A COMPREHENSIVE AND FORMATIVE EXPLORATION OF STUDENT COMPREHENSION AND ASSESSMENT IN UNDERGRADUATE ORGANIC CHEMISTRY

by

RUPA RESHA GOKAL

(Under the Direction of Richard W. Morrison)

ABSTRACT

Organic chemistry, by reputation and in practice, is one of the most challenging disciplines for students to master among all undergraduate courses. Students entering organic chemistry are often only in their second year of undergraduate education and are still honing the study and self-assessment skills necessary for success at the college level and beyond. Additionally, the unique combination of analytical skills, translation abilities and precision required to explain how organic compounds behave and interact challenges the reliance on memorization and application of formulae with which students have become accustomed throughout their secondary education pursuits. Therefore, the challenge for organic chemistry instructors is to not only teach concepts related to the discipline but to also aid in the improvement of critical thinking skills, self-regulated learning skills and academic maturity.

In the realm of chemical education, abundant research exists exploring the positive impact of active-learning strategies on student motivation and comprehension but these studies often report single instance implementations, either not describing or not exploring long-term instructional impact. Current research promotes the utilization of frequent, interactive assessments of student comprehension and progress to identify learning needs and thereby enrich instruction, but this type of comprehensive and formative assessment is considerably underexplored for undergraduate organic chemistry.

The present work describes the demands and advantages of iterative evaluation and analysis of assessment items and contributes comprehensive insight into undergraduate students' thought processes when learning and mastering specific organic chemistry concepts. The study began with the development of targeted clicker questions to better convey instructor expectations, more effectively assess student mastery of concepts, and increase the informative value of answer submissions. The information gleaned from this initial effort served to strengthen lecture presentations and motivated the creation of a clicker question repository for continued use in organic chemistry instruction. Formative assessment efforts were furthered by the development of a departmental cumulative final examination and continued analyses of results. The insight gathered in this study informed the development of tutorial and assessment resources that continue to shape instructional efforts in undergraduate organic chemistry at UGA and contribute to a previously underdeveloped area of chemical education research.

INDEX WORDS: Undergraduate organic chemistry, Chemical education, Formative assessment, Formative analysis, Undergraduate instruction, Undergraduate assessment, STEM instruction, Classroom response systems, Clicker questions, Organic structure

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DEDICATION

To my mom and dad and my dear Uncle Bud. Thank you all for the immense love, guidance, patience and selflessness you have shown me in my life. Thank you for showing me that this life is our most precious gift and how to appreciate every moment. Dad, you will always be the most generous, wonderful, smart, joyous and golden-hearted person I have ever known. I miss you everyday. Thank you for seeing in me what I could not and sending me off to earn my PhD…you and I will walk across that stage together. Mom, thank you for being a pillar of strength throughout my entire life and especially in the past few years. I will forever be in awe of your beauty, grace and selflessness. Uncle Bud, although you've been gone for many years, not a day goes by when I don't think of you and your beautiful smile. Thank you for being my dad's best friend and for sharing your beautiful family with us. I look forward to the day when we all can dance together again.

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CHAPTER 1

INTRODUCTION

The conception, application and study of instructional strategies are motivated by two fundamental goals: to improve the quality of instruction and to improve students' comprehension abilities and critical thinking skills. Irrespective of discipline and student population, educational experts agree that effective instruction engages students and supports their development of cognitive reasoning skills.[1-4] Analogously, the quality of an assessment tool is measured by its ability to successfully probe students' concept mastery, to clearly elucidate expectations and to reveal students' gaps in knowledge.[4-8] Although these pedagogical objectives are readily apparent across all disciplines and instructional environments, identifying the best instructional strategy or system to successfully achieve said goals is much more challenging. Some instructional strategies lend themselves better to certain disciplines, while the applicability of others is based on enrollment numbers, classroom composition, faculty responsibilities or resource accessibility.

Regarding instruction and assessment in higher education settings, academics have encouraged replacing or supplementing classical lecturing techniques and hand-written homework assignments with more engaging and interactive instructional approaches and assessment tools. There are significant disadvantages to lecturing as a standalone strategy for instruction: it places students in a passive role, thereby minimizing their enthusiasm, engagement and personal accountability; and it overemphasizes the knowledge differential between instructors and students, which can cause students to perceive their instructor as unapproachable or uninterested in individual student success.[9-11] As such, experts in education encourage instructional strategies that promote increased student interest and participation.

Hand-written homework assignments are also known to have disadvantages, particularly for high-enrollment courses where prompt grading is extremely challenging. However, educators recognize that the feedback afforded by this grading is essential for students' progress and self-assessment. Thus, educators look to alternative assessment tools, like online homework and classroom response systems, that can provide reliable feedback about student comprehension without a significant time demand for collection and grading. Instructional strategies and learning environments that actively engage students and promote peer interactions are empirically found to increase student comprehension levels and enhance performance.[11-14]

Strategies and Tools for Chemistry Instruction and Assessment

Active-learning strategies for instruction are currently at the forefront of educational practices, particularly in higher education STEM (science, technology, engineering and math) courses.[14-17] Flipping the classroom is one such active-learning strategy that has been studied and endorsed for use in undergraduate science courses, particularly general and organic chemistry. This strategy requires that students read and familiarize themselves with terms and concepts prior to entering the classroom. In-class time is then spent working problems that probe student comprehension of the concepts described in the readings and that integrate multiple concepts for more complex understanding. Flipped classroom setups promote increased instructor-student communication and peer discussion because problem-solving strategies are developed and applied as a group.[18] When employed effectively, the flipped classroom environment provides instructors with frequent opportunities to elucidate and address student comprehension and enhances student engagement in the learning process.

Successful implementation of a flipped classroom requires as much of an instructor's time and effort outside of the classroom, if not more so, as it does within the classroom. Because a significant portion of students' foundational learning is completed before entering class, these guiding resources must be carefully developed and scrutinized. Furthermore, if students are expected to complete assignments to ensure they are reading the given material, these assignments must be generated and organized by the instructor, as well. Though the flipped classroom environment is proven to have significant positive impact on student comprehension and performance, the extensive efforts necessary for initial implementation can dissuade instructors from employing this teaching strategy.[19] It is also important to note that because the flipped classroom relies on students to lead in-class discussions and suggest solution strategies for given problems, the system breaks down if the majority of students come to class unprepared and without questions for group exploration. In this case, the instructor is either forced to resort to a classical lecturing approach or to forego the problem-solving session entirely.

Student-Centered Active Learning Environments with Upside-down Pedagogies (SCALE-UP) have also gained increased popularity in higher education STEM classes over the last decade. The primary goal of the SCALE-UP project is to create an interactive, technology-fueled learning environment that promotes hands-on practice and peer collaboration.[20] Similar to the flipped classroom strategy, SCALE-UP relies on student exposure to new materials outside of the classroom to support in-class problem-solving and discussion. Once again, careful consideration must be given to the planning and design of these materials to ensure they are effective in preparing students for further exploration in class.

The distinguishing factor for SCALE-UP versus the flipped classroom is the emphasis placed on the physical classroom setup. In a typical SCALE-UP classroom, students are arranged in groups around individual round tables that serve as research stations and laboratory benches; computers, simulators and necessary laboratory instruments are placed in the center of each table. For larger classrooms, more technology is incorporated for increased instructor-student and peer-to-peer exposure (e.g. visualizers, networked projectors, or webcams).[21] These round tables have been found to be the most effective in facilitating group discussions and give participating students equal access to the available resources.[21] Camera technology allows instructors to keep track of the happenings at individual tables and bring class attention to individual groups when necessary.

The SCALE-UP classroom is the most technologically advanced instructional setting and, with its tailored setup for increased communication between instructors, students and peers, has rather obvious positive effects on student engagement and comprehension.[22] There are considerable drawbacks, however, associated with the implementation of the SCALEUP strategy for high-enrollment chemistry classes. First, constructing and equipping a SCALEUP classroom involves significant upfront costs. Current functional SCALEUP classrooms accommodate up to 130 students in a single section; even with these numbers, however, several SCALEUP classrooms would be necessary to accommodate enrollments that are typical for the University of Georgia. The costs associated with remodeling multiple classrooms and subsequently outfitting these classrooms with advanced technological tools would be overwhelming, even with the aid of start-up funds and educational grants. Most importantly, the experiments typically associated with chemistry laboratory courses, particular those in organic chemistry, involve hazardous chemicals and dangerous experimental setups that require carefully designed and accessible safety features. The research-experimentation hybrid stations proposed for the SCALEUP strategy lend themselves well to STEM courses like physics and computer science, but are not practically adaptable for chemistry courses with associated laboratories.

In terms of assessing student comprehension in undergraduate chemistry courses and providing opportunities to practice problem-solving prior to formal examination, there are two popular tools: Online homework systems and Classroom Response Systems (CRS). Online homework systems, such as OWL (Online Web-Based Learning) and MasteringChem, are touted for their accessibility because the associated software is often included with the purchase of a textbook. These systems are equipped with predesigned questions and activities of varying utility: short answer and multiple/choice questions for vocabulary and concept assessment; structure-building software for structure elucidation and predict-the-product type questions; simulations for interactive discovery; and tutorials for stepwise problem-solving guidance. For most of these activities, the system is capable of grading student answer submissions according to a rubric set by the instructor, thereby providing immediate feedback for students. Given these features, online homework systems seem ideal for credit-based assessment of large-scale chemistry courses and, in theory, demand a relatively small time investment on the part of the instructor.[23,24]

However, there are some concerns with these online homework systems that undermine their potential for increasing student comprehension of chemical concepts. Experience with these systems reveals an overall lack of complexity in the provided questions, especially with regard to organic chemistry. If questions and problems are less challenging than those provided in the body of the associated text, the potential of these online homework systems to enhance student comprehension is significantly diminished. In order to improve their understanding, students need practice with questions of increasing complexity as they build their knowledge base.[25] Although these systems do allow for instructors to generate and assign their own questions, the features available to the instructor are much more limited than those for system-generated questions; therefore instructor generated questions are less sophisticated and are more difficult to adapt to the associated grading system. These limitations discourage instructors from generating questions within the online homework systems or, in many cases, from using the systems at all.

Classroom Response Systems (CRS) in conjunction with clickers are appreciated for their combination of the prompt feedback aspects of online homework technology and the flipped classroom benefits of peer interaction and real-time assessment.[26-28] Instructors pose questions, either predesigned or in-the-moment, and students submit their answers using either a physical clicker or for newer systems, a mobile phone app. These answer submissions are delivered to a designated USB receiver equipped with data processing software. Anonymous aggregate response statistics are then displayed for the class, at the instructor's discretion, as a bar graph. Clickers have immense potential as assessment tools because of their ease of utility even in large classrooms and because question design is not dictated by the software. The use of clickers provides students with a unique opportunity to practice problem-solving, reinforce their understanding via group discussion and assess their study strategies based on their performance.[26-28] Furthermore, responses provide instructors with real-time insight into student comprehension which suggest specific points of emphases for lecture presentations.

Clickers have growing potential as real-time assessment tools for higher learning, especially as the various support systems (TopHat, TurningPoint) continue to develop software that lends itself to a wider variety of question types and credit assignments. However, as with any assessment tool, the true value of clickers is dependent on the quality of the questions asked and how instructors use the information afforded by these probing sessions. Although there are several reports designed to suggest the most appropriate clicker question design for certain organic chemistry topics (e.g. mechanisms, retrosynthetic analysis, etc), these reports provide constructional guidance, not premade questions.[27,28] Premade clicker questions are not as abundantly available as questions are in online homework systems, so the burden of construction often falls to the course instructor. However, because CRSs lend themselves to in-the-moment assessment, instructors can come up with questions mid-lecture, lessening the time burden that is associated with generating questions in online homework systems.

