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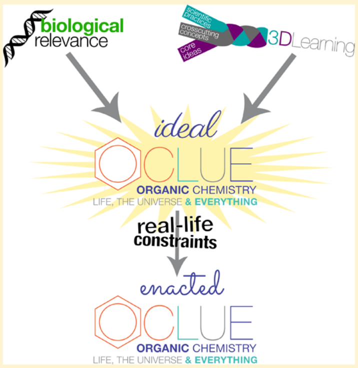
Organic Chemistry, Life, the Universe and Everything (OCLUE): A Transformed Organic Chemistry Curriculum

Melanie M. Cooper,*[†] Ryan L. Stowe,[†] Olivia M. Crandell,[†] and Michael W. Klymkowsky[‡]

[†]Department of Chemistry, Michigan State University, 578 South Shaw Lane, East Lansing, Michigan 48824, United States
[‡]Molecular, Cellular, and Developmental Biology, University of Colorado, Boulder, Boulder, Colorado 80309, United States

Supporting Information



ABSTRACT: The fundamental structure of a typical mainstream two-semester organic chemistry course, populated mostly by life science majors and taught at universities throughout the United States, has changed little since the 1970s. However, much of the research on learning in organic chemistry has been devoted to characterizing student difficulties of various types, and there is now persuasive evidence that organic chemistry as currently taught is neither effective nor relevant for a majority of students. In an attempt to address the problems with traditional approaches to organic chemistry instruction, we have developed an approach to the design of a transformed organic chemistry course (Organic Chemistry, Life, the Universe and Everything or OCLUE) suitable for the vast majority of organic chemistry students that includes (1) using the Framework of three-dimensional learning (3DL) to support knowledge in use and (2) emphasizing biologically important mechanisms. In this course, topics are connected to core ideas by using scientific practices, such as constructing models and explanations, analyzing and interpreting data, and emphasizing causal mechanistic reasoning. Here we discuss the theory and the decisions that went into the development of the course, including the compromises made and the rationales behind those choices. The outcome is a course that emphasizes causal mechanistic reasoning, has an increased focus on biologically prevalent reactions, and uses spectroscopy early and often to support evidence-based arguments about structure−property relationships. The materials we have developed are freely available to students and to potential users.

KEYWORDS: *Organic Chemistry, Second Year Undergraduate, Curriculum, Assessment/Testing*

THE CURRENT STATE OF UNDERGRADUATE ORGANIC CHEMISTRY

With few exceptions, mainstream organic chemistry curricula have remained more or less unchanged for nearly 50 years. The precedent was set in 1959 with the publication of Morrison and Boyd's *Organic Chemistry*[1,2] and has changed little over the intervening decades. Earlier texts presented descriptions of the synthesis and reactivity of functional groups without providing mechanistic explanations, despite the fact that the curved arrow notation had been introduced by Robinson in 1924.[3] Morrison and Boyd's text took the then controversial approach of integrating mechanisms that modeled how and why reactions happen. In the years following the release of the first edition of *Organic Chemistry*, approaches to organic chemistry instruction converged around Morrison and Boyd's treatment of functional groups and the use of the electron pushing formalism to denote how electrons move during reactions. As Raker and Holme noted, the content of practitioner-developed ACS examinations for organic chemistry has changed little since the 1970s, indicating a broad consensus as to what should be taught in such a course.[4] Some have taken consistency in content as an indication that curricula embodying the status quo are effective. For example, after undertaking an analysis of organic chemistry curricula in the mid-1970s (which produced results that would look remarkably familiar today) the organic subcommittee of the Division of Chemical Education curriculum committee stated, "*We feel that undergraduate organic chemistry education is in an excellent state of health*".[5,6] Despite such bold declarations as to the health of organic chemistry instruction, there is little empirical evidence that Morrison and Boyd's organization of material supports most students in developing, organizing, and using their knowledge effectively. At the same time there is a widespread perception that organic chemistry is difficult,[7] and often irrelevant to most students' goals.[8] Moreover, many organic chemistry courses are perceived by students as having high student failure rates,[7] suggesting that the current approach is not optimal for a significant subpopulation of students.

In response to these problems, there is a large body of research on student learning in organic chemistry. The vast majority of this literature has involved characterizing the difficulties that students have while progressing through such courses. By our count, there are at well over 70 peer reviewed papers published from 2010 to the present that are focused on characterizing how students approach organic chemistry tasks.

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Many of these reports discuss student difficulties and misconceptions. For example, many students have trouble with the electron pushing formalism,[9−12] and the use of mechanistic reasoning to predict the outcome of a reaction seems to be especially problematic for both undergraduate and graduate students.[13−15] We know that students may use heuristics rather than considering structure−property relationships when considering acid strength,[16] or reactions of alkyl halides,[17] and that they have problems associated with characterizing electrophiles and nucleophiles.[18,19] Similarly, studies have looked at issues with visualization and strategies for analyzing three-dimensional structures.[20] Others have characterized misconceptions[21,22] and designed concept inventories.[23,24] Student difficulties with synthesis and spectroscopy have been studied and characterized,[25−29] and as in most other areas, novice and expert organic chemists have been shown to think differently about the subject, with novices focusing on surface features and experts looking at underlying concepts and connections.[28,30,31] Taken together, these studies provide a great deal of evidence for the problems that students have with organic chemistry.

On the other hand, there are fewer reports released from 2010 to the present (around 30) that investigate strategies for helping students succeed in organic chemistry. This is almost certainly because measuring improvements in a meaningful way is more difficult than characterizing problems with student thinking in a particular context. Indeed, as noted in the National Academy Report on Discipline Based Education Research (DBER), there are few findings in DBER for which there is strong evidence, defined in the report as "numerous well-designed qualitative and/or quantitative studies, with high convergence of findings".[32] For example, it appears that the use of visualizations and models to support student learning is not well-understood,[33] and there is no evidence-based consensus for how visualizations should be introduced or used.[34] On the other hand, there are a number of studies that investigate the use of physical models that show they support students.[33,35,36] There are also a number of initiatives that have reported reinventions of various aspects of the course. These include the following: spiral curricula,[37] where ideas are initially introduced and then returned to later in more depth; the "organic first" movement, where organic and general chemistry courses are switched so that freshmen first take an introductory course on the structure and properties of organic molecules followed by more traditional general chemistry course;[38,39] curricula organized by mechanism instead of functional groups;[40,41] curricula that emphasize biological chemistry;[42] and a variety of efforts aimed at the goal of "student engagement".[43−45] For example, a study on the use of PLTL[46] showed improvement in student performance (as measured by course grades), retention, and attitude for students engaged in the intervention relative to those taught more traditionally. There are also a number of studies on a "flipped classroom" approach that report improvements in grades and attitudes.[47,48] Flynn and Ogilvie[40] have also reported on a completely revised organic chemistry sequence that cultivates student familiarity with the mechanics of mechanism drawing before introducing content. However, despite the approaches mentioned above, most organic chemistry courses taught today look very much like an organic chemistry course taught during the 1970s.

In this paper we describe the development of a new organic chemistry course, including

1. The theoretical framework for curriculum development
2. What content is most appropriate for the majority of organic chemistry students in the absence of external constraints
3. The compromises made to our vision of organic chemistry in response to real-world constraints
4. The actual course that was enacted; studies on the efficacy of this approach will be presented in subsequent publications.

THE THEORETICAL FRAMEWORK FOR CURRICULUM DEVELOPMENT

We contend that any attempt to design a chemistry learning environment should be informed by what we know about how people learn, both generally, and with respect to the discipline of chemistry. There is broad consensus that students construct their own understanding: Knowledge is not transferred whole cloth from a "sage on the stage" to student observers.[49−51] In chemistry, the development and organization of useful knowledge are complicated by the fact that atoms and molecules are far removed from students' experiences and behave in ways that are not at all intuitive.[52,53] Strategies that can be applied successfully to navigating the observable world very often lead students astray when applied to atomic/molecular level behaviors. This contrasts with introductory physics, where small-grain ideas extrapolated from experience (called "phenomenological primitives" or p-prims) can be applied productively in ways that seem intuitive. For example, the idea that more effort begets a greater result can be productive for physics students (a harder push makes the object move more). However, heavier molecules do not necessarily have a higher boiling point.[53,54] Further, there is little evidence that students possess a stable or usable "mental model" of atoms and molecules which they might draw from when called upon to predict, explain, or model chemical phenomena.[53] While it is tempting to think about student ideas as "misconceptions" and how they may be "overcome", we believe it can be more fruitful to think of them in terms of resources and habits of mind that may be more or less appropriate to explain the phenomena under consideration. Resources may include conceptual and factual knowledge from coursework, ideas intuited from experience, and notions about the appropriate use of knowledge, that are strung together in the context of a particular prompt or instructional scenario.[55,56] Furthermore, one must presume (or at last hope) that most organic instructors do not intend for their students to merely memorize vast swathes of reactions, but rather that their students develop deep and useful knowledge that will help them construct predictive and/or explanatory models for phenomena in organic chemistry: If this is the case, we must carefully consider how learning environments can support cultivation and use of the resources that students will need.

Toward this end, the National Academies produced a consensus report, *A Framework for K−12 Science Education* (the Framework),[57] that provides not only a review and analysis of the extant research on science education, but also a synthesis of this research into a vision for how science learning environments should be structured. While the Framework was designed for K−12 education, the underlying theories and recommendations are equally applicable to higher education settings.[58,59] The Framework proposes that learning in science should be "3-dimensional" and should involve leveraging foundational disciplinary ideas (i.e., core ideas)[57,60] in practices characteristic of work in science (i.e., science and engineering practices), as framed by concepts that direct student sensemaking (i.e., crosscutting concepts). Thus, coursework in science should not simply be about knowing disaggregated facts, or even separate topics, but about supporting students in developing and organizing what they know in order that they be equipped to use their knowledge to make sense of aspects of the world around them.

