curriculum?

There is evidence that the use of knowledge anchored to disciplinary core ideas to make sense of the world, as envisioned by the NGSS and the Framework, is better enabled through a focused, integrated curriculum than short interventions or modules.[12] Interventions are, by their nature, different from the curriculum that surrounds them and so are best thought of as short exposures to a particular pedagogy and/or content area. Unfortunately, return to "business as usual" after an intervention tends to blunt the effects of whatever innovation was briefly implemented. Evidence for the efficacy of whole curricula relative to modules or interventions can be found in a recent meta-analysis by Schunn and colleagues.[12] Schunn's analysis focused on research-based curricular materials funded by the National Science Foundation and Institute for Education Sciences between 2001 and 2010. He observed a significant association between student outcomes, as defined by publications emergent from funded studies, and the scope of curricular materials. Comprehensive curricula were more likely to yield positive outcomes than interventions or modules (Figure 2).

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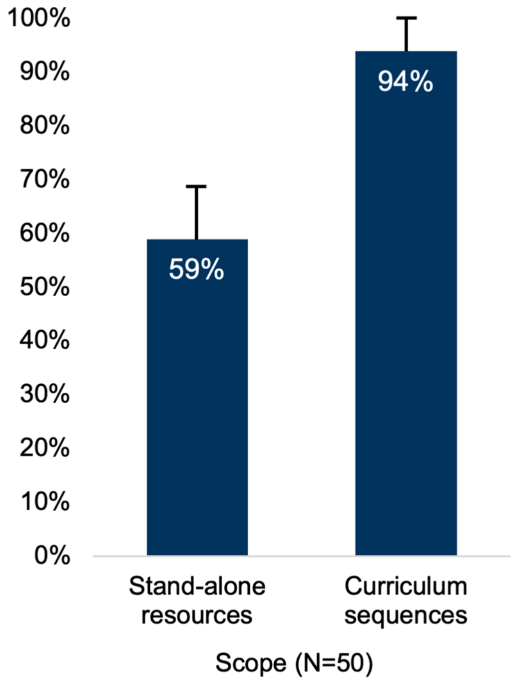

Figure 2. Proportion of projects with mostly positive student outcomes (with standard error bars) for projects characterized as "stand-alone resources" (such as instructional modules) and integrated "curriculum sequences" (i.e., whole curricula). Adapted with permission from ref 12. Copyright 2017 Wiley Periodicals, Inc.

Curriculum Development Model

Our curriculum adaptation program can be thought of as two linked design−research cycles with HS-CLUE learning objectives, curricular resources, and assessments arising from materials developed for the undergraduate CLUE course (Figure 3). The design−research cycles for both CLUE and HS-CLUE are meant to convey a process of backward design[30] and iterative, data-driven refinement of materials. Thus, authorship of learning objectives specifying what students should know and be able to do occurred first followed by consideration of what curricular resources would support progress toward those objectives. Assessments too arose from learning objectives by considering what evidence would be convincing that students have met clusters of objectives and how that evidence might be elicited. For CLUE, learning objectives, curricular resources, and assessments had to be created *de novo* to embody a vision of what instruction centered around core idea progressions should look like. Once this was done, the course was enacted and various assessments were deployed. Materials were refined on the basis of this assessment data, and the cycle continued. CLUE has gone through several design−research cycles with significant evolution of curricular materials and assessments occurring over this time.

Design of the HS-CLUE hypothetical curriculum was dramatically expedited by leveraging materials that were already developed and validated for use in the undergraduate CLUE course. In Figure 3, this process is represented by the red arrow, indicating adaptation of learning objectives, and the violet arrow, indicating adaptation of curricular materials that support these objectives. Grounding our high school learning environment in an existing curricular framework allowed our team to emerge from 2 weeks of intensive work with a rough draft of what 2 semesters of core-idea centered, NGSS-aligned high school chemistry might look like. Materials may be accessed, free of charge, by emailing the corresponding author. As mentioned earlier, efficient development of an integrated two-semester curriculum is vital to meeting the immediate needs of high school chemistry teachers across the country. Here, we focus solely on how the hypothetical HS-CLUE curriculum was developed as well as why we believe the model shown in Figure 3 is a compelling way to create Standards-aligned curricula.