Formative Assessment: Theory and Practice

Each of the previously discussed active-learning strategies has their merits and each has been frequently cited for its utility in improving student engagement and comprehension for undergraduate chemistry courses. However, it is important to recognize that it is not the simple implementation of the individual strategy itself that leads to these noted instructional improvements. The success of these strategies relies on two very important considerations: 1) the quality of resources designed to facilitate and improve instruction and 2) the frequency and quality of instructor response to student feedback. Each of these strategies creates unique opportunities for instructors to assess student comprehension and for students to benefit from that assessment through instruction and feedback; it is vital for instructors to seize these opportunities and respond to student needs. After all, there is no better source of information for instructors to use to make instructional decisions and construct learning objectives than data from their own students.[29] Essentially, these active-learning strategies create *formative assessment* opportunities where students demonstrate their mastery of material, instructors observe these trends and use this newfound insight to enhance instruction and assessment.

Formative assessment refers to frequent, interactive evaluations of student comprehension and progress to suggest instructional modifications that more effectively address student needs.[30] As opposed to summative assessment, in which the goal is to *evaluate* student learning by comparison to a given benchmark, the goal of formative assessment is to *monitor* student learning and respond accordingly to improve that learning.[31] Formative assessment probes specific aspects of student comprehension and places unique emphasis on the elucidation of students' reasoning, the idea being that in order to successfully address misconceptions and difficulties in understanding, one must first precisely identify these misconceptions and difficulties in understanding. A review of literature in science education confirms that formative assessment strategies are effective in improving the quality of instruction and increasing student comprehension.[29-32] This strategy is successful in enriching student learning because the process inherently incorporates a multitude of actions that have been individually proven to advance education (e.g. strengthening student-instructor communication, providing feedback to students for self-assessment, encouraging student engagement, fostering peer interaction, and increasing student exposure to alternative sources of information).

Formative analyses of student response data from summative assessment items gives instructors insight into students' concept mastery and problem solving strategies by placing unique emphasis on incorrect answer submissions and the thought processes involved in generating these answers. These detailed analyses can reveal specific points in students' problem-solving strategies that require more careful consideration; these discoveries can be used to formulate instruction or can be detailed to students as feedback for self-assessment. In either case, the use of students' response data to reveal their unique struggles engages students in the process of learning and connects students to their peers by highlighting commonalities and different learning strategies. In this manner, formative assessment improves students' abilities to self-regulate their learning and communicate their conceptual understanding, both of which are essential skills for matriculation through higher education and enduring success in the workplace.[11]

Despite its immense potential to improve student learning, formative assessment is considerably underutilized by teachers at all levels, but especially those in higher education.[11] This is the case for several reasons. First, formative assessment involves deliberate designing of instructional tools and assignments and continued analysis of results from each implementation; this process can be both labor and time intensive. For many instructors in higher education, instruction of undergraduate courses is just one of several professional endeavors. It is not uncommon for instructors to prioritize graduate student mentorships, grant applications and innovative research over improvement in undergraduate education.[11] Second, because undergraduate instructors are often selected to teach courses based on their area of emphasis and not based on their experience as educators, many lack the pedagogical awareness and training to integrate reform-based instructional strategies into their teaching.[11] This challenge would be even more pronounced for instructors in large-enrollment courses. Finally, formative assessment demands the use of instructional strategies that engage students and promote instruction as a discussion rather than a download. This aspect of formative assessment challenges conventional teaching strategies and alters the traditional instructor-student dynamic. These changes can be met with hesitation from faculty members with more traditional views on instruction.[11]

Although there are exceptions to this general trend in higher education that have been reported in recent years[10, 32-34], the implementation of formative assessment strategies in undergraduate organic chemistry remains largely unexplored. The few existing reports defend the contribution of formative evaluation to the improvement of student engagement and understanding, but lack discussions of long-term impact and concept-specific revelations. Considering that organic chemistry is widely held as one of the most challenging disciplines for students to master and that formative assessment is consistently proven to enhance student comprehension, this study designed a deliberate and formative evaluation of organic chemistry instruction to stimulate significant pedagogical advances.

Organic Chemistry at the University of Georgia

In recent fall semesters, the University of Georgia organic chemistry division experienced enrollments ranging from 800-1000 undergraduate students for first semester organic chemistry (CHEM 2211), 40-90 enrolled for honors first semester organic chemistry (CHEM 2311/2411) and 300-400 enrolled for second semester organic chemistry (CHEM 2212). Spring semester CHEM 2211 enrollments consistently decreased to between 450-550 and CHEM 2212 enrollments increased (450-550). Reflecting the steady increase in the university's undergraduate enrollment since its establishment in 1785, University of Georgia organic chemistry enrollment statistics continue to rise from academic year to academic year.[35]

To accommodate such high enrollment numbers, the University of Georgia organic chemistry department offers multiple sections of CHEM 2211 and CHEM 2212 each semester. Although separate sections of the same course may be taught by different instructors, substantial measures have been taken to ensure consistency in presentation of material, assessment rigor, and credit assignment. All undergraduate organic chemistry courses require the same textbook and accompanying solutions manual: currently, *Organic Chemistry, 8th ed*. by Paula Yurkanis Bruice. The same syllabus is provided across all sections of the same course, standardizing intended coverage, anticipated schedule, suggested homework problems and final grade determination. Results from free-response hour examinations that are administered throughout the semester and a cumulative multiple-choice final examination comprise the majority of student grade assignment; a portion of students' grades is allocated to clicker performance to encourage participation and genuine effort responses. To maintain exam integrity and consistency in evaluation, all students take the same course-specific free-response exam at the exact same time; make-up exams are not given. Graduate student proctors are distributed throughout the testing rooms to ensure academic honesty.

Similarly, considerable attention is dedicated to the consistent application of rubrics when grading these free response exams and the maintenance of exam security when returning graded exams to students. With such high enrollment numbers, prompt and proficient grading of these free response exams cannot be accomplished by course instructors alone. Therefore, grading sessions are organized wherein graduate students are assigned specific exam problems to score based on detailed instructor-generated exam keys and rubrics. Before grading begins, instructors discuss the specific aspects of grading a given problem with the assigned graduate student(s) and also make decisions regarding partial credit assignments as they come up through the session. Until the current year, graded exams were alphabetized, barcoded, scanned and uploaded to *OUTBOX*, a web application generated by a University of Georgia chemistry faculty member for the secure delivery of electronic exam copies to individual students.[36] This system ensured that graded exams could not be altered by students upon receipt, facilitated requests for instructor review of potential grading and totaling errors and brought the organic division into better compliance with the Family Educational Rights and Privacy Act (FERPA).[36] Because the *OUTBOX* system is no longer supported by the University of Georgia Enterprise Information Technology Services (EITS), electronic exam scans are currently sent to student university email accounts in line with FERPA regulations. Commercial grading and exam redistribution alternatives are currently being investigated.

Similarly, exam integrity and security are of the utmost importance during the administration of the multiple-choice final examinations at the close of the semester. From Fall 2005 through Summer 2016, various editions of the American Chemical Society Organic Chemistry standardized exams were administered for cumulative examination of students. University of Georgia main sequence students consistently ranked in the 80th percentile compared to national normalized averages, with Honors/Majors students often ranking above the 90th percentile. These results reflect the strong standard of organic chemistry instruction and the high quality of undergraduate organic chemistry students at the University of Georgia. As with the in-semester free response exams, all students take the final examination at the same time to ensure exam integrity. Graduate student proctors are distributed throughout the testing rooms to discourage cheating and ensure exam security. Scantrons®, scratch paper and exam booklets are carefully distributed to students at the beginning of the testing period and promptly collected after the allotted time has expired. In accordance with ACS Exam Institute regulations, students receive individual raw scores and percentile rankings, but are not granted access to any exam materials after testing is complete.

When it comes to instruction, University of Georgia organic chemistry faculty recognize the challenges that the curriculum presents for students in terms of comprehension, time management, self-assessment and study skills and they employ instructional strategies that assist students in overcoming these challenges. Organic chemistry is a language; it does not lend itself to rote memorization and formulaic application because there are so many factors that must be considered to successfully predict the behavior of a given species or the outcome of a chemical process.[10] Mastery of organic chemistry, even at the undergraduate level, requires keen attention to detail and complex diagnostic skills that reflect those required for the pursuit of advanced degrees and success in associated careers.[10,11] University of Georgia organic chemistry faculty recognize this correlation and hold students to high expectations for knowledge acquisition, pacing and self-assessment to prepare them for such future endeavors.

Students are not the only ones held to a high standard, as instructional resources are consistently scrutinized to ensure accuracy and consistency in presented material throughout the multi-section, multi-instructor curriculum. Errors in associated resources, like the chosen textbook and solutions manual, are identified and corrected; new discoveries that necessitate modification of previous understanding of reaction pathways or reagent utility are integrated appropriately into material presentations; and intriguing real-life applications are described to enhance student engagement and understanding. University of Georgia organic chemistry faculty acknowledge the value of active-learning strategies validated by decades of research in chemical education and employ these strategies to improve instruction. Classroom Response Systems in conjunction with clickers are employed for their efficacy in probing student comprehension, promoting peer interaction and encouraging student self-assessment; CRSs are also appreciated for their unique functionality in large-enrollment classrooms.[26-28] Whether clickers are used in a partial flipped approach to reinforce lecture presentations or for a completely flipped classroom approach depends on the section instructor, but in both cases, the use of clickers affords real-time insight into student comprehension and can enhance instruction. Although laboratory grades are independent of lecture performance, undergraduate laboratory experiments are also considered for their potential to reinforce organic chemistry concepts presented in lecture. Experiments are frequently developed and modified to corroborate material presented in lecture and to provide unique and exciting experience with synthetic techniques and analytical instrumentation. In fact, the University of Georgia organic chemistry department is at the forefront of undergraduate laboratory development both in terms of the instrumentation available in the undergraduate laboratories and in the design of pedagogically-significant multi-outcome experiments (MOEs) that highlight spectroscopic tools and structure elucidation.[37-39]

As evidenced by student performance on standardized exams and program design, faculty members demonstrate a strong standard of instruction and acknowledge the value of formative development for teaching and learning. These features were integral to the inspiration, implementation and success of the present work.

Summary

Extensive exploration of instructional strategies, advances in chemical education, and the epistemologies underlying the formative assessment theory elucidated a series of questions that were considered in the pursuit of improved instruction and student comprehension in undergraduate organic chemistry[40-42]:

1) What do instructors want students to know?
2) How do instructors determine what students know?
3) How do instructors address what students do not know?
4) How do instructors know if their efforts have proved successful?
5) How do instructors design subsequent efforts to more successfully probe that which remains unclear?