There is considerable evidence that chemistry learning environments that make connections between topics and larger-grain "core ideas" explicitly support students in building up, organizing, and using their intellectual "toolkit" to explain a variety of phenomena.[14,61−63] Connecting new knowledge to core ideas helps students develop a more expert-like knowledge framework, that can be built upon, and used, ideally in new situations. Core ideas previously identified for college general chemistry include the following: atomic/molecular structure and properties (SP), electrostatic and bonding interactions (B&I), energy (E), and change and stability in chemical systems (C&S).[60,64]

However, knowing (memorizing) something is of little value unless that information can also be used correctly, that is, applied accurately in appropriate situations. Too often such "inert" (memorized) information is mislabeled as knowledge and is regurgitated on exams. Students must constantly be engaged not only in learning new ideas, but in using those ideas to predict, model, explain, and analyze data and information. It has been proposed that using knowledge in these ways helps develop the connections that lead to more expert-like knowledge structures.[57] The Scientific and Engineering Practices (SEPs) encompass the ways that scientists and engineers use and develop their knowledge.[57] These practices include asking questions, designing and carrying out investigations, analyzing and interpreting data, constructing and using models, mathematical and computational thinking, constructing explanations, engaging in argumentation, and evaluating and communicating information. Together they encompass the work of scientists but are frequently absent from undergraduate science courses. For example, such practices are largely absent from organic examinations[65] and introductory courses.[66]

The Crosscutting Concepts (CCCs) represent the third "dimension" of three-dimensional learning and consist of lenses that focus student attention on particular aspects of a phenomenon to be explained. For example, when looking at trends in ionization energy from left to right across a row in the periodic table, one might focus on emergent regularities in data (leveraging the CCC of patterns), or think about constructing a model that enables explanation of differences in ionization energy (leveraging the CCC of systems and system models), or construct a causal account of why atoms with higher effective nuclear charge have higher ionization energy (leveraging the CCC of cause and effect). Phenomena, particularly in chemistry, may be made sense of in many different ways, and it is crucial we signal to students how we want them to use their knowledge if we want to maximize chances of successful engagement in sensemaking. There are a number of studies in organic chemistry focusing on student reasoning;[10,16,67,68] in our work, we have emphasized causal mechanistic thinking across a range of phenomena.[14,63]

Core-Idea-Centered General Chemistry

The general chemistry course Chemistry, Life, the Universe and Everything (or CLUE), designed by two of the authors (M.M.C. and M.W.K.), is an example of this approach to curriculum design in general chemistry.[64] CLUE engages students in scientific practices such as constructing predictions, explanations, and models and in doing so supports them as they make connections among the core ideas of the course. Mechanistic reasoning is emphasized to help students understand not just that things happen, but also how and why. Increasingly complex, intertwined progressions of core ideas underpin the treatment of all traditional topics in the course and guide content organization (rather than historical precedent). Using knowledge anchored to core ideas through the use of SEPs supports students as they make sense of ever more complex scenario supports. For example, the core ideas of energy, bonding and interactions, and structure−property relationships combine to support the development of ideas about London dispersion forces in the first chapter of the text, providing an explanation for why neutral atoms and molecules stick together, the strength of such interactions, and the relationship between temperature (i.e., the kinetic energy available through molecular collisions) and physical state. The mechanism by which the LDFs form is emphasized. Bonding is introduced subsequently, with a strong emphasis on a model of bonding that relies on electrostatic interactions between valence electrons and the nuclei of the other atoms, both to explain why bonding releases energy and breaking bonds requires energy. These ideas are then connected to energy changes associated with phase changes, caused by forming or breaking new interactions, and the core idea of stability and change. Subsequently, these same ideas are used to build toward understanding how acid−base reactions occur, and how kinetic and thermodynamic factors can control the outcome of reactions. Finally, course core ideas and SEPs are integrated into understanding ideas about how coupled reactions can transfer energy in biological systems.

We have amassed a wealth of data on the impact of CLUE on student outcomes; CLUE enrolled students have higher average grades and lower DWF rates than matched cohorts of students taught according to other approaches.[58] Further, we have evidence from longitudinal research projects not only that CLUE students have more sophisticated understanding of intermolecular forces,[61] structure−property relationships,[62] and acid−base reactions,[14,63] but also that these improvements persist throughout a full year of organic chemistry (taught in a conventional manner). We have also shown that, in a typical semester at Michigan State University, over 700 more students than in earlier years have been able to continue to the next course with a grade of 2.0 (C) or higher, and, more importantly, to continue successfully throughout their coursework: They do not fail the next courses in the sequence.[58] Indeed, it appears that students who participate in the CLUE curriculum do better than one might expect in the next two semesters of an organic chemistry course; their average grades are similar to peers who have taken more selective general chemistry courses and who have higher ACT scores and GPAs.[14]

Toward Core-Idea-Centered Organic Chemistry

The challenges to designing a meaningful organic chemistry learning environment mirror those encountered in general chemistry but are further magnified. While the inferences required to explain a nucleophilic substitution reaction can be thought of as an extension of those that students must make to explain differences in boiling points in terms of molecular charge distribution, the chain of such inferences is longer and more complex. If we want to go beyond having students simply memorize products of a reaction, we must help them develop the necessary causal mechanistic reasoning skills (as aligned with the CCC cause and effect: mechanism and explanation). That is, we want students to go beyond the idea **that** a reaction occurs (e.g., generates a product), and beyond **how** a reaction occurs (i.e., draw a mechanism), to construct a causal mechanistic explanation in order to explain **why** a reaction occurs. For example, to construct a causal mechanistic model for an acid−base reaction as shown in Figure 1, students need to figure out the charge distribution within and between the reacting molecules by considering bond dipoles and molecular geometries. They must then determine which sites are electron-rich and which are electron-deficient in order to identify likely Lewis acidic and basic sites. Such predictions rely heavily on understanding and using the forces within and between atoms and molecules and how they influence molecular interactions. In addition to grounding their reasoning in core ideas, students must be also be familiar with a variety of skills, such as how to draw Lewis structures and how to use the curved arrow formalism, in order to construct and use a mechanism as a model, that is, as a predictive tool.

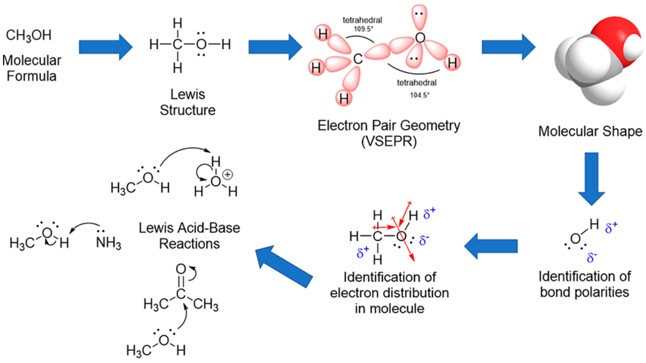

Figure 1. Sequence of inferences and connections that students must be able to make to construct a causal mechanistic explanation about acid−base reactions.

The thinking required to make connections among all these ideas can be made more explicit and measurable by articulating performances in terms of scientific practices. In organic chemistry courses, we expect students to be able to perform a diverse array of tasks, including providing mechanisms for reactions, predicting outcomes by drawing a mechanism, constructing syntheses for particular functional groups and for target compounds, identifying compounds using spectroscopic data, identifying and distinguishing between different types of isomers, and constructing energy diagrams showing the stability of reactants, products, and different conformations. As discussed in more detail in the assessment section, almost all of these goals can be clarified by thinking of them in terms of the scientific practices.

In 2015 we began development of a two-semester organic chemistry course: Organic Chemistry, Life, the Universe and Everything (OCLUE). While many of the design decisions are analogous to those involved in CLUE, organic chemistry poses new challenges and increased complexity. In the next section we describe our vision for a hypothetical organic chemistry curriculum, that is, what the curriculum would look like in an ideal situation. We then describe the various compromises associated with the enacted curriculum, a curriculum that has been taught for three years, and discuss the factors that led to changes from the hypothetical curriculum.

■ THE VISION FOR A TRANSFORMED ORGANIC CHEMISTRY COURSE: ORGANIC CHEMISTRY, LIFE, THE UNIVERSE AND EVERYTHING (OCLUE)

In this section we discuss our vision for a transformed organic chemistry course if there were no constraints on what such a course could look like. This vision is dictated by the student population enrolled in a typical organic chemistry course (rather than the perceived needs of graduate-school-bound chemistry majors). For example, most (over 95%) of the students at Michigan State University take organic chemistry courses because they are required by their biology degree program or as a preprofessional health sciences requirement. Organic chemistry is also often a prerequisite for a biochemistry course required by several of these programs. This requires us to ask the following question: What do such students need to know and to do with their organic chemistry knowledge? As discussed earlier, the course should be developed over interconnected progressions of the core ideas which we have defined as structure−property relationships, bonding and interactions, energy, and chemical change and stability.[60] These are the overarching ideas behind much of chemistry, and when used to predict, explain, and/or model phenomena, they provide a very different way of thinking about what student understanding of organic chemistry would look like. However, for a course to be "recognizable" as an organic chemistry course it should also cover topics that are traditionally included in such a course. The question we should ask ourselves is which topics are relevant and necessary for a robust comprehension of organic chemistry that would also be useful in understanding the chemistry of biological systems?

Depth over Breadth

We do not believe that it is necessary to "cover" all the material outlined in a typical organic chemistry text. A great deal of the material presented is not relevant for students' understanding of organic chemistry, and the sheer volume of content to be "covered" often leads them to resort to surface learning and memorization. In our work designing college chemistry learning environments we have chosen to emphasize depth over breadth. As previously discussed, and as evidenced by our work on CLUE,[14,61−63] developing and organizing resources in a mindful way requires explicit and repeated support for students; a "drive by" approach in which whole chapters can be covered in one or two lectures in complete isolation from other chapters precludes the development of deep and coherent understanding. That is, the course needs to "cover" less than the traditional course, but in more depth and with more explicit connections that are perceived and most importantly used by the student.