Aligning CLUE Learning Objectives with NGSS Performance Expectations

The *Next Generation Science Standards* and *The Framework* seek to precisely define how students should use their

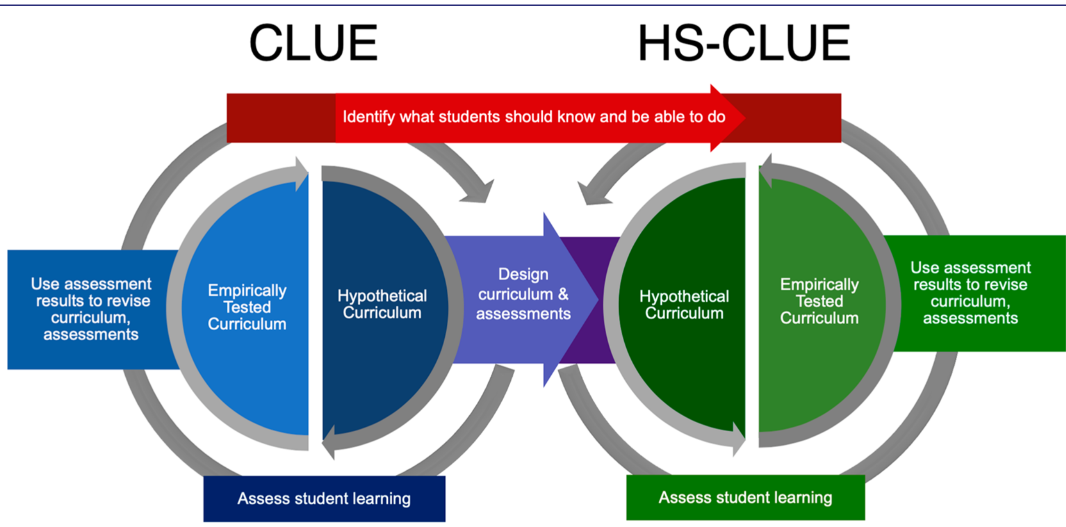

Figure 3. Linked design−research cycles that model the development of HS-CLUE from CLUE. HS-CLUE learning objectives ("what students should know and be able to do") arose directly from CLUE learning objectives, as signified by the red arrow. In a similar manner, curricular materials and assessments were adapted from existing CLUE materials, as signified by the violet arrow. Adaptation of objectives and materials represents development of the HS-CLUE hypothetical curriculum. Work disclosed here represents the beginning of a design−research cycle in which curricular refinements will be informed by assessment data gathered from teacher enactments.

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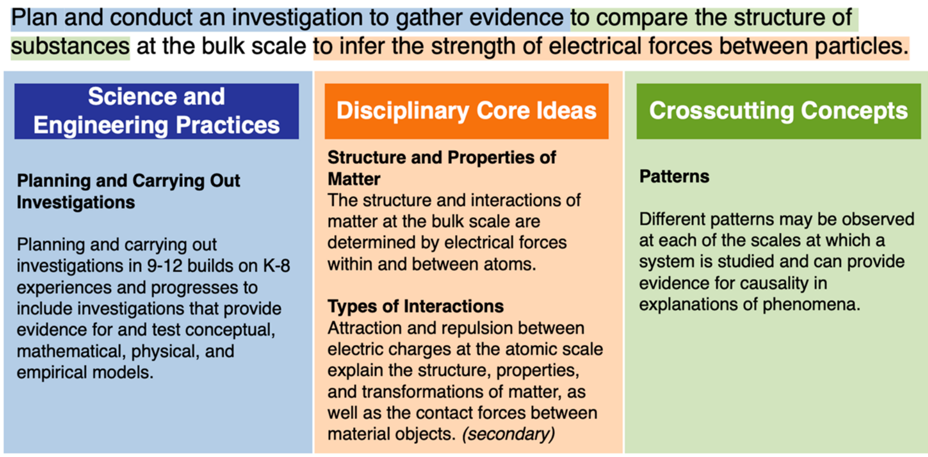