The first question in the series stresses the establishment of clear learning objectives for use in instructional planning and for elucidating faculty expectations of students; consistency in rigor, presentation and expectation is vital for students' development of study and self-assessment skills. University of Georgia organic chemistry faculty have excelled in establishing an effective standard of rigor to help prepare undergraduate students for future challenges and in maintaining consistency throughout the multi-section, multi-instructor, high-enrollment program. Elucidating answers to the remaining questions necessitated a keen balance of summative efforts and formative analyses, as described in the present work. The generation of more complex and targeted clicker questions than were previously available for organic chemistry instruction afforded more precise, real-time information regarding student comprehension and in turn, made lecture presentations more efficient and more profitable. Post-lecture analyses of aggregate clicker response data exposed common misconceptions and revealed specific stages in problem-solving where students struggled most. These revelations suggested instructional reforms with intent to preclude these expected misconceptions and misapplications of theory; these reforms included the generation of problem-solving guides to accompany clicker questions and reinforce critical thinking skills. A developed proficiency for assessing STEM content lent itself to the fulfillment of faculty requests to design cumulative multiple-choice final examinations that were more representative of the rigor level and content coverage associated with the University of Georgia organic chemistry curriculum.

In total, the present work constitutes a significant contribution to the educational literature describing how undergraduates conceptualize organic chemistry content and the role that information plays in improving instruction and assessment within the discipline. Additionally, the comprehensive question repositories developed to promote student content mastery and facilitate continued formative evaluation have revolutionized organic chemistry instruction at the University of Georgia and have enduring potential for further academic investigation.

CHAPTER 2

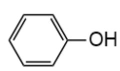
ADVANCED PROBING: DESIGNING QUESTIONS TO MORE EFFECTIVELY ELUCIDATE STUDENT COMPREHENSION

The inherent benefits of using clicker technology in the classroom (i.e. real-time assessment of student comprehension, increased student engagement, and increased peer interaction) are not exclusively dependent on the composition, format and subject matter of the questions employed. In theory, all forms of inquiry, whether true/false, multiple-choice or free response, have the potential to reveal aspects of student comprehension and knowledge retention. However, research indicates that the most accurate measure of student comprehension is achieved when students generate solutions de novo, as they would in a free response type assessment.[25,26,43] Essentially, decreasing the potential for guessing correctly and increasing the degrees of freedom for responses provides a more accurate measure of student comprehension levels. If the most apparent benefit of using clickers is the opportunity for instructors to determine what students know and address knowledge gaps in real-time, then a more precise measure of student comprehension would make resultant instructional efforts more effective. Recognizing untapped pedagogical potential in the construction of existing organic chemistry clicker questions, this study sought to maximize the utility of the CRS technology already being employed in University of Georgia courses by developing more probing and targeted clicker questions for instructional use.

Clicker Questions for Organic Chemistry

The use of CRS technology for prompt in-class inquiry in undergraduate organic chemistry courses has become increasingly popular over the past ten years. Increased recognition of the value of clicker technology for organic chemistry instruction led to the creation of open-access, web-based clicker repositories for use in organic chemistry classrooms.[44-46] These repositories are important because they provide resources for instructors who hesitate to employ active-learning strategies when tasked with the personal construction of associated materials. Figures 1, 2 and 3 provide representative examples of the questions available from the largest and most comprehensive of the referenced collections.[44]

Arrange the following compounds in order of INCREASING acid strength (from least acidic to most acidic).

	HCl	CH_3OH
I	II	III

A) III < II < I

B) III < I < II

C) I < III < II

D) II < III < I

E) I < II < III

Figure 1. Clicker question exploring relative acid strengths

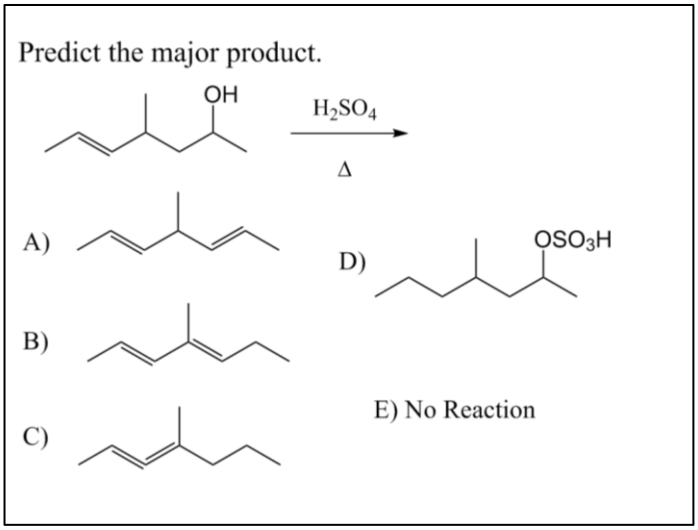


Figure 2. Clicker question exploring the acid-catalyzed dehydration of an alcohol

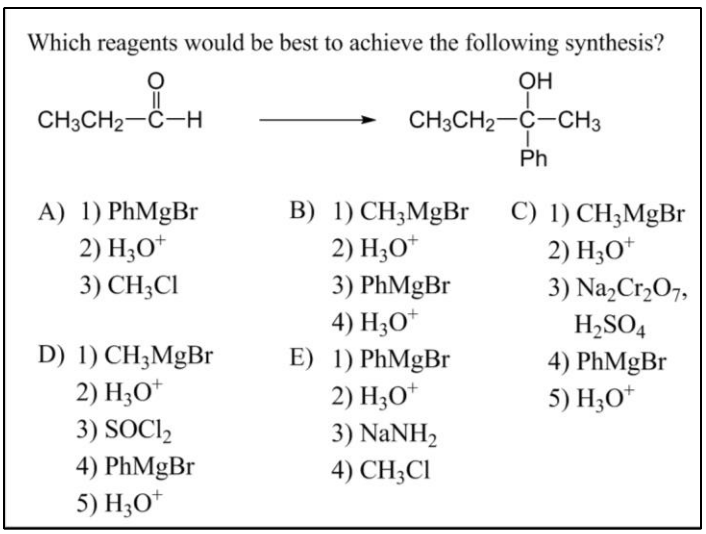


Figure 3. Clicker question exploring the synthesis of a tertiary alcohol

As in the provided examples, clicker questions across all current open-access web-based sources share this classic multiple-choice format with 3-5 response options and a single correct answer. This popular question format is associated with prompt feedback and readily lends itself to the software constraints of classroom response systems (e.g. character allowance, all-or-nothing credit assignments, etc.). Despite their popularity, these traditionally structured multiple-choice type assessment items are thought to encourage guessing and rote memorization and as such, are limited in their ability to precisely elucidate student comprehension. Further scrutiny of these multiple-choice clicker questions shows that correctly identifying just one aspect of the problem solution often eliminates all or most of the incorrect answer options.[25,26,47] Hence, it is increasingly difficult to justify the ability of multiple-choice items with limited answer options to distinguish between students with partial understanding and students with more complete understanding.

Inspired by suggestions for the construction of creative, guided inquiry-based clicker questions for organic chemistry first described by Dr. Richard Morrison in 2007[48], the researcher began the design and implementation of more probing clicker questions in first and second semester organic chemistry courses at the University of Georgia. Generation of new questions and informed modification of previously developed questions have continued over the course of five years leading to the development of an advanced clicker question repository detailed in a subsequent chapter.

Multiple-Choice: Encouraging a Free-Response Approach to Problem-Solving

Research and experience have shown that students are more successful in generating a correct answer than in selecting that same correct answer from a list of options. This may be because multiple answer options serve to "distract" students from recognizing the correct answer. However, it is also important to note that when students generate their own response, they are awarded credit for correct answers, regardless of how these correct answers are rendered spatially or structurally. In contrast, for multiple-choice questions, the question author decides how answers will be rendered and the burden falls to the student to recognize these constructions and associate them back to their predicted answer. This added responsibility can have a significant impact on student performance in a course like organic chemistry, where mastery of structural representations and translations is essential, but consistently proves difficult for students overall.[49] Nevertheless, because the TurningTechnologies clicker response system does not have an associated drawing tool and because some organic chemistry topics (e.g. structural relationships, ^{1}H NMR splitting patterns, and configuration assignments) are successfully probed using multiple-choice questions, this question format was not excluded. Rather, multiple-choice questions were designed to more closely simulate student answer generation for free-response format questions.[50]

Constrained only by the available space on the question slide, multiple-choice prompts are accompanied by seven to twelve answer options, depending on question topic. Attempts to extend answer options over the span of multiple slides proved unprofitable. The marginal increase in formative value afforded by the inclusion of more potential answers was counteracted by the decrease in the number of students who were successfully able to identify and submit their proposed answer in a timely manner. Additionally, having too many answer options can lead to response distributions that are too close to contribute formative insight for the instructor in real-time or to provide students the opportunity to draw meaningful conclusions regarding their own understanding.[25, 51-53] To compensate for the limited degrees of freedom dictated by slide organization, the formative value of each answer option is re-evaluated after each implementation of the corresponding question. Answer items with significantly low selection rates are replaced with different options that are informed by the tendencies observed in student generation of free-response answers for in-semester hour exams. The researcher is involved in an ongoing study, adjacent to but not described in the present work, that corroborates the effectiveness of free-response analysis for more effective multiple-choice response option construction.

The final effort for encouraging students to apply a free-response type analysis when answering a multiple-choice question is to withhold the answer palette from view while students engage one another in analytical discussion and hopefully, generate hand-written responses in their notebooks. A significant portion of the allotted response time involves student answer generation with no exposure to the palette of answer options to bias their problem-solving approach. Finally, students are shown the answer options and are given a reasonable amount of time, typically 30-60 seconds, to match their generated answer to one of the given answer options. Integrated spectroscopy problems make the best use of each of the strategies associated with the improved construction of multiple-choice clicker questions (Figures 4 and 5).

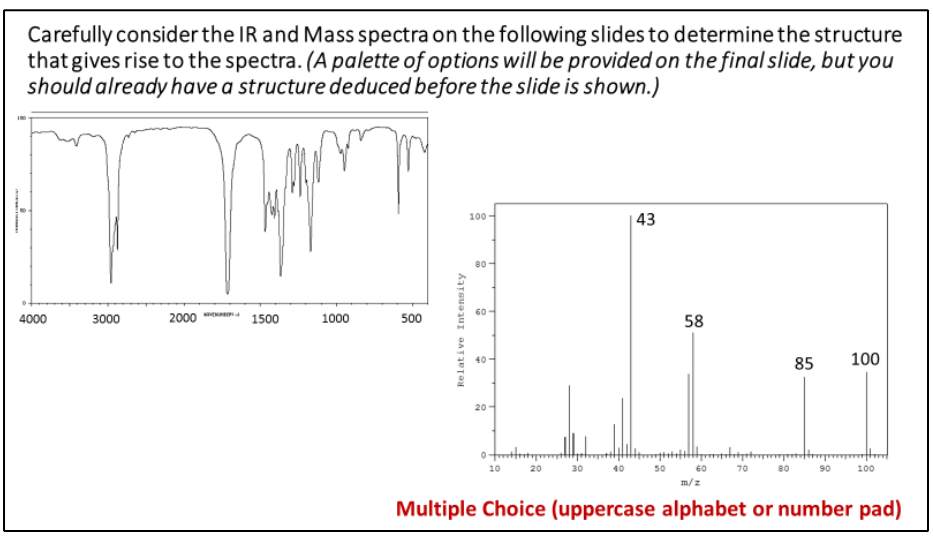


Figure 4. Multiple-choice clicker question exploring integrated spectroscopy and structure elucidation for first semester organic chemistry