Covering less requires us to be selective about what material to include, and therefore, we choose to emphasize reactions and mechanisms of biological importance (given the aspirations of enrolled students). One way to identify such reactions is to consult the MaCiE (Mechanism, Annotation and Classification in Enzymes) database of enzyme catalyzed

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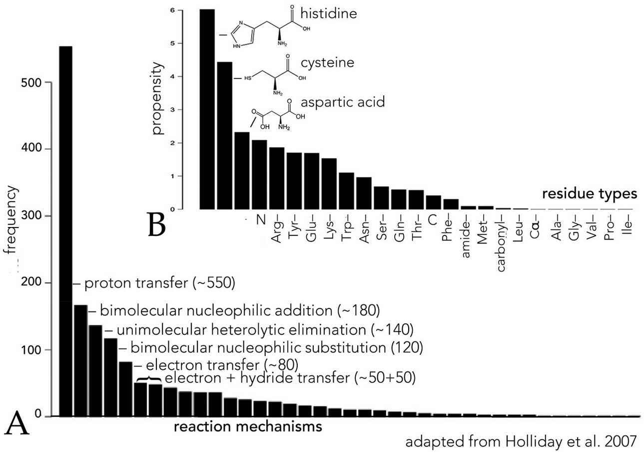
reactions[69] to determine both the most common types of reaction mechanisms present in biological systems, and the most common amino acid side chains involved in catalytic mechanisms.[70] As shown in Figure 2A, a vast majority of mechanistic steps mediated by enzyme catalysis involve proton transfer reactions, with bimolecular nucleophilic addition being the second most common type of mechanistic step. Nucleophilic additions in biological systems typically involve amino acid residues with a N, S, or O nucleophilic site adding to a carbonyl (or phosphate ester). S_N2 reactions at an sp^3 hybridized center are also common. Unimolecular elimination reactions via the conjugate base (E1cb) reactions (such as the elimination step after an aldol reaction) are also prevalent, but the more often taught E1 (via a cationic intermediate) and E2 reactions are rare. Electrophilic reactions (i.e., reaction at an electron-rich substrate) are quite rare in biological systems. Rather, most reactions involve nucleophilic amino acid residues such as histidine or cysteine (and their termini) and are strongly stabilized by interactions with other parts of the enzyme and metal ions, and by interactions with the aqueous solvent. Leaving groups are often anions of weak acids (for example, phosphates) rather than the ubiquitous halide seen in traditional organic courses.



adapted from Holliday et al. 2007

Figure 2. (A) Frequency of enzyme mediated mechanisms (out of 872 classified reactions). (B) Relative catalytic propensity of amino acid residues. Adapted with permission from ref 70. Copyright 2007 Elsevier.

Considering these data, it appears that many of the reactions typically included in the first semester of organic chemistry are not especially relevant to those students with biomedical aspirations, in particular, the cognitively complex material usually included in discussions of alkyl halides, which involves differentiating and predicting when S_N1, S_N2, E1, and E2 reactions are likely to occur. In biological systems, S_N1 mechanisms are rare and not, apparently, particularly important. We might therefore de-emphasize or postpone (to the second semester) the chemistry of carbocations, with their concomitant complexities (rearrangements, alkyl and hydride shifts, and eliminations). In fact, while most practicing chemists go to great lengths to avoid generating carbocations, a large portion of many first-semester organic chemistry courses focus on these reactive intermediates. We are not alone in considering the aforementioned quartet of substitution and elimination reactions to be too complex for the first semester of an organic chemistry course.[71] Indeed, in the transformed course designed by Flynn et al., this quartet is postponed until students are better able to grapple with all the necessary ideas.[40] Unfortunately, organic chemistry courses patterned after Morrison and Boyd's progenitor text delay introduction of reactions involving the carbonyl group (and by analogy, imines and phosphate and sulfonate esters) until the second semester, despite the fact that chemistry of the carbonyl and its analogues is the most prevalent reactivity observed in biological systems. We agree with Flynn et al.: We should include an introduction to carbonyl chemistry (nucleophilic attack at the carbonyl) in the first semester.

Many have sought to appeal to nonchemistry STEM majors enrolled in organic chemistry by adding biological examples into otherwise conventional texts so that students can see illustrations of particular reactions in biological systems.[42] However, like the physics community discovered before us,[72] providing meaningful education for the vast majority of the students who come from the biological sciences is more difficult than simply adding "relevant" examples to conventional approaches. Teaching the same material with add-on examples does not address the problems at hand; evidence from the CLUE transformation suggests that the curriculum as a whole needs to be redesigned so that each topic is progressively introduced, built upon, and connected to core ideas. This approach stands in contrast to an isolated intervention approach or a simple reorganization of chapters, where the new curriculum appears as a patchwork quilt version of its prior self. As Schunn et al. have reported, there is evidence that wholesale curriculum design is more effective than development of "units" that are incorporated into a pre-existing curriculum.[73]

It seems clear that the traditional format and topic sequence, which may make perfect sense to practicing organic chemists, are not what most students need from organic chemistry. Certainly, students should have a strong grasp of Brønsted acid−base reactions involving a wide range of potential organic acids and bases. However, if we want students to understand mechanisms that are biologically prevalent, we need to emphasize nucleophilic attack at electrophilic carbons including carbonyls, and also the parallels between attack at carbonyls and attack at phosphate and sulfonate esters. Because of the prevalence of the histidine, cysteine, and aspartic acid residues within the catalytic sites of enzymes, the similarities and differences between N, O, and S nucleophiles should be introduced early, and used often. Similarly, as halide leaving groups are not prevalent in biological systems, strategies to improve leaving group ability in physiologically relevant contexts (e.g., by protonation of OH or by forming phosphate or sulfonate esters) should be introduced relatively early.

The electrophilic addition chemistry of alkenes and alkynes does not seem to be as important as its central role in most first-semester courses might imply. Additionally, if students are to understand how organic reactions are catalyzed in biological systems, it is important to explicitly discuss the role of stabilizing interactions and solvation, activation by protonation or by metal ion complexation, pH effects, and the coupling of reactions that drive energetically unfavorable reactions. The trade-off, of course, is time: We believe that taking the time to make explicit connections to students' other relevant knowledge is valuable and within students' capabilities given appropriate assistance. Without this explicit assistance, however, students may not make explicit connections between their chemistry and biology experiences.[74,75] If the number of reactions and associated esoteric reagents can be reduced, it may be possible to build a more meaningful understanding of the chemistry relevant to biological systems. All of this should be done so that the knowledge students gain is connected and seen as potentially useful (to them).

Increasing Complexity

Another problem with creating meaningful materials for biology and health majors is the complexity and historical contingency (the result of evolutionary processes) of biological systems. Many biological molecules are far more structurally complex than the chemical systems that we use in introductory organic chemistry courses. Students can rapidly become overwhelmed by the cognitive demand of decoding such structures and will fall back on memorization strategies that most organic chemists believe are not appropriate. Most students enter OChem without the level of facility in reading and interpreting chemical structures required to make sense of even simple organic structures.[76,77] Consequently, they do not (and cannot) see such structures as models that convey information about the properties and function of physiologically relevant molecules. Development of such skills takes time and must be approached explicitly, something that may not occur in conventional courses.[76] Dependence on decoding complex representations (and conflation of memorization with understanding) is not unique to chemistry or organic chemistry; many introductory biology and biochemistry courses appear to underestimate the difficulties involved in making sense of structural representation of complex (and simple) molecules.[78,79] The introduction of such complex structures must be done carefully and intentionally. Students must be supported as they look for meaning in the structure at reactive centers, since we know that otherwise learners tend to focus on surface features.[80]

■ THE COMPROMISES

All of this being said, there are a number of compromises that we have had to make in response to the nature of our student population and the operation of the course. While it would be ideal to design a course using the best available evidence and theories, with the goal of emphasizing the material that is relevant to biological systems, several real-world issues make this problematic. The most important local reason at Michigan State University (MSU), is that students are not likely to take both semesters of organic chemistry with the same professor. At this institution registration takes place a year in advance, and students do not know who teaches a particular section at the time they sign up. Therefore, each professor must agree to "cover" the same general topics in the first semester of the course. Inevitably this has led to trade-offs and compromises. In our case this means that we have (reluctantly) agreed to keep the nucleophilic substitution/elimination ($S_N1/S_N2/E1/E2$) mechanisms in the first semester. In return, professors teaching from a traditional text agreed to move spectroscopy into the first semester, so that it can be used as an evidence base for what we know about structure−property relationships.

On a more universal note, many of our students intend to take preprofessional admissions tests, and while the MCAT has been revised fairly recently, it still hews rather closely to a traditional topic set;[81,82] we would be doing our premedical students a disservice if we removed whole sections that are covered on the MCAT whether or not they are, in our opinion, actually relevant to a future biological/health career or practice. The result of all these considerations is that, in our initial pilot tests, we were unable to enact all of the ideas about scope and sequence discussed earlier. That being said, we have been able to keep a focus on biologically important mechanisms and remain faithful to the theoretical approach that relies on core ideas connected by scientific practices as discussed below.

■ THE ENACTMENT OF OCLUE: TRANSFORMATION IN PRACTICE

In the development of the General Chemistry course CLUE, particular attention was paid to the sequential development of the interconnected progressions of the core ideas. Because we were assuming that students brought little relevant knowledge to the course, we were able to "more or less" start from scratch. In the case of organic chemistry, there are a number of concepts, skills, and practices that are, ideally, prerequisites for the course. At a minimum, students should bring with them a facility with simple structural representations, an understanding of bonding models, and an appreciation for acid−base chemistry. Unfortunately, there is ample evidence that many students do not develop a robust and useful understanding of this prior knowledge. For example, studies have shown that organic chemistry students struggle to draw appropriate Lewis structures,[76] many students believe that intermolecular forces operate within molecules (rather than between them),[83] and, even by the end of organic chemistry, only about 50% of students understand that structural representations can be used to predict physical and chemical properties.[83,84] At MSU the students enrolled in OCLUE have a variety of backgrounds. Only around 50% of students have taken two semesters of CLUE General Chemistry, around 25% have taken a more selective version of general chemistry, and around 25% have not taken a relevant General Chemistry II course (GC II is not required at MSU for enrollment in OC I).

Because of all of these factors, we emphasize the important prior knowledge including structural representations and bonding models at the beginning of OC I. These ideas are (re)introduced in the context of acid−base chemistry, because we believe that for meaningful learning to occur students must understand the purpose of what they are learning; otherwise, it will not be connected and may be easily forgotten.[85] The beginning of the course is an expanded version of that commonly found in many organic texts. The Lewis acid−base model is emphasized because it is integral to organic chemistry and leads naturally into an introduction to simple nucleophilic substitution (S_N2 reactions) and attack at a ketone carbonyl. Parallels between S_N2 substitutions and attack at a carbonyl carbon are highlighted throughout this discussion. This background section takes 3−4 weeks of class time. During this period, we introduce the expectation that students will learn not only what happens during a reaction, but also why it happens. That is, we introduce students to constructing causal mechanistic explanations, and to using mechanistic arrows. We introduce the electron pushing formalism in the context of acid−base, nucleophilic substitution, and addition reactions, and we emphasize that they are more than a tool; that is, not only do they represent a model for how electrons flow in a reaction, but also they must be used with an understanding of why the electrons move this way.