Figure 4. A high school physical science Performance Expectation (HS-PS1-3) shown with each dimension highlighted. Scientific and Engineering Practices are highlighted in blue. Disciplinary Core Ideas are highlighted in orange, and Crosscutting Concepts are highlighted in green.[1]

knowledge by describing the learning desired of STEM-enrolled students as "3-dimensional". These dimensions integrate what students should know (expressed as large-grain, foundational, disciplinary core ideas or DCIs), what students should be able to do with that knowledge (expressed as the practices characteristic of work in science), and lenses that focus students on aspects of phenomena to be explained (expressed as concepts that cut across phenomena). The NGSS lists performance expectations (PEs) intended to explicitly blend each of these dimensions for physical science, earth and space science, and life science for grades K−12. As an example, a PE for high school physical science reads "Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles" (Figure 4). This PE integrates a Practice ("Plan and conduct investigations"), two Disciplinary Core Ideas ("Matter and Its Interactions", "Motion and Stability: Forces and Interactions"), and a Crosscutting Concept ("Patterns"). It is, in essence, asking students to relate the strength of electrostatic forces between populations of molecules to a substance's melting and boiling point (as phase is what is meant by "structure of substances at the bulk scale").

Science and Engineering Practices (SEPs) are the means by which students connect topics to core ideas as they predict, explain, and model ever more complex phenomena in a "core-idea centered" learning environment. Focus on connection and use of knowledge elements differs markedly from an emphasis on knowing facts. For example, while a traditional learning environment may require students to know the definitions for a variety of intermolecular forces, CLUE-enrolled students are expected to explain the relative boiling points of different substances in terms of the amount of energy required to disrupt electrostatic interactions between populations of molecules. To support students in using SEPs to connect topics to core ideas, CLUE consistently provides opportunities for students to relate atomic/molecular behavior to phenomena. A detailed list of CLUE learning objectives, which integrate core ideas and SEPs, may be found in Table S1 in the Supporting Information. A subset of this table was reproduced for Table 1 to illustrate how CLUE builds to a particular Performance Expectation.

HS-CLUE learning objectives specifying what students should know and be able to do emerged from examination of alignment between CLUE learning objectives and the physical science disciplinary core ideas (DCIs) and performance expectations (PEs) the NGSS lists for the 9−12 grade band. Note that CLUE core ideas (Figure 1) differ from those specified in *The Framework* because CLUE was designed as a chemistry course rather than a physical science course. Three coauthors (R.L.S., D.G.H., and R.L.M.) independently examined each CLUE learning objective to discern whether it clustered under a particular DCI and/or PE. We then met and reached consensus as to the learning objectives appropriately categorized as building to each DCI and PE. It is important to note that the PEs represent goals to be met after significant instruction, not lesson-level or even chapter-level learning performances. For this reason, it was the intent of the NGSS writing team that PEs be built to slowly rather than addressed in one chapter by a couple of learning objectives. Accordingly, a learning objective was clustered under a PE if it was viewed as building up to that PE. A PE might be built to without being wholly addressed by the curriculum. For example, PE HS-PS1-3 reads, "plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles." CLUE places substantial emphasis on the inferences needed to connect molecular-level structure to measurable properties but does not place any emphasis on designing and carrying out investigations, as the curriculum was designed for large-enrollment lectures and does not address laboratory activities. Thus, this particular PE had numerous CLUE learning objectives clustered beneath it but was not fully addressed.

Nearly all CLUE learning objectives cluster under one of the five physical science disciplinary core ideas given by the NGSS for the 9−12 grade band. This is not surprising as one of the authors (M.M.C.) was a member of the NGSS leadership team, and although CLUE predates the NGSS, it was designed from the outset as a curriculum focused on anchoring knowledge to core ideas rather than topics which may or may not be related to each other (or to core ideas).[15] 16 of the 24 HS physical science Performance Expectations (PEs) would be, in whole or in part, built up to by clusters of CLUE learning objectives. Alignment between CLUE learning objectives and physical science PEs may be found in Table S1 in the Supporting Information. Importantly, the 8 PEs not addressed by CLUE do not relate to molecular-level reasoning,

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Table 1. CLUE Big Ideas and Learning Objectives That Cluster under an NGSS Performance Expectation (HS-PS3-2)