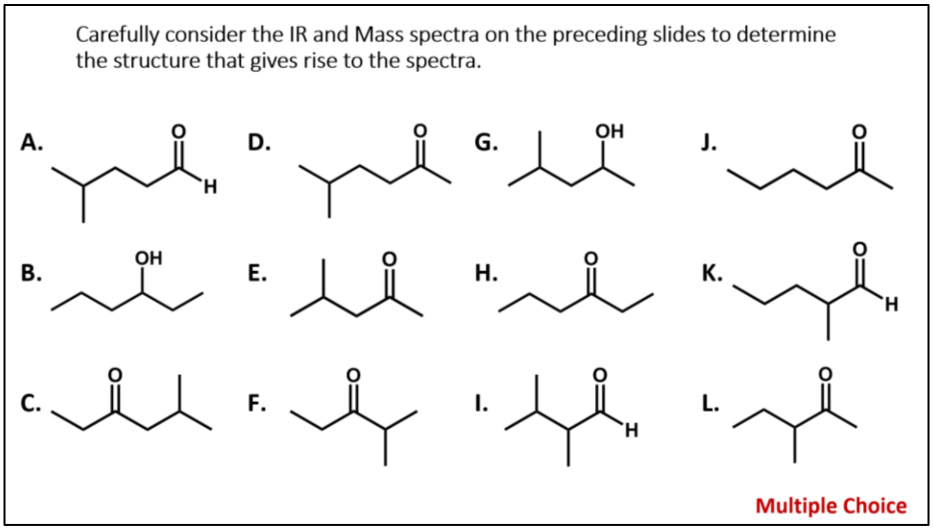


Figure 5. Delayed-display answer palette for integrated spectroscopy clicker question

Because the solutions require structure elucidation, integrated spectroscopy problems must be given as multiple-choice questions; and because a given molecular formula can represent a wide range of organic species, a larger palette is preferred for more illustrative probing of student analytical skills.

The aforementioned strategies for mimicking free-response answer generation widen the range of organic chemistry topics that can be successfully probed using multiple-choice formats. This affords instructors some flexibility in designing questions that provide reliable feedback in terms of student comprehension without the increase in generation and submission time associated more often with short answer problems.

Short Answer: Assessing Complete Understanding with Multiple Answer Questions

As discussed, one of the drawbacks of multiple-choice questions is that they only assess students' abilities to apply problem-solving for a single answer choice. Encouraging the application of strategic problem-solving for multiple examples improves students' diagnostic skills and assesses partial versus complete understanding.[25,26] Multiple-choice, multiple answer questions are designed as short answer questions because of limitations in TurningTechnologies software to award partial credit for accuracy and credit for participation simultaneously. By designing these questions as short answer submissions, the instructor has the freedom to determine precisely which set(s) of answers will be awarded credit. Although credit is awarded for all correct answer submissions, students are encouraged to submit multiple answers in alphabetical order to ensure that displayed response statistics are representative of overall class understanding. Multiple-choice multiple answer questions are useful for questions exploring categorization, multiple product formation and mechanistic pathways. Representative examples of each are provided below.

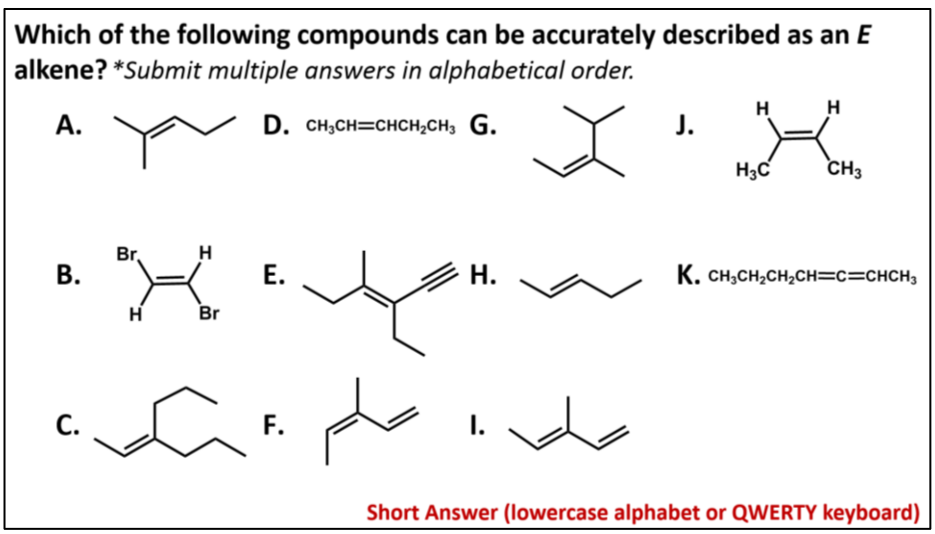


Figure 6. Multiple-choice multiple answer clicker question exploring alkene stereochemistry for first semester organic chemistry

The example provided in Figure 6 requires students to consider multiple alkene structures and determine whether the species can exhibit stereoisomerism and if so, which specific stereoisomer is represented. By challenging students' application of structural analysis and

Cahn-Ingold-Prelog rules for prioritization to a variety of examples, results for this question can provide specific insight into the types of representations with which students struggle most. In gaining this insight, the instructor uses class time more profitably by addressing only the necessary examples. Additionally, students have a clearer indication of whether they have mastered their understanding of alkene stereochemistry or need additional practice.

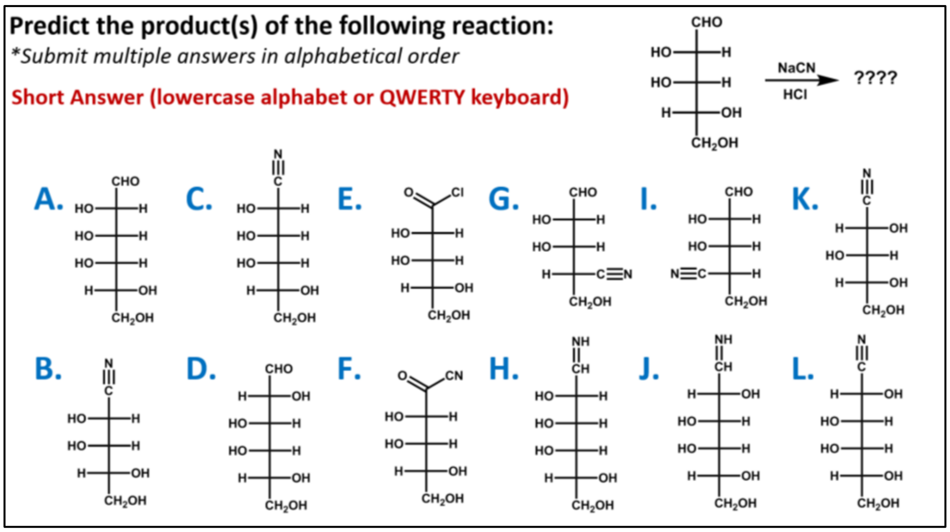


Figure 7. Multiple-choice multiple answer clicker question exploring common reactions of carbohydrates for second semester organic chemistry

The question shown in Figure 7 is designed to emphasize two specific aspects of student concept mastery: 1) that they have studied and understood each individual step of the Kiliani-Fischer elongation synthesis and not just the consequences of the process as a whole and 2) that they recognize that the first step proceeds with nucleophilic attack of the sp^2 hybridized carbon of the aldehyde to produce an equal mixture of two epimers. Response statistics from implementation of this question allow instructors to ascertain student mastery of these two aspects rather quickly.

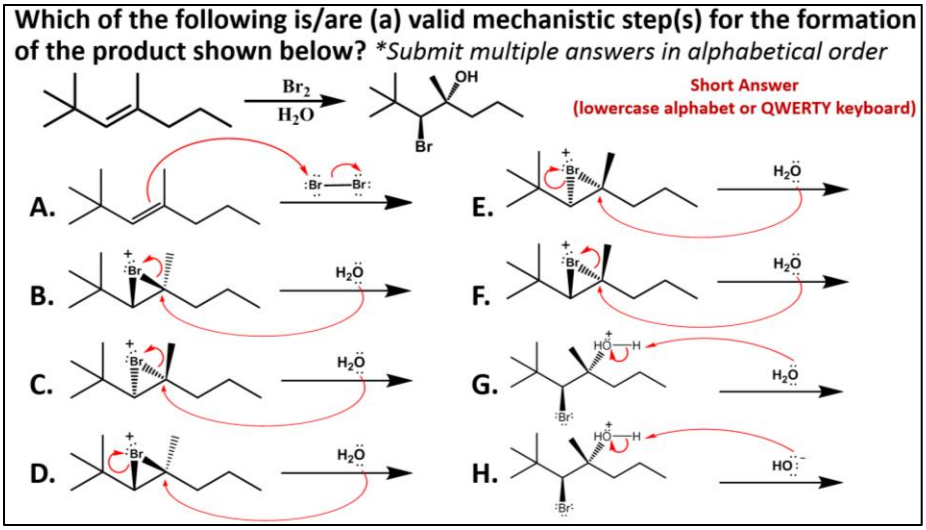


Figure 8. Multiple-choice multiple answer clicker question exploring electron movements for bromohydrin formation for first semester organic chemistry

The question shown in Figure 8 is unique in its exploration of students' understanding of mechanistic theory as it does so rather effectively without the use of drawing tools that are often considered the most successful in probing such content. The inclusion of stereochemical considerations and the representation of multiple steps forces students to navigate through the entire mechanism to generate the correct solution.

Multiple-choice multiple answer questions are unique in their ability to probe student mastery and to explore multiple aspects of a given topic simultaneously. In this regard, they prove much more successful in elucidating student comprehension than standard multiple-choice questions.

Short Answer: Eliminating Process of Elimination with String-of-Character Questions

The most significant disadvantage to the use of standard multiple-choice questions is that results from multi-variable examination of student comprehension are often tainted by students relying on process of elimination strategies instead of analytical skills to ascertain correct answers.[25,26] For ranking problems, the more variables students are asked to consider, the fewer options are actually able to be encompassed by the five answer options given in a standard multiple-choice question. In this way, multiple-choice answer options serve as prompts and student identification of even one correct rank assignment can potentially eliminate the majority of other options[25,26]. Traditional multiple-choice questions have similar limitations in exploring student comprehension for synthetic processes. Because synthesis planning is one of the most challenging skills for students to master in organic chemistry, it is increasingly important for instructors to effectively probe student problem-solving for syntheses and identify limitations.[27,53] The utilization of string-of-character questions more effectively probes complete understanding by compelling students to generate correct answers instead of simply recognizing correct aspects of a provided answer.[26] Moreover, the formative value analyses of string-of-character responses has on instruction is significant compared to that afforded by standard multiple-choice questions. Some aspects of this formative impact are explored in a subsequent chapter.