The next unit introduces spectroscopy. While spectroscopy does not appear in some textbooks until the second semester, we believe it is crucial to provide students with evidence as to

Table 1. Example Topics and Learning Objectives from the First Semester of OCLUE

		Learning Dimensions Objectives Address		
Example Topics	Example Learning Objectives	Core Ideas[a]	SEP[b]	Crosscutting Concepts
Week 1: Review of First Principles, Tools, and Skills				
Effective nuclear charge, hybridization, structural representations, bonding models	Use chemical structures to predict and explain polarity of molecules and types of intermolecular forces.	SP; B&I	Explanation	Cause and effect
Introduction to explanations	Construct a causal mechanistic explanation for how and why a bond forms between two atoms.	B&I; E	Explanation	Cause and effect
Week 2−4: Acid−Base Reactions				
Introduction of mechanistic arrows in the context of review of Lewis acid−base	Construct an explanation about why one compound is more acidic or basic than another and support your answer using your knowledge of molecular structure, electronegativity, and the stability of the conjugate acid or base.	S&P; B&I; E	Explanation	Cause and effect
Introduction of mechanistic arrows in the context of nucleophile and electrophile terminology (S_N2 with alkyl halides and carbonyl centers)	Discuss the factors that affect relative rates of reaction for nucleophiles and leaving groups (i.e., predict and explain trends in nucleophile strength and leaving group ability for a given set of reagents).	S&P; C&S	Explanation	Cause and effect
Week 5−6: Spectroscopy				
Infrared, ^{13}C NMR, ^{1}H NMR spectroscopy	Predict the structure of a compound from its molecular weight and infrared, ^{13}C NMR, and ^{1}H NMR spectra and be able to justify your prediction.	SP; B&I; E	AID; CA	Patterns
Week 7−9: Conformation and Configurations				
Conformational analysis for cyclic and acyclic compounds; Newman projections, chair conformations, and Fisher projections	Construct representations and use them to explain why cycloalkanes have differing stabilities using angle strain, torsional strain, and steric strain to support your discussion.	B&I; E	Models	Cause and effect
Stereoisomers, enantiomers, and diastereomers	Construct potential energy curves for compounds showing how the energy changes as groups move closer and further apart. Explain why this happens.	B&I; E	Models	Cause and effect
Week 10−13: Nucleophilic Substitution and Eliminations				
S_N2, S_N1, E2, E1 reaction mechanisms	Explain the role of the solvent in each of these reaction types: S_N2, S_N1, E2, E1. Explain why a particular solvent type promotes a given reaction.	S&P; B&I; E	Models	Cause and effect
Solvent effects				
Competing reactions				
Hydride and alkyl shifts	Using molecular structure drawings, explain why the structure of the substrate determines the type of reaction. Include ideas about steric hindrance and stability of transition states and intermediates.	S&P; B&I; E	Models	Cause and effect
Spectroscopic evidence				
Week 13−15: Alkenes and Alkynes				
Electrophilic addition across alkenes and alkynes	Predict and explain the outcome of the reversible reaction that involves addition of water to the double bond of an alkene. Discuss how you would manipulate the reaction conditions so that either the addition product or the elimination product could be obtained.	E; C&S	Explanation	Systems
Oxidation and reduction of alkenes and alkynes				
Radical reactions				
Spectroscopic evidence				

[a] Core idea abbreviations indicate the following: S&P, atomic/molecular structure and properties; B&I, electrostatic and bonding interactions; E, energy; C&S, change and stability in chemical systems.

[b] Scientific and engineering practices (SEP) abbreviations indicate the following: AID, analysis and interpretation of data; CA, constructing an argument.

Table 2. Example Topics and Learning Objectives from the Second Semester of OCLUE

		Learning Dimensions Objectives Address		
Example Topics	Example Learning Objectives	Core Ideas[a]	Scientific and Engineering Practices	Crosscutting Concepts
Week 1−3: Alcohols, Thiols, and Amines				
Nucleophilicity of alcohols, thiols, and amines	Construct explanations about relative acidities of alcohols using resonance and induction arguments about the stability of the conjugate bases.	S&P; B&I; E; C&S	Models	Cause and effect
Oxidation and reduction; spectroscopic evidence	Predict and explain the relative nucleophilicity of alcohols, thiols, and amines.	S&P; B&I; E	Explanation	Cause and effect
Week 4−7: Nucleophilic Attack at Carbonyl Carbons				
Nucleophilic attack at aldehydes, ketones, esters, carboxylic acids, acid chlorides with reversible nucleophiles and irreversible nucleophiles	Explain how and why the carbonyl absorption in the IR differs for a range of carboxylic acid derivatives.	S&P; B&I; E	Explanation	Cause and effect
Spectroscopic evidence	Construct mechanisms for the interconversion of carboxylic acids and derivatives, and predict and explain the expected products.	S&P; B&I; C&S	Models	Cause and effect
Week 8−10: Conjugated Compounds and Aromaticity				
Conjugated and aromatic systems	Explain, using appropriate bonding models, how and why UV−vis spectra provide evidence of conjugation.	B&I	Models	Systems
Electrophilic and nucleophilic additions to aromatic rings	Construct representations to explain why the presence of one substituent impacts the position of the next substituent on a benzene ring.	S&P; B&I; E	Models	Cause and effect
Pericyclic reactions	Construct representations and use them to explain why some heterocyclic compounds are quite basic while others are not.	S&P; B&I	Models	Cause and effect
Spectroscopy of aromatic compounds				
Week 11−14: Returning to the Carbonyl				
Enols and enolates (aldol and Claisen condensations, Michael additions)	Construct energy diagrams to show how and why kinetic or thermodynamic products can be formed by alkylation at the α carbon.	S&P; B&I; energy	Models	Cause and effect
Introduction to sugar chemistry	Construct mechanisms to show how and why sugars may exist in both open chain and cyclic forms.	S&P; B&I; energy	Models	Systems
Various biological systems				

[a] Core idea abbreviations indicate the following: S&P, atomic/molecular structure and properties; B&I, electrostatic and bonding interactions; E, energy; C&S, change and stability in chemical systems.

why structure impacts reactivity as well as to show how the structures of reaction products are characterized. Leaving spectroscopy to the middle of the second semester means students must take much of organic chemistry on faith. Including spectroscopy early provides opportunities to incorporate the practice of the "analysis and interpretation of data" throughout the course and affords the option of using evidence from this analysis to inform arguments.

Following the discussion of spectroscopy is a unit on the structure of organic compounds that includes conformational analysis and an emphasis on why certain conformations are more stable than others. In earlier work, we found that students often did not understand the meaning of the term "potential energy",[86] and that they were unlikely to be able to predict potential energy changes resulting from interactions (repulsions) in different conformations. The information from these studies was integrated into CLUE during discussions of the relationship between forces and energy, and these ideas are reviewed in OCLUE. We expect this overview will be particularly beneficial to students who have not considered ideas about potential energy in prior coursework. Once students are familiar with and understand how three-dimensional structures adopt particular conformations, they are then introduced to chiral species and the different types of stereoisomers. The use of hand-held models is emphasized, as Stieff et al. have found that such use improves a student's ability to deduce configurations at chiral centers and removes any gender disparity in this skill.[36]

In the second half of the first semester, we return to nucleophilic substitutions and introduce the S_N1 mechanism, the effect of substrate structure, nucleophile, leaving group, solvents, and temperature, and the experimental evidence for the two mechanisms. This leads directly into elimination reactions, both E1 and E2, the effect of all the other variables and base strength, and stereoelectronic requirements. In our opinion (and that of others)[71] this complex interplay of expected reaction mechanism, reagents, and conditions is one of the most cognitively difficult units in any organic chemistry course. Ideally, this material would be simplified here and reintroduced in semester two, but currently, that is not possible due to student scheduling problems and necessary curricular compromises as discussed earlier.

In the second semester, we begin with a review of OC I in the context of alcohols, ethers, thiols, and amines. This allows review of acid−base chemistry and S_N1, S_N2, E1, and E2 mechanisms once more, with a wider array of substrates, nucleophiles, and bases that are more applicable to biological systems than those covered in the first semester. Nucleophilic attack at carbonyl carbons, and, by analogy, phosphates and sulfates, is then introduced. This discussion includes treatment of aldehydes, ketones, carboxylic acids and derivatives, phosphates, and esters. At this point we begin to introduce the effects of conjugation on functional groups, first with conjugated alkenes, which are compared and contrasted with conjugated ketones, and then with aromatic systems. Electrophilic and nucleophilic aromatic substitutions are introduced and unpacked shortly after the introduction of aromaticity. Particular attention is paid to aromatic bases and the rationale for why some nitrogenous aromatics are basic and some are not.

In the final third of the second semester we revisit the chemistry of carbonyls to emphasize the reactivity at α carbons, condensation reactions, and the parallels between simple model systems and biological reactions that both build and break up complex polymeric molecules. In the final sections we discuss a range of biological systems that include sugars, glycolysis, peptide bond formation, and activation of reactants by ATP in preparation for coupling reactions. We make explicit connections between these complex biological systems and the foundational carbonyl reactivity discussed earlier in the semester.

In some ways OCLUE as we enacted it looks similar to a traditional curriculum, albeit with fewer topics and less emphasis on memorization of specific reaction conditions and reagents. It is the connections to core ideas and emphasis on reasoning as defined by engagement in SEPs that constitute the major differences in approach. Tables 1 and 2 provide examples of traditional topics and associated learning objectives.