NGSS HS PE	CLUE Big Ideas	CLUE Learning Objectives
HS-PS3-2 Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative position of particles (objects).	Ch 1. Attractions lower the potential energy of a system, and repulsions tend to raise the potential energy. Ch 1. We use models (mental and physical) to represent many chemical entities. We use models for different purposes. Ch 1. Stable systems form where the attractive forces and repulsive forces are equal. Ch 5. As a molecular substance changes phase, intermolecular forces are overcome (not chemical bonds).	Ch 1. Construct an atomic-level explanation for why two isolated atoms would attract each other as they approach, and why they would repel if they get too close together. Ch 1. Predict and explain the changes in the potential energy, the kinetic energy, and the total energy as two isolated helium atoms approach each other. Ch 1. Draw an energy diagram showing potential energy as a function of internuclear distance. Ch 1. Differentiate between London dispersion forces and covalent bonding without providing an explanation. Ch 1. Contrast the energy change that occurs when two He atoms or two H atoms combine. Ch 3. Explain the energy changes that occur when two atoms approach each other and form a bond; explain what forces and energy changes take place when a bond is formed. Ch 5. Explain the difference/relationship between temperature, thermal energy, and kinetic energy. Ch 5. Explain how temperature and kinetic energy are related, including the energy associated with vibration, rotation, and translation in different phases. Ch 5. Draw heating or cooling curves showing how the temperature changes when thermal energy is added to a substance (including a phase change). Explain why the temperature changes except during the phase change.

and so it would likely not receive significant attention in any chemistry course.

To get a sense as to how students should advance toward PEs over the course of the HS-CLUE curriculum, consider the CLUE learning objectives and big ideas that build to HS-PS3-2 (Table 1). Learning objectives represent a particular application of a contextualized scientific practice that might occur in a lesson or lessons during a chapter. Big ideas, by contrast, represent overarching conceptual themes that suffuse a good portion of the chapter in which they appear. As the potential and kinetic energy changes that accompany the breaking and forming of electrostatic interactions are a central focus of CLUE, competencies that support progress toward HS-PS3-2 are introduced early in the course. For example, in the first chapter students are tasked with constructing a model that depicts the change in system potential energy as a function of internuclear distance as two noble gas atoms approach each other. Various features of this model are explored including the driving force behind initial atom approach, the meaning of the potential energy minima, and the dramatic increase in potential energy that occurs as the two atoms get extremely close. Simulations are leveraged to show how both potential and kinetic energy change as neutral atoms approach. Through use of these models in class and on homework, CLUE-enrolled students are to understand that energy must be transferred out of a two-atom system by collision with a third body to trap those two atoms in a potential energy well. Later in the course, students are tasked with relating changes in temperature to changes in molecular motion and disruption of intermolecular forces (IMFs) to answer the following question: "Why do substances boil at different temperatures?" Fully explaining this question requires one to appreciate the direct relationship between temperature and average kinetic energy of a population of molecules as well as what "phase change" means at the molecular level (that is, disruption of IMFs and not covalent bonds).

Due to the integrated, core-idea focused nature of the CLUE curriculum, many PEs are constructed over an extended period, as shown above, rather than simply covered in a short burst of instruction as a topic or unit. As we have said before, many of the inferences needed to relate the world of atoms and molecules to the macroscopic level are counterintuitive and will require students to reconstruct intuitively appealing ideas with more scientifically appropriate concepts. This takes time and requires explicit support; it is unlikely to occur over the course of a short module. We hypothesize that an integrated, core-idea focused curriculum will be more successful in helping students develop, organize, and use their knowledge to make molecular-level sense of phenomena than a series of loosely associated modules or traditional topical treatment.

Assembling a Rough Draft of CLUE for High School

After determining the alignment of CLUE learning objectives with NGSS PEs and DCIs, a group of 9 teachers was convened to assemble a working model of CLUE appropriate in scope and sequence for high school. Teachers were recruited from across Michigan and represent a variety of experience levels from beginning (1 year of experience) to veteran (15+ years of experience). Our cohort of educators and researchers examined the DCI and PE alignment grids, as well as the full list of CLUE learning objectives, to determine where material existed in CLUE that was beyond the scope of the expectations in the NGSS as well as where CLUE materials fell short of