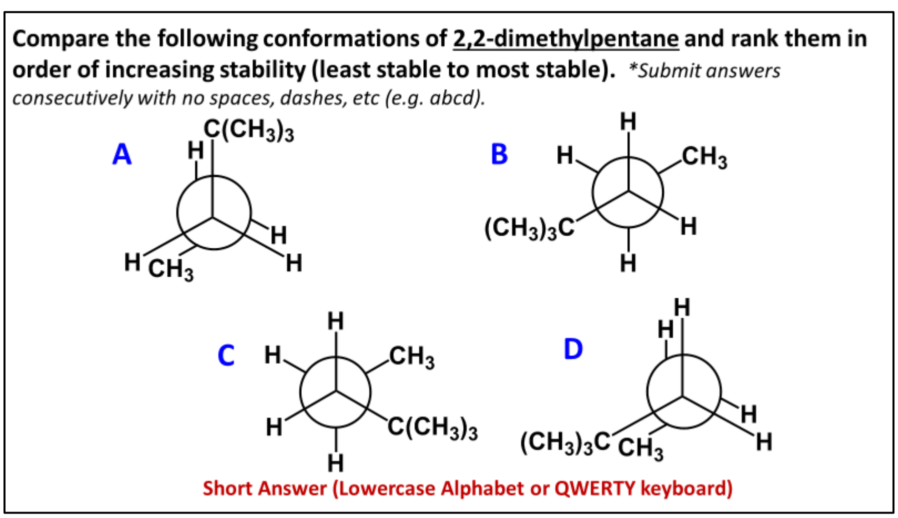


Figure 9. String-of-characters clicker question exploring relative conformer stabilities for first semester organic chemistry

The ranking problem given in Figure 9 explores student comprehension of Newman projections and relative stabilities. For the ranking of four items, as in this example, there are 24 permutations possible for answer submission, which simply cannot be encompassed practically by a multiple-choice question. Using the string-of-character style question still allows for prompt polling, but provides a much more accurate picture of student understanding.[26]

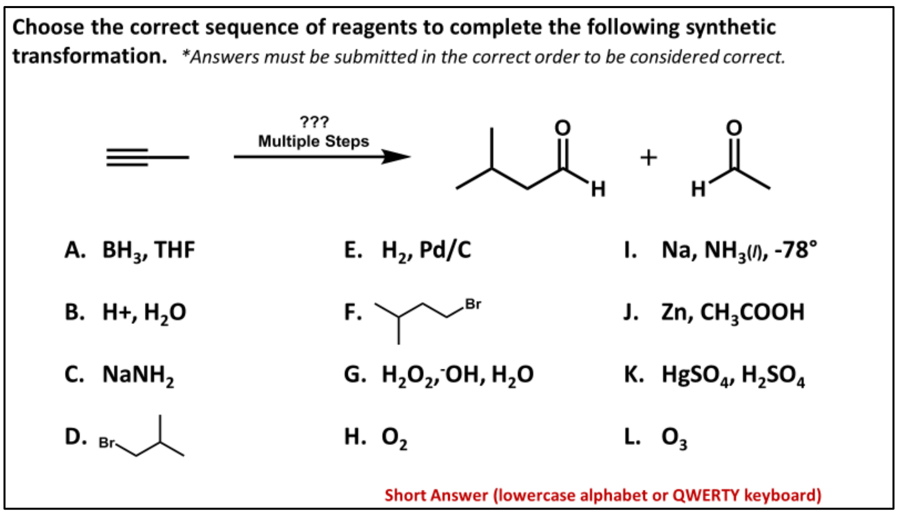


Figure 10. String-of-characters clicker question exploring synthesis design

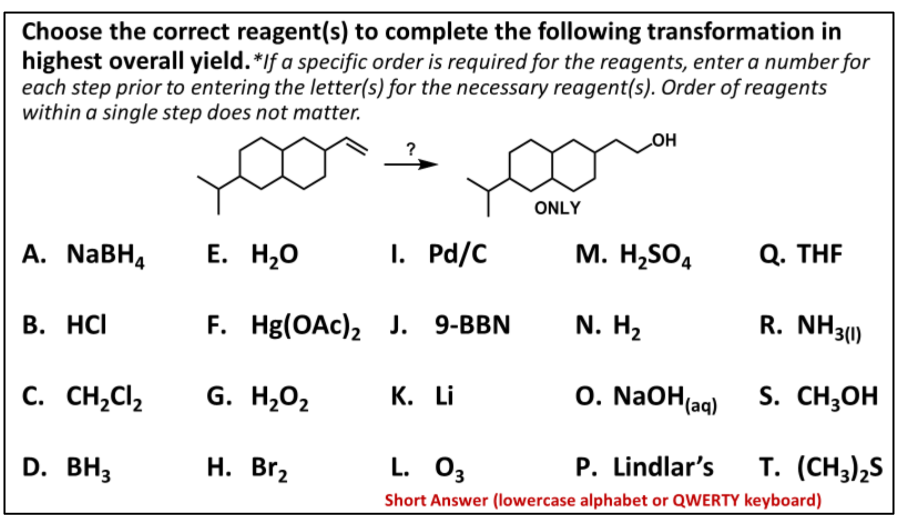


Figure 11. String-of-characters clicker question exploring alkene hydration

The design of the preceding questions plays a significant role in the successful exploration of student comprehension of line reactions and synthetic transformations in first semester organic chemistry. The provided palette of reagents promotes a degree of uniformity to student answer submissions, leading to response statistics that provide the desired real-time insight into student understanding. A significant amount of time would be required to sort through the various correct answer submissions for a short answer question without a palette, which would defeat the "prompt assessment" aspect of using clickers in the first place. Additionally, careful planning of the palette allows instructors to limit students to choosing one specific set of reagents or synthetic pathway among several options. This strategy requires students to consider alternative reagents and pathways than the ones with which they may be most familiar. For instance, the synthesis explored in Figure 10 requires alkyne reduction to the alkene as one step of the synthesis. While either dissolving metal reduction or reduction with hydrogen gas and Lindlar's catalyst would be acceptable for use, only the dissolving metal reaction is provided for use in developing this synthesis. Students who skip this step or attempt to include the palladium-catalyzed reduction are indicating an unfamiliarity with the dissolving metal reduction or an exclusive a reliance on the Lindlar reduction.

Furthermore, this strategy highlights student recognition of varying utility for similar reactions. The line reaction probed in Figure 11 involves hydration of an alkene to produce a single alcohol product. Because students are taught three different alkene hydration strategies (acid-catalyzed hydration, oxymercuration-reduction, and hydroboration-oxidation) and the necessary reagents for each are provided in the palette, responses will indicate which students recognized the reaction as a hydration as well as which students were able to analyze further to determine which hydration strategy was most appropriate. Further analysis can reveal the number of students who recognize the enhanced regioselective bias afforded by use of 9-BBN over BH_3 for this anti-Markovnikov product formation. The deliberate construction of both the question prompt and the reagents available for use in the palette give rise to many more considerations in student understanding than are afforded by classic true-false or multiple-choice questions.

Nomenclature skills are also poorly investigated by standard multiple-choice questions. It is known that students are more capable of accurately translating a name to a structure than a structure to a name. By probing nomenclature understanding with multiple choice name options, instructors are really just assessing students' abilities to match features in the structure to those described by the name.[26] Whether the employed CRS technology has a limited character allowance for answer submissions or not, short answer is the most effective format for analyzing student mastery of systematic nomenclature (Figures 12 and 13).

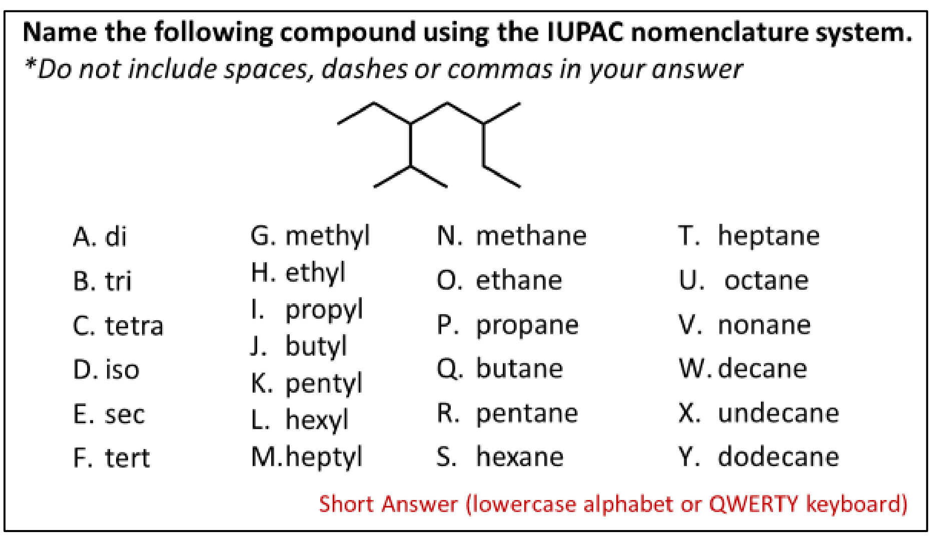


Figure 12. String-of-characters clicker question exploring alkane nomenclature for first semester organic chemistry (limited character allowance for answer submissions)

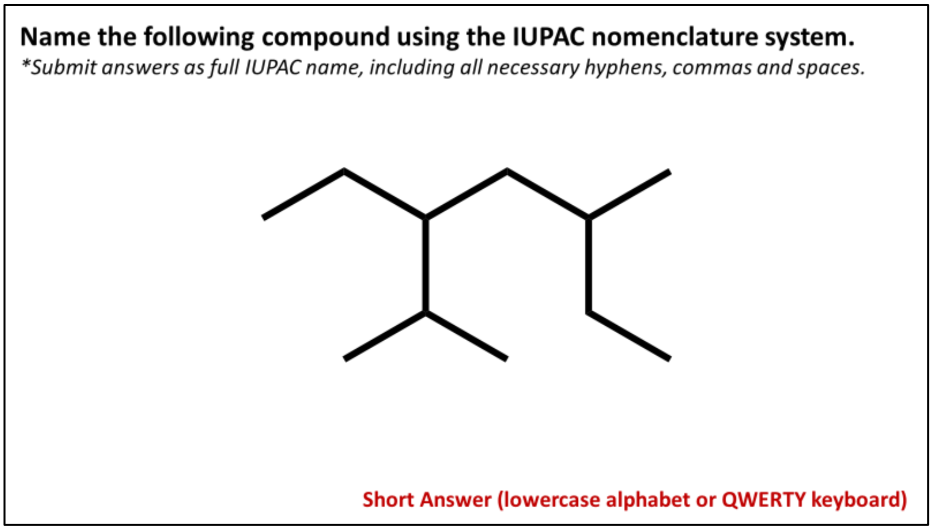


Figure 13. Short answer clicker question exploring alkane nomenclature for first semester organic chemistry (extended character allowance for answer submissions)

Although these formats for nomenclature questions are indeed the most informative in terms of student comprehension and problem-solving, answer generation and submission for these types of questions can be time-intensive compared to those for other formats. If more prompt assessment of student nomenclature skills is desired, adapting questions to the multiple-choice format can still be indicative of student comprehension *if* answer options are informed by student responses observed from other, more probing assessments.[25]

Another useful application for string-of-character questions is in the simultaneous exploration of independent, but related concepts to assess complete understanding versus partial understanding (Figure 14).