The materials developed for the course are freely available[87] and include the following: (1) There is a text, modeled on the CLUE text, that is intended to provide the narrative driver and the "essential basics" for the course. It contains no boxes, no asides (except for footnotes to resources and literature), and while it does have questions to consider designed to promote reflection as students are reading, there are no end-of-chapter practice problems. Rather, the text is a description of how and why the course is organized this way and provides students with a thread of ideas to follow. (2) Instructor resources are available including lecture outline PowerPoint slides that can be elaborated using an iPad or other drawing technology, clicker questions, and learning objectives. (3) There are a wide range of both formative and summative assessments including homework, recitation worksheets, and exams. As with CLUE, we do not use or recommend randomly generated multiple choice or fill in the blank questions. The formative assessment items are designed to support student learning, rather than test it, and are a major component of the course. For example, students complete both retrospective tasks that are designed to consolidate ideas, and prospective tasks that introduce new material and allow students to use their knowledge and skills to, for example, predict outcomes for systems that will be discussed in the next class. These tasks are delivered via the beSocratic system,[88,89] a web-based system that can recognize and respond to some inputs (for example, the placement of mechanistic arrows). While skills can be practiced using this system, its major advantage is that students can write and draw freely and thereby engage in practices such as modeling, explanation, or argumentation in order to make connections among the ideas and skills they are learning. beSocratic can simulate the use of pencil and paper tasks but also provides the added benefit of recording all student actions (for example, the order in which they write mechanisms) for later analysis. At MSU, students also attend a weekly recitation where they work on more complex activities in groups. Summative assessment tasks are a mixture of more traditional organic chemistry tasks (e.g., predict products, draw mechanisms), and tasks that have the potential to elicit evidence that students are engaging with core ideas and practices in both multiple choice and short answer formats. On a typical exam, about 50% of the points come from the latter types of tasks. In contrast, Stowe and Cooper report that few traditional exams (including an ACS organic exam) allow explicit engagement with scientific practices.[65]

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EXAMPLE TASKS THAT ENGAGE STUDENTS IN SCIENTIFIC PRACTICES

The kinds of activities that are central to a course send a strong message to students about what knowledge and skills they are expected to master.[90−92] If students listen to lectures and then go away and practice rote skills, and reaction completion by pattern recognition and/or memorization, we should not be surprised if they take away the message that organic chemistry is about memorization, or when students cannot use their knowledge in new situations. Evidence-based instructional practices[93] that emphasize student-centered instruction have been shown to improve student outcomes across a range of disciplines;[94] however, there are also studies that show that even students who have been in active learning classrooms may emerge with profoundly problematic ideas (such as the idea that intermolecular forces operate within molecules[83]). If student-centered instruction is not focused on making connections to core ideas by using scientific practices, it is entirely possible that students will not develop a coherent and useful understanding of the domain under study. Actively learning fragmented pieces of knowledge will fail to result in more connected knowledge structure, although it may improve recall of those knowledge fragments. It is our contention that student-centered instruction must be accompanied by activities that require students to engage with core ideas and practices.

While the major goal for designing formative assessments is that they support student learning, assessments should also provide information to instructors about what students know and can do. In other words, assessments should be constructed for, and used for, the purposes of making evidentiary arguments about what students know and are able to do.[95] We have previously argued the importance of knowledge in use (i.e., the use scientific practices[58]), and here, we discuss the importance of assessing such practices within the context of organic chemistry. Further examples of these assessment tasks are provided in Supporting Information S1.

Models and Modeling: Explanation

The practice of developing and using models involves developing a simplified representation of a system that is grounded in principles or evidence, and that enables prediction or explanation of a phenomenon.[96,97] For example, a reaction mechanism can be thought of a model of the reaction system, where the components of the model are the molecules (starting material or products), the distribution of the electron density, and how the electrons move during a reaction (the electron pushing formalism arrows). There are three major tasks that one might expect an organic chemistry student to master:

(1) Draw the products of a reaction step when given the starting materials and mechanism.

(2) Draw a mechanism when given the starting materials and products.

(3) Draw a mechanism to predict the product of a reaction.

We consider these tasks to be in order of increasing complexity. Task 1 requires students to produce a drawing of the result of the mechanistic arrows. This is a necessary skill, but we do not consider such a task as incorporating core ideas or practices because it simply requires students to be able to interpret the meaning of the arrows. Task 2 may or may not elicit thinking about the causal mechanisms by which species react, but without explicit evidence we cannot infer that students who complete such a task are using the electron pushing formalism to explain the course of the reaction. That is, it does not **provide evidence** that they are using the core ideas of structure−property relationships or interactions and bonding to support their thinking about the course of the reaction.[9,13] Similarly, task 3, which could be thought of as a predictive modeling task, also does not produce explicit evidence about how students are reasoning about the use of mechanistic arrows. For example, we know that many students do not use mechanistic arrows in a predictive way and some may add arrows after drawing the product.[9]

Assessment items that do not require explicit reasoning about how and why reactions occur cannot provide evidence of the ideas that students are using, whether they are using the electron pushing formalism as part of a model or just because “it gets me to the product”.[13] To address this issue we typically design assessment tasks that explicitly ask students to reason about the reaction they are asked to model. We have shown that such tasks can provide a richer evidence base about how students understand acid−base reactions,[14,63] and there are a number of reports discussing how prompting students to verbalize about particular tasks can contribute to a more metacognitive approach to the task.[98] Box 1 provides a generic prompt that allows us to identify the reasoning, both mechanistic (how the electrons move) and causal (how and why the species interact), that underlies a reaction.

Box 1. Generic Task Designed To Elicit Causal Mechanistic Reasoning

For a reaction (shown):

(a) Construct a mechanism using curved arrows for the formation of the product

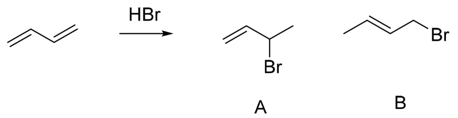
(b) Explain in words **how** the reaction takes place

(c) Explain in words **why** the reaction happens in this way

It is almost certain that most instructors discuss why and how reactions occur, but it is far less certain that students can leverage fundamental ideas to reason across phenomena as they move through the course. For example, Anderson and Bodner have reported on “Parker”, a good student who did well in general chemistry but did not seem to hear when the instructor explained how and why reactions occur.[99] It is our contention that students must constantly and consistently be asked to provide causal mechanistic explanations if they are to develop facility with the use of core ideas to make sense of reactions both familiar and unfamiliar.

Mechanisms are not the only types of models in organic chemistry. For the example in Box 2, students are asked to draw a mechanism to show how kinetic and thermodynamic products form from a simple diene. Again, we must go beyond the simple mechanism to elicit evidence of student understanding by asking students to construct another model, in this case an energy diagram. Graphs may be viewed as models because they can serve as tools to predict or explain a given phenomenon.[56] Next, students are asked to predict which product will be produced at a given temperature and to link their models together with their understanding of structure−property relationships and energy changes via explanation. Additional examples of modeling assessments are provided in the Supporting Information (SI).

Box 2. Task Designed To Elicit Use of a Graphical Model To Predict and Explain

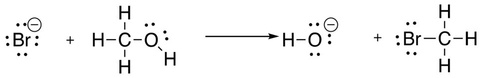


(a) Construct a mechanism using curved arrows for the formation of products A and B.
(b) Draw an energy diagram for the formation of both products A and B. Explicitly label the reactants, products, activation energies, and the structure(s) of any intermediates.
(c) Which product would predominate at low temperatures? Explain your choice using your mechanism from part a and your graph in part b and drawing on your knowledge of energy, molecular structure, and electrostatic forces.

Constructing Explanations: Cause and Effect

Scientists are united by the desire to understand and the need to explain what happens in the natural world and *why*. The act of constructing a scientific explanation requires coordination of scientific principles relevant to the phenomenon in question in order to clarify why events proceeded as they did. As previously discussed, explaining organic chemical phenomena is particularly difficult because it requires an operational understanding of structure−property relationships, different models of bonding and types of interactions, energy, and many other resources. Implicit in (almost) every organic reaction is an understanding of why and how particular parts of molecules interact. Why does the nucleophile attack the electron-deficient carbon? Why does the first step of addition to a double bond involve interaction with an electrophile? What do those curved arrows actually mean? In OCLUE we explicitly invoke explanations about how and why reactions occur as we discuss the mechanism. Students learn to use curved arrows as representations of electron flow, and at the same time, they are asked to construct written explanations discussing the cause (typically electrostatic interactions) and the effect of such interactions. The assessment item in Box 3 illustrates how the addition of a reasoning component (part b) can elicit evidence of student thinking about structure−property relationships affecting this process at the molecular level. For additional examples of explanation in short response questions such as these, see the SI.

Box 3. Task Designed To Elicit an Explanation Based on Structure−Property Relationships


$$\mathrm{:\ddot{Br}:^{\ominus}} + \mathrm{H{-}CH_2{-}\ddot{O}{-}H} \longrightarrow \mathrm{H{-}\ddot{O}:^{\ominus}} + \mathrm{:\ddot{Br}{-}CH_3}$$

(a) Is this reaction likely to occur as written (yes or no)?
(b) Explain your answer, being sure to support your response with a discussion of the factors that affect the rates and outcomes of nucleophilic substitutions. Be sure to indicate how and why the structure of the reactants affects their reactivity.
(c) Provide an alternate approach to the production of CH_3Br from CH_3OH.

Analysis and Interpretation of Data: Constructing an Argument

Argumentation has been extensively studied in chemistry classrooms,[100,101] although not, to our knowledge, in the context of spectroscopic determination of structure. Analysis and interpretation of spectroscopic data is certainly an important aspect of organic chemistry. It is therefore surprising that spectroscopy is often relegated to the course's second semester. Spectroscopy is one of the few ways that we can provide students with actual evidence about the organic species and the reactions we are discussing, and therefore, it can provide an ongoing thread through the course: What do we know and how do we know it? There are at least two approaches to using spectroscopy: the first required students to analyze spectroscopic data to determine the structure of an unknown. This type of question is one of the few traditional Organic chemistry tasks that incorporate scientific practices, in this case evaluation and interpretation of data and construction of an argument from evidence. The second involves using spectroscopic data to provide evidence of how the structure of a molecule can affect its properties. For example (Box 4), students might be asked to predict relative carbonyl stretches in infrared spectra, followed by reasoning about the scientific principles that govern this phenomenon, or when provided with a ^{13}C NMR spectrum might assign signals on the basis of which carbon(s) they would predict to be most deshielded.

Box 4. Task That Requires Analysis and Interpretation of Data, Where Students Must Support Their Argument with an Explanation That Involves Structure−Property Relationships

You have three unmarked vials I, II, and III, each of which contains either an acid chloride, an ester, or an amide. You choose to identify them by collecting infrared spectra on the samples. You observe in each spectrum a strong peak around 1700 cm^{-1}. For sample I the peak appears at 1650 cm^{-1}, for vial II at 1780 cm^{-1}, and for vial III at 1710 cm^{-1}. Using this data

(a) Identify the contents of vials I, II, and III.
(b) Explain how you made this determination. Be sure to discuss how and why the structure of each substance affects the energy of the absorption peak.