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supporting students in reaching particular PEs. Small groups of 2−3 teachers examined 1−2 CLUE chapters in this manner and presented their thoughts to the whole group for discussion. A working plan for modification of CLUE materials arose from group comments. Our cohort then split into two groups, one consisting of four teachers and the other consisting of five; each subgroup handled detailed revisions to half of the CLUE curriculum. The subgroups were charged with adding student-centered investigations that complimented CLUE core idea sequences, and generating materials for piloting including the following: a modified text, homework assignments, a bank of exam items, annotated PowerPoint slides, and detailed teacher notes listing Standards alignment and giving a lesson-by-lesson breakdown of each chapter. CLUE materials were supplemented in order to address Performance Expectations built to by existing materials but not wholly addressed. For example, while CLUE includes substantial focus on relating the strength of forces between molecules to observable properties, it offers no opportunities for students to "plan and conduct investigations" as called for by HS-PS1-3 (Figure 4). To support students in this performance, we integrated an activity that requires students to plan and conduct an investigation into the relative evaporation rates of several substances and subsequently relate evaporation rate to the strength of electrostatic interactions between molecules of a substance. As CLUE is a well-developed curriculum, many of the resources assembled into the HS-CLUE hypothetical curriculum were adaptations of existing materials rather than new materials created *de novo*. At the end of our summer development workshop, the group met again as a whole and reviewed each chapter of HS-CLUE in detail. By the end of our two-week developer workshop, a suite of materials that embodied the HS-CLUE hypothetical curriculum (e.g., text, sequencing documents, assessment banks, annotated PowerPoint slides) were organized in a Google drive for easy access by piloting teachers.

Our teacher/researcher development team dedicated substantial effort to discerning which aspects of CLUE were appropriate in scope for a high school course. Importantly, while materials were streamlined, the overall sequence of topics in HS-CLUE is virtually the same as the conceptual sequencing found in CLUE.[14] The first half of the undergraduate course, in which students are supported in refining their model of the atom, and ultimately relating atomic/molecular structure to observable properties, required minimal changes to be suitable for high school audiences. A section on the mole was added after discussion of properties emergent from ensembles of atoms/molecules, and all mention of molecular orbital theory and the properties it helps explain was removed. As the second half of CLUE extends substantially beyond the level appropriate for an introductory high school chemistry course, much of the material from later CLUE chapters was simplified or omitted. For example, only changes in enthalpy are mentioned when discussing chemical reactions and solutions: entropy and Gibbs free energy are not exhaustively treated, as they fall beyond the scope of the NGSS DCIs and PEs. As in the undergraduate CLUE curriculum, acid−base and oxidation−reduction reactions are the focus of all discussion on chemical reactions in HS-CLUE, as opposed to subtypes such as "double displacement" or "synthesis" that are not mechanistically useful nor employed by practicing chemists. A section on stoichiometry was added to HS-CLUE following introduction of chemical reactions. Crucially, as the NGSS places focus on the conservation of matter in chemical reactions rather than algorithmic problem solving, treatment of stoichiometry in HS-CLUE emphasizes reactants combining in defined ratios to form products, not endless number crunching. The final section of the undergraduate CLUE text, which focuses on coupled reaction systems, was entirely omitted from the high school course.

The investigations, demonstrations, and activities chosen by our team to complement the CLUE conceptual progressions arose from several sources. A significant number of the student-centered activities used were derived from work conducted by teachers enrolled in the Target Inquiry program at Grand Valley State University (GVSU) or Miami University (MU), which was designed and administered by one of the authors (D.G.H.). The Target Inquiry (TI) program encompasses a summer Research Experience for Teachers (RET) in the lab of faculty at GVSU or MU coupled with a Master's program focused on development, piloting, and refinement of inquiry-based instructional materials derived from that RET.[31−33] Accordingly, all TI materials used as part of HS-CLUE have undergone prior analysis and revision. Other sources of material include the *Interactions* curriculum published by the Concord Consortium[34] and POGIL activities.[35]