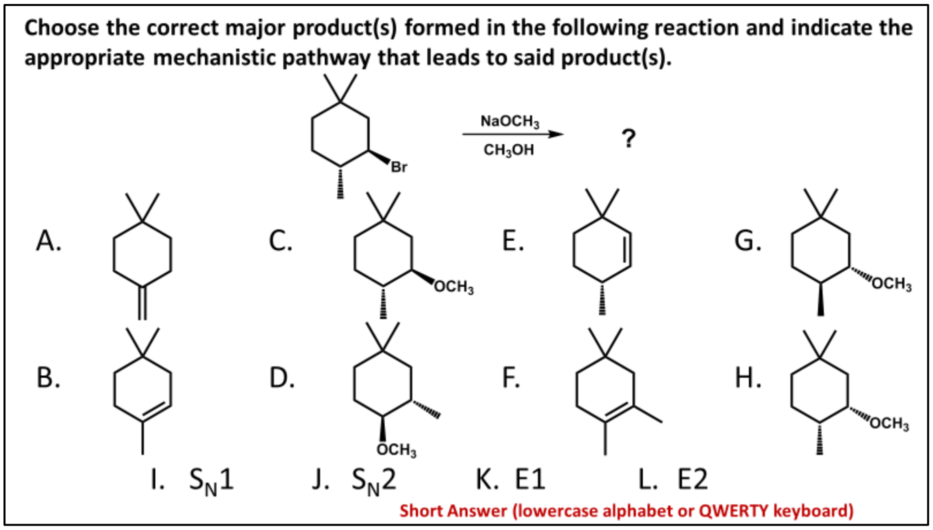


Figure 14. String-of-character clicker question exploring substitution/elimination reactions for first semester organic chemistry

Because the mechanistic pathway most promoted by the given conditions dictates which product will form in greatest abundance, the two considerations are certainly linked. Students who are unable to identify both correct answers in unison are indicating a fundamental lack of complete understanding or are relying on guessing strategies to solve one or both problems.

There is another noteworthy consideration in favor of these short answer string-of-character questions: their ability to identify, at least in part, the number of students that are submitting answers without applying any genuine efforts to determine the correct answer. In these large lecture courses, there is always a certain percentage of students who submit answers solely for the purpose of receiving the small portion of credit associated with participation.[26,28] These submissions do not contribute to interpretation of student comprehension and when associated with standard multiple-choice questions, they often serve to skew representative statistics.[26,28] In implementing string-of-character type questions, answer submissions that have no relation to the palette or question prompt can be removed from statistical analyses, thereby minimizing the percentage of results that must be attributed to guessing.

Summary

In pursuit of determining exactly what organic chemistry students know and what they do not, the researcher determined the need for more creative and targeted question prompts than were previously available for organic chemistry assessment. These efforts were applied to the design of clicker questions in anticipation of formative development of instruction. For instruction to be truly formative, presentations of material must address student needs; and to clearly identify student needs, assessment tools must be designed to elucidate clear and specific conclusions about student comprehension. While this type of information is best afforded by analyses of students' answers to free response questions, this is impractical in most higher learning settings, but especially so for high-enrollment courses. Therefore, it is imperative to design assessment items to more effectively simulate student approaches to free response questions. This can be accomplished through advantageous use of CRS technology software, establishment of clear objectives for question implementation, and careful consideration of question design.

CHAPTER 3

FORMATIVE ASSESSMENT: USING RESPONSE DATA TO ELUCIDATE AND IMPROVE STUDENT COMPREHENSION

The implementation of the more complex and targeted clicker questions described in the preceding chapter offered several immediate benefits with potential for improving instruction and student success. First, the frequent implementation of these complex and multi-faceted questions aided in clearly conveying course rigor and instructor expectations for pacing. In this same vein, clicker questions served to bridge the gap between introductory level questions found in the textbook and more complex exam-level questions that probe multiple concepts simultaneously. Clicker questions were also helpful in supporting presentation of material that is not covered in the textbook and in reinforcing corrections made to errors in the textbook. In this way, clicker questions were utilized to guide instructional pacing, encourage student pacing and promote consistency in material presentation.

The most impactful benefit of using clickers in the high-enrollment organic chemistry courses was the immediate feedback afforded regarding student comprehension. Correct response statistics indicated class understanding overall and prompt review of popular incorrect answers guided subsequent instruction to immediately address mass misconceptions and struggles. The following work explores specific implementations of these advanced clicker questions and their formative influence on instruction in the given semester. Comprehensive conclusions afforded by use of the described clicker questions and associated long-term instructional impacts are discussed in a subsequent chapter.

Clickers for Pacing and Promoting Self-Assessment

Homework assignments are not collected in organic chemistry courses at the University of Georgia because prompt grading of these hand-written assignments is nearly impossible for such high-enrollment courses, and more importantly, because instructors hope to encourage the development of the self-regulated learning skills necessary for success in subsequent coursework. Students in organic chemistry are typically in their second year of their undergraduate work and as such, are still honing their study and time-management skills.[55,56] Studies also indicate that students at this level often lack the emotional maturity to accept responsibility for their own success and must work to develop this understanding in the early years of their undergraduate career.[55-57] These deficiencies in student maturity and learning skills can present significant challenges to the successful instruction of an already difficult discipline.[56-58] As such, instructors employ strategies that promote learning while simultaneously encouraging students to take personal responsibility for their academic development. To assist in these transformative efforts, clickers are often implemented to indicate where students should be in terms of practicing and understanding concepts and to encourage students to take ownership of their progress in the course.

Numerous educational studies and years of instructional experience indicate that the efficacy of instruction is remarkably diminished when students come to class without any exposure to the material being presented.[59] In these situations, students cannot or do not communicate with the instructor because they are behind in their practice of already presented material and because they lack familiarity with the new material. In turn, the instructor does not receive any feedback regarding student comprehension and must unknowingly decide how to use class time most profitably.[60] To encourage student pacing, or demonstrate their lack of pacing when it is recognized by instructors, clicker questions addressing material that has already been covered in lecture are implemented and results are discussed with the class. When accuracy rates for these questions are unusually low, the solution to the problem is not explored during lecture time. In this way, students are encouraged to explore the solution to the problem outside of class. Oftentimes, the same question or a comparable one is implemented during the following class period to monitor student progress.

Examples and related statistics for these instances of assessment to encourage pacing and personal responsibility are not included in the present work. However, this acknowledgment is important for the development of these assessment tools and efforts to improve them.

General Chemistry Background of Incoming Students

University of Georgia organic chemistry instructors have carefully planned coverage of material to adequately prepare students for standardized exams, graduate entry exams and future efforts in research and analysis. The demands of this coverage necessitate that instructional time focus mostly on the introduction and development of organic chemistry concepts and reactions. However, the study and understanding of organic chemistry is inherently grounded in the understanding of certain fundamental general chemistry concepts. Without knowing the background of incoming organic chemistry students, instructors cannot be certain that students have the understanding of general chemistry concepts necessary to support learning in organic chemistry. To assess overall class understanding, clicker questions addressing key general chemistry concepts are implemented in the first days of the semester. Results from these probes reveal to students the concepts that they must review and indicate to instructors the concepts that must be specifically addressed in lecture.

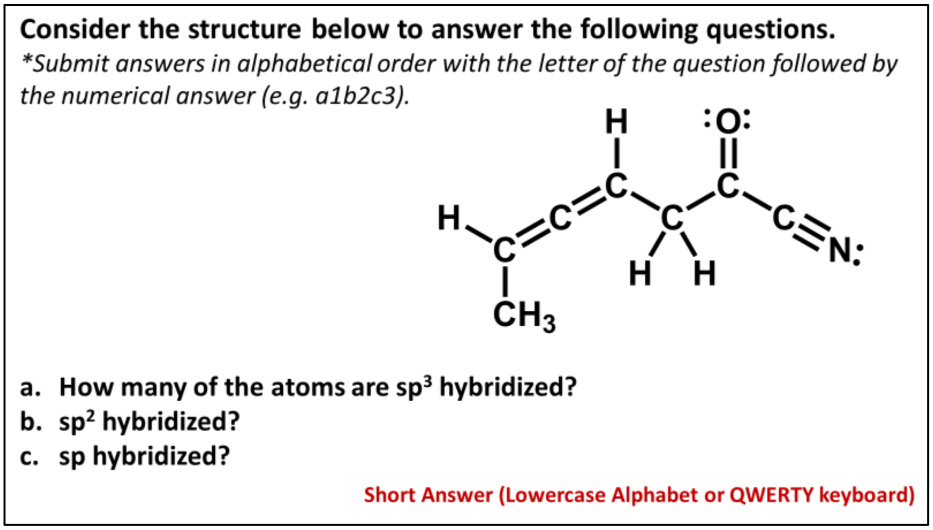


Figure 15. Clicker question exploring atom hybridization for first semester organic chemistry

Because hybridization is a concept learned rather early on in general chemistry, organic chemistry instructors expect students to possess an introductory mastery of this concept. Therefore, the question presented in Figure 15 asks students to assess hybridization patterns for several atoms across a given species.

Table 1. Top student responses to hybridization clicker question—Fall 2013

TOTAL RESPONDENTS: 157 of 299 active participants (343 enrolled students)	
Answer Submission	**Student Percentage**
a1b3c2	13.38%
a2b3c2	8.28%
a6b1c1	8.28%
a1b3c8	6.37%
a2b4c3 **correct**	0.00%

Students enrolled in first semester organic chemistry in fall 2013 struggled immensely in their efforts to accurately identify the hybridization patterns of multiple atoms in the given structure. There were no apparent commonalities between the most popular answer and the correct answer, indicating that there was no particular hybridization pattern that gave students more difficulty than another. Further analysis of popular responses indicated that students were not even able to conclude the correct number of atoms that were hybridized in the given structure, or perhaps that they considered some of the atoms to have a hybridization pattern beyond that of the given options. Though the original intention of these clicker questions was to provide students feedback to guide their personal general chemistry review, these dramatic results prompted the instructor to take class time to review the concept of hybridization. Several weeks following this discussion, in a review session for the first exam, student comprehension of hybridization patterns was probed again using a different question.

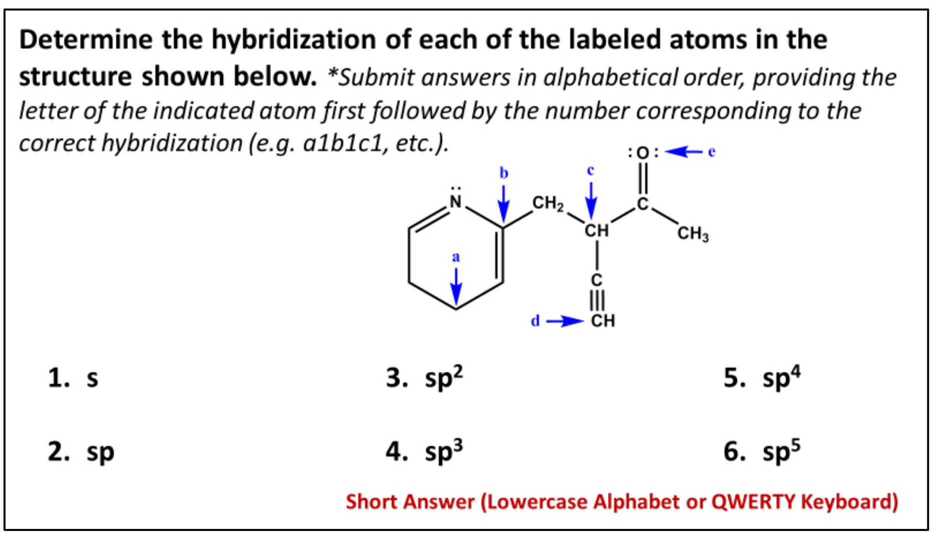


Figure 16. Follow-up clicker question exploring hybridization for first semester organic chemistry

Table 2. Top student responses to follow-up hybridization clicker question—Fall 2013

TOTAL RESPONDENTS: 307 of 322 active participants (353 enrolled students)	
Answer Submission	**Student Percentage**
a4b3c4d2e3 **correct**	66.1%
a4b3c4d1e3	1.95%

Students showed significant improvements in identifying atom hybridization following an instructor led discussion on the topic. Because these results were observed from the initial implementation of these advanced clicker questions, this example was significant in supporting the continued implementation of targeted clicker questions and formative instruction in University of Georgia organic chemistry courses. However, this example was also unique in that instructors recognized a complete lack of understanding for a given concept and therefore administered a thorough review. More often, formative analysis of these clicker results affords insight into the specific aspects of a topic that must be addressed, instead of prompting review of the topic as a whole. For instance, in implementing the question on Lewis structures given in Figure 17, instructors were able to ascertain the percentage of students who understood Lewis structures but also determine common struggles in problem-solving by analyzing popular incorrect response statistics.