Synthesis

In the Framework, "designing solutions" is designated as an engineering, rather than science, practice. In fact, especially in chemistry, there is no demarcation line between science and engineering. Many chemists "design solutions" for a host of problems. For example, they design drugs to target specific enzyme sites, and more generally they design materials for specific purposes. Focus on design can be incorporated into an organic course under the more recognizable "synthesis". As noted by Raker and Towns,[102] a typical synthesis task in organic chemistry provides a target and asks students to synthesize it from given starting materials. What is often missing is why one would want to synthesize this compound in the first place. A synthesis task in which a student is asked to design a compound with particular properties (for example a substance that would be negatively charged at pH 7, that also has a hydrophobic moiety), or a substance that would interact with a (simplified) enzyme binding site, might engage students in "designing solutions". An example of such a task is shown in Box 5.

Box 5. Synthesis Task with a Specific Target That Will Address a Problem

Starting from benzene and any other reactants and reagents, design a synthesis of a substance that will dissolve in aqueous solution at pH 7

The Role of Skills

We define skills as those things students must learn to be able to do that typically follow a set of rules. For example, assigning a configuration or *E*−*Z* isomerism requires application of the Cahn−Ingold−Prelog convention; knowing what arrows mean in terms of electron movement, bond breaking, and formation; and translating among different representational systems, e.g., from Lewis to line structures to Newman projections. All of these skills must be explicitly taught and practiced, but they do not require any reasoning or connections to core ideas on the part of the student. It should be noted that while some have proposed that organic chemistry requires particular spatial skills, there is little evidence that this is the case. For example, Stieff has shown that teaching students explicit heuristics for assigning configuration increases students' ability in this area.[36] Careful attention to teaching these skills, and the purpose for learning them, is of significant importance. However, that being said, the skills alone do not mean much if students cannot use their knowledge in the context of scientific practices. Finally, we do not consider meaningful use of mechanistic arrows solely as a rule-based skill (although obviously students must understand what arrows mean). Rather, arrows are parts of a model of a reaction, and their use should be accompanied by an understanding of structure−property relationships (where electron density is located), and why electrons might move in a particular way (usually related to electrostatic attractions).

■ SUMMARY

Here we have described the development of a new approach to organic chemistry that prioritizes connections to core ideas and supports students as they engage in scientific practices. Our original intent was to completely redesign the course in terms of both the scope and sequence. However, it was not possible to omit major sections of a traditional course without putting some students at a disadvantage if they were unable to continue in the transformed section. Additionally, even though the MCAT has undergone a purported update,[81] in fact little has changed, and we would be doing students a disservice if we did not cover most "traditional" topics, even though many of them are not necessary to understand the chemistry of biological systems. These constraints mean that, at present, we still retain the cognitively demanding, but largely biologically irrelevant, quartet of S_N1, S_N2, E1, and E2 mechanisms in semester one. However, we *are* able to introduce spectroscopy early so that students can make evidentiary arguments about structure and properties. Additionally, we have emphasized causal mechanistic reasoning, and modeling in the context of reaction mechanisms.

The attentive reader will note that we do not offer evidence for the efficacy of our approach in this contribution, but rather we outline the theoretical principles that influenced final course design and provide examples of how materials were constructed to emphasize scientific practices. We will report on our assessment of the effects of the curriculum in separate publications. We will note, however, that, despite the fact that the course has been somewhat streamlined, students from OCLUE score around the national average on the two-semester organic chemistry exam authored by the ACS Examinations Institute.[103] That is, we are "doing no harm", but we should also note that this exam does not assess mechanistic reasoning and students who do well on it have also been shown to have problematic ideas about chemical phenomena and, often, are unable to construct reaction mechanisms appropriately.[9,104] To this end, we are conducting longitudinal, replicated studies to determine how the course impacts student reasoning about reactions, mechanistic arrow use, and understanding of organic chemistry as a coherent and connected discipline.

■ IMPLICATIONS FOR TEACHING

So what might the organic chemistry instructor take from all of this? Even though compromises were made in translating the hypothetical OCLUE curriculum to the real world, it does not "look" like a typical organic chemistry course; just as with the CLUE curriculum, it would require considerable effort on the part of the instructor to change from a more traditional approach. For those who are dissatisfied with the current state of organic chemistry instruction, but do not want or are unable to adopt a new curriculum, we recommend the following ideas:

(1) Attempt to connect everything that is taught to the four core ideas we identified previously: structure−property relationships, bonding and interactions, energy, and stability and change. In this way students will have a chance to build connected networks of ideas that are accessible.[60] Examples of how to explicitly assess these connections are provided in the Supporting Information and have also been published for the general chemistry context.[105]

(2) Ensure that students *use* their knowledge, rather than memorize and regurgitate. The easiest way to accomplish this is to incorporate the scientific practices into everything that students do. They should predict, model, explain, and argue on a daily basis. Homework and group activities that involve scientific practices as well as content send a strong message to students about what is important. This should be followed by summative assessments that also engage students in these practices. Make sure to allow adequate time for students to grapple with using their knowledge to make sense of assessment scenarios. Engaging in scientific practices such as explanation takes more thought and time on the part of the student than regurgitating memorized facts and mechanisms. Many organic examinations are composed of a large number of questions, which means students may not have time to think and therefore must memorize how to do problems.

(3) All activities assigned to students should be designed with particular goals in mind, and it should be clear to students what these goals are. Students should understand what they are doing and why they are doing it.

(4) Rather than adding biological applications (in boxes) on top of an existing curriculum, we recommend that more attention be paid to the development of complexity in structure over time, with emphasis on supporting

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students in identifying the appropriate reactive parts of the molecules and explicitly connecting these biological examples to their relevant prior knowledge. The catalytic mechanisms of enzymes make a good (and surprisingly compact) scaffold to link organic chemistry to biological systems.

(5) Emphasize the reactions that actually occur in biological systems and the nucleophiles and leaving groups that are present in such systems (rather than focusing on the halides).

(6) Finally, we emphasize that learning in this way requires time and effort on the part of students. It is important to provide them with a supportive learning environment where mistakes can be made without penalty, and where students have the opportunity to reflect on what they are doing and why they are doing it.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00401.

Examples of assessment tasks (PDF, DOCX)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: mmc@msu.edu.

ORCID

Melanie M. Cooper: 0000-0002-7050-8649
Ryan L. Stowe: 0000-0002-5548-495X
Olivia M. Crandell: 0000-0003-2748-8942

Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Morrison, R.; Boyd, R. *Organic Chemistry*, 3rd ed.; Allyn and Bacon: Boston, MA, 1976.

(2) Borman, S. A Tale Of Two Textbooks: History and Influence of Sienko & Plane and Morrison & Boyd Detailed at Symposium. *Chem. Eng. News* **2005**, *83* (41), 48−51.

(3) Kermack, W. O.; Robinson, R. An explanation of the property of induced polarity of atoms and an interpretation of the theory of partial valencies on an electron basis. *J. Chem. Soc., Trans.* **1922**, *121*, 427−440.

(4) Raker, J. R.; Holme, T. A. A Historical Analysis of the Curriculum of Organic Chemistry Using ACS Exams as Artifacts. *J. Chem. Educ.* **2013**, *90* (11), 1437−1442.

(5) Report of the Organic Subcommittee of the Curriculum Committee. *J. Chem. Educ.* **1972**, *49* (11), 761.

(6) Report of the Organic Subcommittee of the Curriculum Committee, Part II. *J. Chem. Educ.* **1976**, *53* (1), 25.

(7) Moran, B. How to Get an A- in Organic Chemistry. *The New York Times*; October 19, 2018.

(8) Morris, N. P. It's Time to Retire Premed. https://blogs.scientificamerican.com/guest-blog/it-s-time-to-retire-premed/ (accessed July 17, 2019).

(9) Grove, N. P.; Cooper, M. M.; Rush, K. M. Decorating with Arrows: Toward the Development of Representational Competence in Organic Chemistry. *J. Chem. Educ.* **2012**, *89*, 844−849.

(10) Bhattacharyya, G. From Source to Sink: Mechanistic Reasoning Using the Electron-Pushing Formalism. *J. Chem. Educ.* **2013**, *90*, 1282−1289.

(11) Bhattacharyya, G. Trials and Tribulations: Student Approaches and Difficulties with Proposing Mechanisms Using the Electron-Pushing Formalism. *Chem. Educ. Res. Pract.* **2014**, *15*, 594.

(12) Flynn, A. B.; Featherstone, R. B. Language of Mechanisms: Exam Analysis Reveals Students' Strengths, Strategies, and Errors When Using the Electron-Pushing Formalism (Curved Arrows) in New Reactions. *Chem. Educ. Res. Pract.* **2017**, *18* (1), 64−77.

(13) Bhattacharyya, G.; Bodner, G. M. It Gets Me to the Product": How Students Propose Organic Mechanisms. *J. Chem. Educ.* **2005**, *82* (9), 1402.

(14) Crandell, O. M.; Kouyoumdjian, H.; Underwood, S. M.; Cooper, M. M. Reasoning about Reactions in Organic Chemistry: Starting It in General Chemistry. *J. Chem. Educ.* **2019**, *96* (2), 213−226.

(15) Galloway, K. R.; Stoyanovich, C.; Flynn, A. B. Students' Interpretations of Mechanistic Language in Organic Chemistry before Learning Reactions. *Chem. Educ. Res. Pract.* **2017**, *18* (2), 353−374.

(16) McClary, L.; Talanquer, V. Heuristic Reasoning in Chemistry: Making Decisions about Acid Strength. *Int. J. Sci. Educ.* **2011**, *33* (10), 1433−1454.

(17) Cruz-Ramirez de Arellano, D.; Towns, M. H. Students' Understanding of Alkyl Halide Reactions in Undergraduate Organic Chemistry. *Chem. Educ. Res. Pract.* **2014**, *15* (4), 501−515.

(18) Anzovino, M. E.; Bretz, S. L. Organic Chemistry Students' Fragmented Ideas about the Structure and Function of Nucleophiles and Electrophiles: A Concept Map Analysis. *Chem. Educ. Res. Pract.* **2016**, *17*, 1019−1029.