■ NEW MODEL FOR THE DEVELOPMENT OF NGSS-ALIGNED CURRICULA

Here we have focused on the merits of core-idea centered chemistry instruction in general, as exemplified by CLUE, as well as detailed a specific program wherein we adapted validated core-idea progressions underpinning a college course for use in high school. As far as we are aware, this is the first time a high school curriculum designed to meet national standards has arisen from intentional, theoretically grounded adaptation of conceptual progressions from a research-based college course. There is much to recommend the general model underpinning our approach (shown in Figure 3) from both a design and assessment perspective. In terms of design, we argue that one must have organized, contextualized, and useful knowledge of the discipline being taught to assemble a course around core-idea sequences. This is doubly true in chemistry where so many of the connections between topics and core ideas are extremely counterintuitive. Domain experts that deeply understand modern theories of learning (that is, discipline-based education researchers) are ideally positioned for this sort of learning environment design. Additionally, college faculty often have significant authority to assemble and revise curricula, and so CLUE could be envisioned and enacted whole-cloth in a manner that would be very difficult for a high school teacher to manage. From an assessment perspective, learning environment designers who are college faculty have access to large, matched cohorts of students from which to draw outcomes data. This is important because, to support robust statistical comparisons between groups, those groups should be (1) of appropriately large size[36] and (2) matched by a variety of demographic and achievement criteria. Studies on the efficacy of CLUE in supporting student atomic/molecular understanding have repeatedly compared the performance of large, matched cohorts of students in a manner difficult to manage in the high school space.[6,37−39]

The fruits of substantial discipline-based education research work on core-idea centered instruction can be efficiently adapted by a team of researchers and teachers to be more

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appropriate in scope for use in high school by carefully aligning course learning objectives to performance expectations contained in standards, as we have discussed at length here. This enables a rough draft standards-aligned curriculum to be built from integrated conceptual progressions that span a whole year rather than assembled piecemeal from chains of "interesting" phenomena or modules dedicated to some pedagogy or other. We hypothesize, drawing from the meta-analysis published by Schunn and colleagues,[12] that the integrated, core-idea focused nature of HS-CLUE will result in enrolled students being substantially better prepared for molecular-level sensemaking than students taught using other approaches. A study in which the responses of HS-CLUE enrolled students to a knowledge-in-use assessment are compared to the responses of students taught according to other approaches is published immediately following this piece.[19]

■ NEXT STEPS: ASSESSING OUTCOMES FOR CORE-IDEA CENTERED HIGH SCHOOL CHEMISTRY

Assessing the outcomes of any curricular transformation effort is a challenging business, especially considering the heterogeneous nature of America's high school system. Our ongoing efforts in this space will leverage data from a variety of sources including the following: student responses to assessment instruments that have been used to evaluate CLUE (such as the Implicit Information from Lewis Structures Survey[40] and Intermolecular Forces Assessment[37]), detailed teacher enactment accounts, and classroom observations. When making comparisons between classes taught by HS-CLUE and those taught using another curriculum, we will endeavor to account for school demographics, preinstruction understanding (as measured by middle-school physical science assessments aligned with the *NGSS*), and teacher content knowledge (as measured by the ACS General Chemistry Conceptual Exam). In keeping with the model put forth in Figure 3, materials will be refined each summer in light of assessment data gathered from the classrooms of enacting teachers and teacher feedback.

■ SUMMARY

Expecting chemistry-enrolled students to develop reasonable molecular-level explanations for observable phenomena is a tall order. Students must have, and recognize they have, appropriate intellectual resources at their command and know how to connect these resources as they construct and revise explanatory accounts. As there is essentially no chance students will *de novo* arrive at organized and useful molecular-level understanding by observing phenomena, developers of *NGSS*-aligned chemistry curricula must figure out strategies to prepare students for sensemaking. The substantial success of CLUE in promoting molecular-level understanding indicates that making connections between topics and core ideas explicit during instruction helps students develop, organize, and use their knowledge. As novices enter a chemistry course with a fragmented view of the discipline, coursework should first focus on simple systems and eventually build toward explaining more relatable phenomena once students have an appropriate level of expertise. Adapting CLUE core-idea progressions to be appropriate in scope for high school has allowed us to efficiently create a prototype of what core-idea centered, *NGSS*-aligned instruction could look like for high school chemistry. The HS-CLUE hypothetical curriculum is currently being enacted in several classrooms and will be refined on the basis of data from these enactments.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00071.

Alignment between CLUE learning objectives and the physical science performance expectations given by the NGSS for 9–12 grade band [assembled by three of the authors (R.L.S., D.G.H., and R.L.M.) and double-checked by our teacher development team] (PDF, DOCX)

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Notes

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