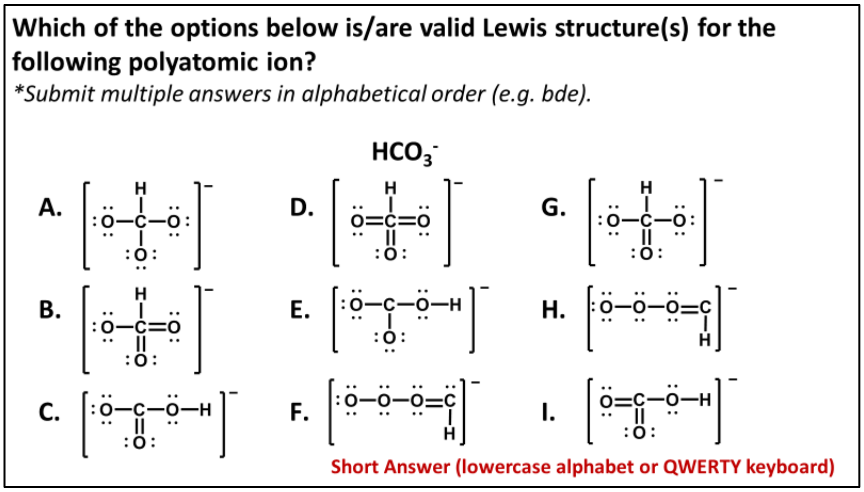


Figure 17. Clicker question exploring the generation of Lewis structures for first semester organic chemistry

Table 3. Top student responses to generation of Lewis structures clicker question—Fall 2017

TOTAL RESPONDENTS: 252 of 264 active participants (277 enrolled students)	
Answer Submission	**Student Percentage**
C *correct*	36.9%
AC	11.5%
A	8.73%
CE *correct*	5.56%
B	3.97%

Upon analysis of these results, the instructor recognized that a plurality of students were able to determine the most reasonable Lewis structure for the bicarbonate ion (C). Based on question phrasing, credit was also awarded for students who chose both the most reasonable Lewis structure representation (C) and the higher energy representation with more individual formal charges (E). Because the majority of the class was not able to determine the correct answer to this question, a brief discussion was warranted. Based upon the incorrect answers most popularly chosen, it was clear that while most students were able to determine the appropriate central atom, many had faltered in recognizing the correct number of valence electrons that were distributed in the bicarbonate ion. A prompt discussion of electron complements, formal charge calculation and charge minimization ensued.

A similar trend in incorrect response selection was observed when the same question was implemented with the fall 2018 first semester organic chemistry students (Table 4), prompting a similar discussion.

Table 4. Top student responses to generation of Lewis structures clicker question—Fall 2018

TOTAL RESPONDENTS: 231 of 239 active participants (239 enrolled students)	
Answer Submission	**Student Percentage**
C *correct*	29.44%
A	15.58%
AC	12.12%
CE *correct*	0.83%

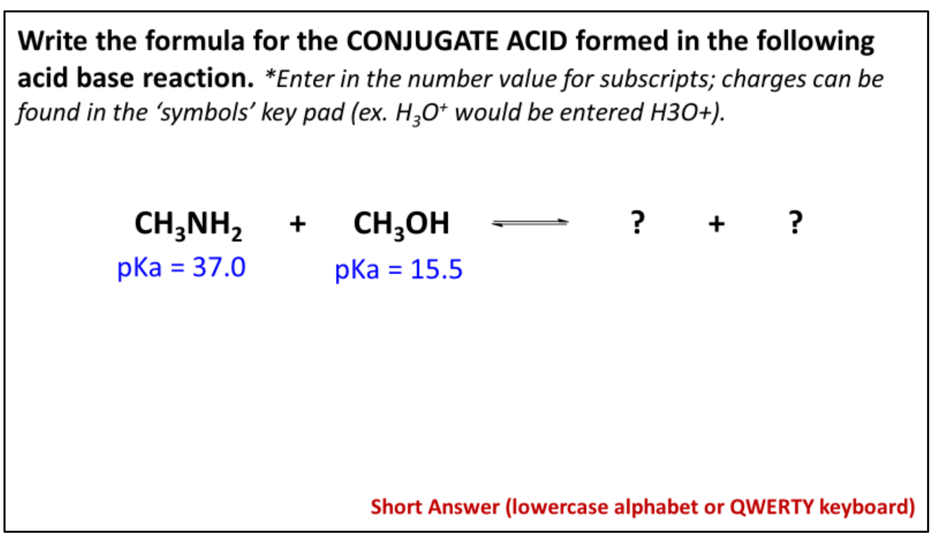


Figure 18. Clicker question exploring acid-base reaction completion for first semester organic chemistry

For the reaction completion problem given in Figure 18, students were asked to provide the conjugate acid product species formed from the acid-base reaction of methylamine and methanol. Following implementation of this question with the incoming first semester organic class in fall 2016, it was observed that almost half of all respondents were able to successfully deduce the protonated amine conjugate acid.

Table 5. Top student responses to acid-base reaction completion clicker question—Fall 2016

TOTAL RESPONDENTS: 230 of 259 active participants (278 enrolled students)	
Answer Submission	**Student Percentage**
CH3NH3+ *correct*	47.4%
CH3NH3	25.2%
CH3O-	12.12%

Because a fourth of students were able to correctly determine the formula for the conjugate acid, but failed to acknowledge the resultant formal charge, an explanation regarding electron complements was necessary. This discussion validated a brief introduction into electron movements and the curved arrow formalism to highlight the nitrogen's "loss of ownership" over one of two electrons used to form the new bond.

Structure and Relationships

One of the more challenging aspects of organic chemistry involves the various structural representations that are used to highlight different features of a given molecule.[49] Students are expected to be able to readily translate between Lewis structures, Kekulé structures, condensed structures and skeletal structures rather early in the curriculum. These translation skills help students to consider atom connectivity and bonding patterns when learning other necessary structural representations like Newman projections and Fischer projections. The examples below explore structural features related to asymmetry, spatial orientation and electron delocalization.

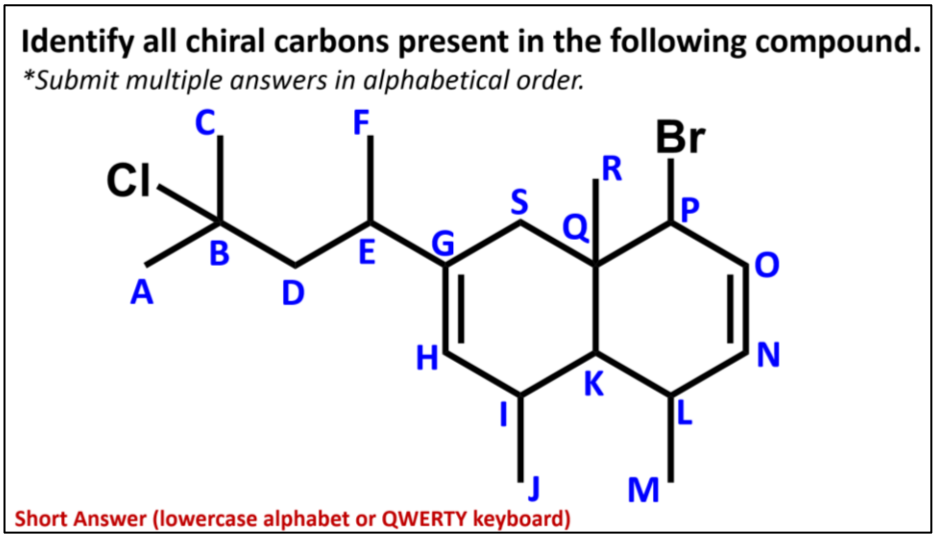


Figure 19. Clicker question exploring chiral carbon identification for first semester organic chemistry

Table 6. Top student responses to chiral carbons clicker question—Fall 2016

TOTAL RESPONDENTS: 221 of 232 active participants (258 enrolled students)	
Answer Submission	**Student Percentage**
EIKLPQ *correct*	59.3%
EILPQ	14.5%
EGIKLPQ	2.26%
EGILPQ	2.26%

The example provided in Figure 19 asks students to consider asymmetry for several carbon atoms with varying hybridizations and bonding patterns. This analysis tests their precision in methodically analyzing the atoms or groups bonded to each carbon atom. While the majority of students in the fall 2016 course were able to correctly identify all chiral centers, the formative value lies in the analysis of popular incorrect answers. A large group of students (14.5%) are shown to have recognized all appropriate centers as chiral *except* for the center labelled (K). Because this group of students were able to identify carbon (Q) as chiral, but not carbon (K), this indicates that the issue was not related to the fact that these are bridgehead carbons. Instead, these results show that students struggled to identify carbon (K) as chiral because of the extended series of bonds that must be iteratively considered to locate a point of difference in substituent groups related back to carbon (K). In recognizing this, instructors utitlized class time to specifically remind students that the entire molecule must be considered in determining chirality, not just the groups directly adjacent to the carbon being considered.

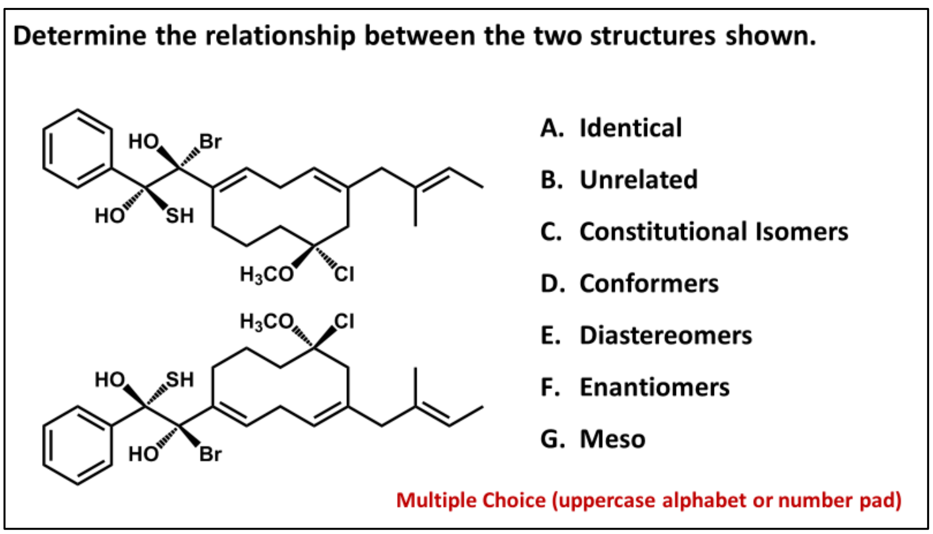


Figure 20. Clicker question exploring structural relationships for first semester organic chemistry

For the exploration of structural relationships given in Figure 20, the majority of students converged on an incorrect answer, as shown in Table 7.