(19) Anzovino, M. E.; Bretz, S. L. Organic Chemistry Students' Ideas about Nucleophiles and Electrophiles: The Role of Charges and Mechanisms. *Chem. Educ. Res. Pract.* **2015**, *16* (4), 797−810.

(20) Head, J.; Bucat, R.; Mocerino, M.; Treagust, D. Exploring Students' Abilities to Use Two Different Styles of Structural Representation in Organic Chemistry. *Can. J. Sci. Math. Techn. Educ.* **2005**, *5* (1), 133−152.

(21) Rushton, G. T.; Hardy, R. C.; Gwaltney, K. P.; Lewis, S. E. Alternative Conceptions of Organic Chemistry Topics among Fourth Year Chemistry Students. *Chem. Educ. Res. Pract.* **2008**, *9* (2), 122−130.

(22) Cartrette, D. P.; Mayo, P. M. Students' Understanding of Acids/Bases in Organic Chemistry Contexts. *Chem. Educ. Res. Pract.* **2011**, *12* (1), 29−39.

(23) Bretz, S. L.; McClary, L. Students' Understandings of Acid Strength: How Meaningful Is Reliability When Measuring Alternative Conceptions? *J. Chem. Educ.* **2015**, *92* (2), 212−219.

(24) McClary, L. M.; Bretz, S. L. Development and Assessment of A Diagnostic Tool to Identify Organic Chemistry Students' Alternative Conceptions Related to Acid Strength. *Int. J. Sci. Educ.* **2012**, *34* (15), 2317−2341.

(25) Bodé, N. E.; Flynn, A. B. Strategies of Successful Synthesis Solutions: Mapping, Mechanisms, and More. *J. Chem. Educ.* **2016**, *93* (4), 593−604.

(26) Flynn, A. B. How Do Students Work through Organic Synthesis Learning Activities? *Chem. Educ. Res. Pract.* **2014**, *15* (4), 747−762.

(27) Cartrette, D. P.; Bodner, G. M. Non-Mathematical Problem Solving in Organic Chemistry. *J. Res. Sci. Teach.* **2010**, *47* (6), 643−660.

(28) Topczewski, J. J.; Topczewski, A. M.; Tang, H.; Kendhammer, L. K.; Pienta, N. J. NMR Spectra through the Eyes of a Student: Eye Tracking Applied to NMR Items. *J. Chem. Educ.* **2017**, *94* (1), 29−37.

(29) Connor, M. C.; Finkenstaedt-Quinn, S. A.; Shultz, G. V. Constraints on Organic Chemistry Students' Reasoning during IR and

1H NMR Spectral Interpretation. *Chem. Educ. Res. Pract.* **2019**, *20*, 522.

(30) Galloway, K. R.; Leung, M. W.; Flynn, A. B. Patterns of Reactions: A Card Sort Task to Investigate Students' Organization of Organic Chemistry Reactions. *Chem. Educ. Res. Pract.* **2019**, *20* (1), 30−52.

(31) Galloway, K. R.; Leung, M. W.; Flynn, A. B. A Comparison of How Undergraduates, Graduate Students, and Professors Organize Organic Chemistry Reactions. *J. Chem. Educ.* **2018**, *95* (3), 355−365.

(32) National Research Council. *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*; Singer, S. R, Nielson, N. R., Schweingruber, H. A., Eds.; National Academies Press: Washington, DC, 2012.

(33) Padalkar, S.; Hegarty, M. Models as Feedback: Developing Representational Competence in Chemistry. *J. Educ. Psych.* **2015**, *107* (2), 451−497.

(34) Cooper, M. M.; Stowe, R. L. Chemistry Education Research—From Personal Empiricism to Evidence, Theory, and Informed Practice. *Chem. Rev.* **2018**, *118* (12), 6053−6087.

(35) Taagepera, M.; Arasasingham, R. D.; King, S.; Potter, F.; Martorell, I.; Ford, D.; Wu, J.; Kearney, A. M. Integrating Symmetry in Stereochemical Analysis in Introductory Organic Chemistry. *Chem. Educ. Res. Pract.* **2011**, *12* (3), 322−330.

(36) Stieff, M.; Dixon, B. L.; Ryu, M.; Kumi, B. C.; Hegarty, M. Strategy Training Eliminates Sex Differences in Spatial Problem Solving in a Stem Domain. *J. Educ. Psychol.* **2014**, *106* (2), 390−402.

(37) Grove, N. P.; Hershberger, J. W.; Bretz, S. L. Impact of a Spiral Organic Curriculum on Student Attrition and Learning. *Chem. Educ. Res. Pract.* **2008**, *9* (2), 157−162.

(38) Ege, S. N.; Coppola, B. P.; Lawton, R. G. The University of Michigan Undergraduate Chemistry Curriculum 1. Philosophy, Curriculum, and the Nature of Change. *J. Chem. Educ.* **1997**, *74* (1), 74.

(39) Malinak, S. M.; Bayline, J. L.; Brletic, P. A.; Harris, M. F.; Iuliucci, R. J.; Leonard, M. S.; Matsuno, N.; Pallack, L. A.; Stringfield, T. W.; Sunderland, D. P. The Impacts of an "Organic First" Chemistry Curriculum at a Liberal Arts College. *J. Chem. Educ.* **2014**, *91* (7), 994−1000.

(40) Flynn, A. B.; Ogilvie, W. W. Mechanisms before Reactions: A Mechanistic Approach to the Organic Chemistry Curriculum Based on Patterns of Electron Flow. *J. Chem. Educ.* **2015**, *92* (5), 803−810.

(41) Karty, J. *Organic Chemistry—Principles and Mechanisms*, 2nd ed.; W. W. Norton & Company: New York, NY, 2018.

(42) McMurray, J. E. *Organic Chemistry*, 8th ed.; Cengage Learning: Boston, MA, 2012.

(43) Hein, S. M. Positive Impacts Using POGIL in Organic Chemistry. *J. Chem. Educ.* **2012**, *89* (7), 860−864.

(44) Tien, L. T.; Roth, V.; Kampmeier, J. a. Implementation of a Peer-Led Team Learning Instructional Approach in an Undergraduate Organic Chemistry Course. *J. Res. Sci. Teach.* **2002**, *39*, 606−632.

(45) Fautch, J. M. The Flipped Classroom for Teaching Organic Chemistry in Small Classes: Is It Effective? *Chem. Educ. Res. Pract.* **2015**, *16* (1), 179−186.

(46) Tien, L. T.; Roth, V.; Kampmeier, J. a. Implementation of a Peer-Led Team Learning Instructional Approach in an Undergraduate Organic Chemistry Course. *J. Res. Sci. Teach.* **2002**, *39* (7), 606−632.

(47) Mooring, S. R.; Mitchell, C. E.; Burrows, N. L. Evaluation of a Flipped, Large-Enrollment Organic Chemistry Course on Student Attitude and Achievement. *J. Chem. Educ.* **2016**, *93* (12), 1972−1983.

(48) Liu, Y.; Raker, J. R.; Lewis, J. E. Evaluating Student Motivation in Organic Chemistry Courses: Moving from a Lecture-Based to a Flipped Approach with Peer-Led Team Learning. *Chem. Educ. Res. Pract.* **2018**, *19* (1), 251−264.

(49) National Research Council. *How People Learn: Brain, Mind, Experience, and School*; National Academies Press: Washington, DC, 1999.

(50) National Academies of Sciences, Engineering, and Medicine. *How People Learn II: Learners, Contexts, and Cultures*; National Academies Press: Washington, DC, 2018. DOI: 10.17226/24783.

(51) Bodner, G. M. Constructivism: A Theory of Knowledge. *J. Chem. Educ.* **1986**, *63*, 873−878.

(52) Taber, K. S. Conceptual Resources for Learning Science: Issues of Transience and Grain-Size in Cognition and Cognitive Structure. *Int. J. Sci. Educ.* **2008**, *30* (8), 1027−1053.

(53) Cooper, M. M.; Corley, L. M.; Underwood, S. M. An Investigation of College Chemistry Students' Understanding of Structure−Property Relationships. *J. Res. Sci. Teach.* **2013**, *50*, 699−721.

(54) diSessa, A. Alternative Conceptions and P-Prims. In *Encyclopedia of Science Education*; Gunstone, R., Ed.; Springer: Dordrecht, 2015; pp 34−37. DOI: 10.1007/978-94-007-2150-0_87.

(55) Hammer, D. Student Resources for Learning Introductory Physics. *Am. J. Phys.* **2000**, *68*, S52−S59.

(56) Becker, N. M.; Rupp, C. A.; Brandriet, A. Engaging Students in Analyzing and Interpreting Data to Construct Mathematical Models: An Analysis of Students' Reasoning in a Method of Initial Rates Task. *Chem. Educ. Res. Pract.* **2017**, *18*, 798−810.

(57) *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; National Academies Press: Washington, DC, 2012.

(58) Matz, R. L.; Fata-Hartley, C. L.; Posey, L. A.; Laverty, J. T.; Underwood, S. M.; Carmel, J. H.; Herrington, D. G.; Stowe, R. L.; Caballero, M. D.; Ebert-May, D.; et al. Evaluating the Extent of a Large-Scale Transformation in Gateway Science Courses. *Science Advances* **2018**, *4* (10), No. eaau0554.

(59) Cooper, M. M.; Caballero, M. D.; Ebert-May, D.; Fata-Hartley, C. L.; Jardeleza, S. E.; Krajcik, J. S.; Laverty, J. T.; Matz, R. L.; Posey, L. A.; Underwood, S. M. Challenge Faculty to Transform STEM Learning. *Science* **2015**, *350* (6258), 281−282.

(60) Cooper, M. M.; Posey, L. A.; Underwood, S. M. Core Ideas and Topics: Building up or Drilling Down? *J. Chem. Educ.* **2017**, *94* (5), 541−548.

(61) Williams, L. C.; Underwood, S. M.; Klymkowsky, M. W.; Cooper, M. M. Are Noncovalent Interactions an Achilles Heel in Chemistry Education? A Comparison of Instructional Approaches. *J. Chem. Educ.* **2015**, *92*, 1979−1987.

(62) Underwood, S. M.; Reyes-Gastelum, D.; Cooper, M. M. When Do Students Recognize Relationships between Molecular Structure and Properties? A Longitudinal Comparison of the Impact of Traditional and Transformed Curricula. *Chem. Educ. Res. Pract.* **2016**, *17*, 365−380.

(63) Cooper, M. M.; Kouyoumdjian, H.; Underwood, S. M. Investigating Students' Reasoning about Acid−Base Reactions. *J. Chem. Educ.* **2016**, *93* (10), 1703−1712.

(64) Cooper, M. M.; Klymkowsky, M. W. CLUE: Chemistry, Life, the Universe & Everything. http://clue.chemistry.msu.edu/ (accessed Jul 17, 2019).

(65) Stowe, R. L.; Cooper, M. M. Practice What We Preach: Assessing "Critical Thinking" in Organic Chemistry. *J. Chem. Educ.* **2017**, *94* (12), 1852−1859.

(66) Carmel, J. H.; Herrington, D. G.; Posey, L. A.; Ward, J. S.; Pollock, A. M.; Cooper, M. M. Helping Students to "Do Science": Characterizing Scientific Practices in General Chemistry Laboratory Curricula. *J. Chem. Educ.* **2019**, *96* (3), 423−434.

(67) Caspari, I.; Weinrich, M. L.; Sevian, H.; Graulich, N. This Mechanistic Step Is "Productive": Organic Chemistry Students' Backward-Oriented Reasoning. *Chem. Educ. Res. Pract.* **2018**, *19* (1), 42−59.

(68) Kraft, A.; Strickland, A. M.; Bhattacharyya, G. Reasonable Reasoning: Multi-Variate Problem-Solving in Organic Chemistry. *Chem. Educ. Res. Pract.* **2010**, *11* (4), 281−292.

(69) EMBL-EBI. MACiE. https://www.ebi.ac.uk/miriam/main/datatypes/MIR:00000077 (accessed July 17, 2019).

(70) Holliday, G. L.; Almonacid, D. E.; Mitchell, J. B. O.; Thornton, J. M. The Chemistry of Protein Catalysis. *J. Mol. Biol.* **2007**, *372* (5), 1261−1277.

(71) Flynn, A. B. Structure and Evaluation of Flipped Chemistry Courses: Organic & Spectroscopy, Large and Small, First to Third

Year, English and French. *Chem. Educ. Res. Pract.* **2015**, *16* (2), 198−211.

(72) Redish, E. F.; Bauer, C.; Carleton, K. L.; Cooke, T. J.; Cooper, M.; Crouch, C. H.; Dreyfus, B. W.; Geller, B. D.; Giannini, J.; Gouvea, J. S.; et al. NEXUS/Physics: An Interdisciplinary Repurposing of Physics for Biologists. *Am. J. Phys.* **2014**, *82* (5), 368−377.

(73) Roblin, N. P.; Schunn, C.; McKenney, S. What Are Critical Features of Science Curriculum Materials That Impact Student and Teacher Outcomes? *Sci. Educ.* **2018**, *102* (2), 260−282.

(74) Kohn, K. P.; Underwood, S. M.; Cooper, M. M. Energy Connections and Misconnections across Chemistry and Biology. *CBE Life. Sci. Educ.* **2018**, *17* (1), No. ar3.

(75) Kohn, K. P.; Underwood, S. M.; Cooper, M. M. Connecting Structure−Property and Structure−Function Relationships across the Disciplines of Chemistry and Biology: Exploring Student Perceptions. *CBE Life. Sci. Educ.* **2018**, *17* (2), No. ar33.

(76) Cooper, M. M.; Grove, N.; Underwood, S. M.; Klymkowsky, M. W. Lost in Lewis Structures: An Investigation of Student Difficulties in Developing Representational Competence. *J. Chem. Educ.* **2010**, *87*, 869−874.

(77) Nicoll, G. A Qualitative Investigation of Undergraduate Chemistry Students' Macroscopic Interpretations of the Submicroscopic Structures of Molecules. *J. Chem. Educ.* **2003**, *80* (2), 205.

(78) Bretz, S. L.; Linenberger, K. J. Development of the Enzyme−Substrate Interactions Concept Inventory. *Biochem. Mol. Biol. Educ.* **2012**, *40* (4), 229−233.

(79) Loertscher, J.; Villafañe, S. M.; Lewis, J. E.; Minderhout, V. Probing and Improving Student's Understanding of Protein α-Helix Structure Using Targeted Assessment and Classroom Interventions in Collaboration with a Faculty Community of Practice. *Biochem. Mol. Biol. Educ.* **2014**, *42* (3), 213−223.

(80) A Comparison of How Undergraduates, Graduate Students, and Professors Organize Organic Chemistry Reactions. *J. Chem. Educ.* **2018**, *95* (3), 355−365.

(81) Cooper, M. M. The New MCAT: An Incentive for Reform or a Lost Opportunity? *J. Chem. Educ.* **2013**, *90* (7), 820−822.

(82) Brenner, C. Rethinking Premedical and Health Professional Curricula in Light of MCAT 2015. *J. Chem. Educ.* **2013**, *90* (7), 807−812.

(83) Cooper, M. M.; Williams, L. C.; Underwood, S. M. Student Understanding of Intermolecular Forces: A Multimodal Study. *J. Chem. Educ.* **2015**, *92* (8), 1288−1298.

(84) Underwood, S. M.; Reyes-Gastelum, D.; Cooper, M. M. Answering the Questions of Whether and When Student Learning Occurs: Using Discrete-Time Survival Analysis to Investigate How College Chemistry Students' Understanding of Structure-Property Relationships Evolves. *Sci. Educ.* **2015**, *99*, 1055−1072.

(85) Bretz, S. L. Novak's Theory of Education: Human Constructivism and Meaningful Learning. *J. Chem. Educ.* **2001**, *78*, 1107−1117.

(86) Becker, N. M.; Cooper, M. M. College Chemistry Students' Understanding of Potential Energy in the Context of Atomic-Molecular Interactions. *J. Res. Sci. Teach.* **2014**, *51* (6), 789−808.

(87) CLUE: Chemistry, Life, the Universe and Everything. https://clue.chemistry.msu.edu/oclue.html (accessed July 17, 2019).

(88) Bryfczynski, S. P. Be Socratic: An Intelligent Tutoring System for the Recognition, Evaluation, and Analysis of Free-Form Student Input. Doctoral Dissertation, Clemson University, 2012.

(89) Cooper, M. M.; Underwood, S. M.; Bryfczynski, S. P.; Klymkowsky, M. W. A Short History of the Use of Technology To Model and Analyze Student Data for Teaching and Research. In *Tools of Chemistry Education Research*; ACS Symposium Series; American Chemical Society: Washington, DC, 2014; Vol. *1166*, pp 219−239. DOI: 10.1021/bk-2014-1166.ch012.

(90) Scouller, K.; Prosser, M. Students' Experiences in Studying for Multiple Choice Question Examiniations. *Stud. High. Educ.* **1994**, *19* (3), 267−279.

(91) Entwistle, N. J. Approaches to Learning and Perceptions of the Learning Environment. *High. Educ.* **1991**, *22* (3), 201−204.

(92) Crooks, T. J. The Impact of Classroom Evaluation Practices on Students. *Rev. High. Educ.* **1988**, *58* (4), 438−481.

(93) Stains, M.; Harshman, J.; Barker, M. K.; Chasteen, S. V.; Cole, R.; DeChenne-Peters, S. E.; Eagan, M. K.; Esson, J. M.; Knight, J. K.; Laski, F. A.; et al. Anatomy of STEM Teaching in North American Universities. *Science* **2018**, *359* (6383), 1468−1470.

(94) Freeman, S.; Eddy, S. L.; McDonough, M.; Smith, M. K.; Okoroafor, N.; Jordt, H.; Wenderoth, M. P. Active Learning Increases Student Performance in Science, Engineering, and Mathematics. *Proc. Natl. Acad. Sci. U. S. A.* **2014**, *111*, 8410−8415.

(95) National Research Council. *Knowing What Students Know: The Science and Design of Educational Assessment*; Pellegrino, J. W., Chudowsky, N., Glaser, R., Eds.; National Academies Press: Washington, DC, 2001.

(96) Schwarz, C. V.; Reiser, B. J.; Davis, E. A.; Kenyon, L.; Achér, A.; Fortus, D.; Shwartz, Y.; Hug, B.; Krajcik, J. S. Developing a Learning Progression for Scientific Modeling: Making Scientific Modeling Accessible and Meaningful for Learners. *J. Res. Sci. Teach.* **2009**, *46*, 632−654.

(97) Windschitl, M.; Thompson, J.; Braaten, M. Beyond the Scientific Method: Model-Based Inquiry as a New Paradigm of Preference for School Science Investigations. *Sci. Educ.* **2008**, *92*, 941−967.

(98) Dominowski, R. L. Verbalization and Problem Solving. In *Metacognition in Educational Theory and Practice*; Routledge: New York, 1998; pp 39−60.

(99) Anderson, T. L.; Bodner, G. M. What Can We Do about 'Parker'? A Case Study of a Good Student Who Didn't 'Get' Organic Chemistry. *Chem. Educ. Res. Pract.* **2008**, *9* (2), 93−101.

(100) Pabuccu, A.; Erduran, S. Beyond Rote Learning in Organic Chemistry: The Infusion and Impact of Argumentation in Tertiary Education. *Int. J. Sci. Educ.* **2017**, *39* (9), 1154−1172.

(101) Cole, R.; Becker, N.; Towns, M.; Sweeney, G.; Wawro, M.; Rasmussen, C. Adapting a Methodology from Mathematics Education Research to Chemistry Education Research: Documenting Collective Activity. *Int. J. of Sci. and Math. Educ.* **2012**, *10* (1), 193−211.

(102) Raker, J. R.; Towns, M. H. Problem Types in Synthetic Organic Chemistry Research: Implications for the Development of Curricular Problems for Second-Year Level Organic Chemistry Instruction. *Chem. Educ. Res. Pract.* **2012**, *13* (3), 179−185.

(103) ACS Division of Chemical Education Examinations Institute. https://uwm.edu/acs-exams/ (accessed July 27, 2019).

(104) Grove, N. P.; Cooper, M. M.; Cox, E. L. Does Mechanistic Thinking Improve Student Success in Organic Chemistry? *J. Chem. Educ.* **2012**, *89*, 850−853.

(105) Underwood, S. M.; Posey, L. A.; Herrington, D. G.; Carmel, J. H.; Cooper, M. M. Adapting Assessment Tasks To Support Three-Dimensional Learning. *J. Chem. Educ.* **2018**, *95* (2), 207−217.