Table 7. Top student responses to structural relationships clicker question—Fall 2017

TOTAL RESPONDENTS: 197 of 207 active participants (230 enrolled students)	
Answer Submission	**Student Percentage**
F. Enantiomers	52.8%
A. Identical **correct**	30.0%
E. Diastereomers	12.69%

By selecting F (enantiomers) as the relationship between the two structures, students are indicating that they recognized the presence of chiral centers in both molecules and the maintenance of atom connectivity between the two structures. This selection also indicates that these students recognized either the reflection across the horizontal plane *or* the exchange of groups at each chiral center, but not both. The same is true for the group of students who incorrectly chose E (diastereomers). Students who chose E (diastereomers) also recognized the presence of chiral centers in both molecules and the maintenance of atom connectivity, but it is more difficult to ascertain what led them to assume different configurations at some but not all chiral centers. However, instructors determined that addressing the need to recognize both the reflection across the horizontal plane and the exchange of groups at each asymmetric center would mitigate confusion for both incorrect response groups. Formative instruction based on analyses of incorrect answer responses is especially effective when the majority of the class is encompassed in top response statistics. In these cases, instructors can be confident in determining the specific reason why these students were unable to identify the correct answer, or can confirm this via open communication with the students themselves. Instructors can also be confident that they are addressing the most commonly held misconceptions and not just those of a small subset of students.

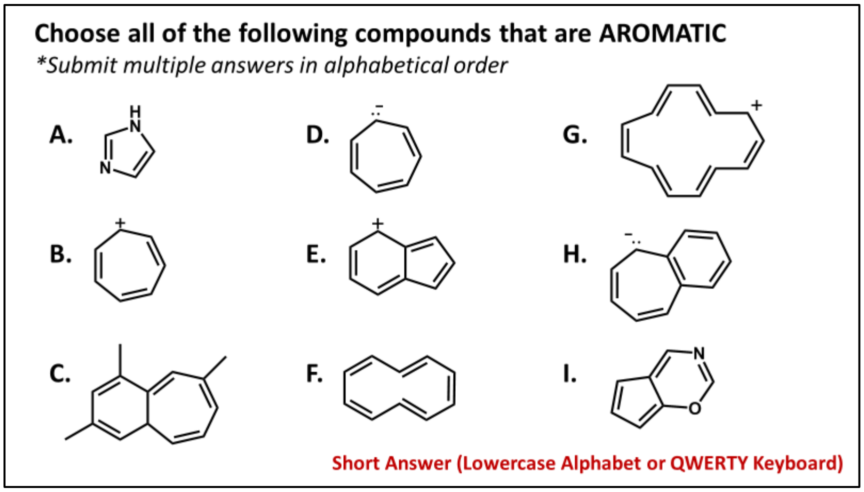


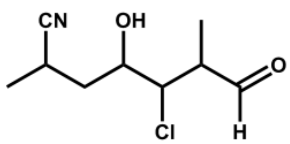
Figure 21. Clicker question exploring aromatic compounds for first semester organic chemistry

Table 8. Top student responses to aromatic compounds clicker question—Fall 2015

TOTAL RESPONDENTS: 206 of 234 active participants (272 enrolled students)	
Answer Submission	**Student Percentage**
ABI	26.2%
BI	9.22%
ABFI **correct**	8.74%
ABCFI	4.85%

For the question given by Figure 21, exploring the identification of aromatic compounds, students in general struggled to correctly identify all aromatic species from the given options. Quick observation indicates that for the larger groups of responders that chose incorrect answers, they were all in agreement that both (B) and (I) were aromatic. Given these results, it was clear that instructors needed to focus particular attention on structure (A) and even more so on structure (F). It was difficult to immediately determine what specific aspects of structure (A) presented challenges for students, so a brief discussion and application of the criteria for aromaticity ensued, using (A) as the example structure. For structure (F), discussions with students from previous semesters indicated that they often misinterpreted the rule for aromaticity determination with cycles made up of eight or more atoms. Because antiaromaticity is destabilizing, species that can avoid this high energy state will disrupt conjugation by bending out of plane. Cycles consisting of eight or more atoms indeed have the flexibility to bend out of plane to avoid antiaromaticity, but will certainly not avoid aromaticity, which is a stabilizing factor. Students mistakenly assumed that cyclic species with this described flexibility are never planar. Knowing this, instructors clarified the rule with students, reminding them that aromaticity is markedly stabilizing and that species that planar species that meet the criteria will exhibit aromatic stabilization.

Choose the correct systematic name for the compound shown below:



Multiple Choice
(Uppercase Alphabet or Number Pad)

A. 5-chloro-4-hydroxy-6-methyl-7-oxo-2-heptanenitrile
B. 5-chloro-4-hydroxy-6-methyl-7-oxo-2-carbonitrile
C. 3-chloro-6-cyano-4-hydroxy-2-methylheptanal
D. 5-chloro-4-hydroxy-2,6-dimethyl-7-oxoheptanenitrile
E. 3-chloro-6-carbonitrile-4-hydroxy-2-methylheptanal
F. 5-chloro-4-hydroxy-2,6-dimethyl-7-oxohexanecarbonitrile

Figure 22. Clicker question exploring nitrile nomenclature for second semester organic chemistry

Table 9. Top student responses to nitrile nomenclature clicker question—Spring 2017

TOTAL RESPONDENTS: 222 of 230 active participants (230 enrolled students)	
Answer Submission	**Student Percentage**
A. 5-chloro-4-hydroxy-6-methyl-7-oxo-2-heptanenitrile	34.7%
D. 5-chloro-4-hydroxy-2,6-dimethyl-7-oxoheptanenitrile **correct**	24.8%
C. 3-chloro-6-cyano-4-hydroxy-2-methylheptanal	24.3%
B. 5-chloro-4-hydroxy-6-methyl-7-oxo-2-carbonitrile	9.01%

Although nomenclature clicker problems are typically designed as free response items for more effective probing of student comprehension, they are occasionally adapted as standard multiple-choice questions for faster implementation. When this is done, multiple-choice answer options are specifically informed by observations made from student free response assessments (clickers, homework problems, and exams). Such is the case for the nomenclature example given in Figure 22.

The high percentage of students who chose incorrect answers reflect common mistakes that students make when attempting to name nitrile species. Because of the informed construction of each of these response items, instructors were already aware of the important considerations to discuss given response results. For response (A), the nitrile is seemingly given priority (parent chain name) but the carbon of the nitrile is not actually incorporated into the parent chain. Students who chose response (A) were reminded of the first rule for nomenclature: *identify the longest continuous carbon chain that includes all carbons of highest priority groups*. Students who chose response (C) simply did not properly recall priority rankings and were reminded of the priority chart for nomenclature provided for them. Informed construction of the answer options for multiple-choice nomenclature problems allows for more rapid, but still effective, probing of student understanding and problem-solving.

Reactions and Reagents

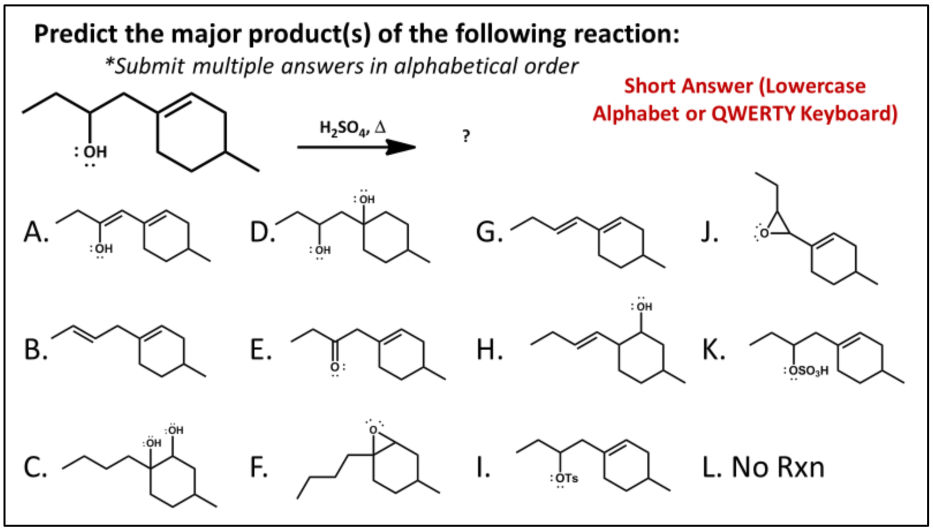


Figure 23. Clicker question exploring acid-catalyzed dehydration of alcohols for second semester organic chemistry

Table 10. Top student responses to alcohol dehydration clicker question—Spring 2017

TOTAL RESPONDENTS: 223 of 231 active participants (231 enrolled students)	
Answer Submission	**Student Percentage**
BG	52.0%
G *correct*	37.7%
B	1.35%

Because response statistics for the dehydration question explored in Figure 23 encompass the majority of students, formative analysis for this question was especially successful in identifying students' missteps in comprehension. The majority of students were successful in identifying the reaction as a dehydration to form an alkene. However, the vast majority indicated the two expected products of the dehydration to be essentially equal in stability, likely based on the fact that they have comparable substitution about the formed double bond. However, upon closer inspection, it is observed that double bonds formed in conjugation with existing double bonds have increased stability due to electron delocalization. Hence, it is expected that product (G) will form as the major product and product (B) as a minor product. Students were reminded of this important consideration as well as the equilibrium parameters that govern reactions under thermodynamic control.

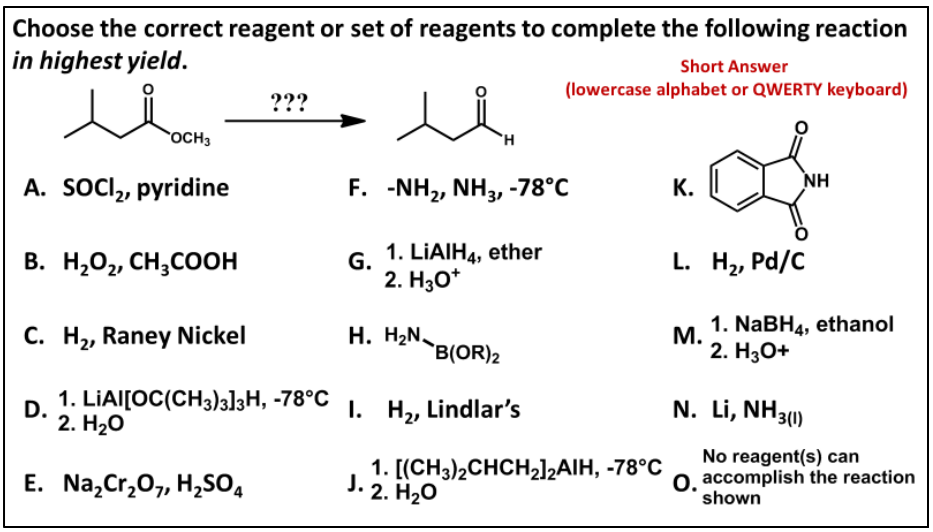


Figure 24. Clicker question exploring reduction of esters for second semester organic chemistry

Table 11. Top student responses to ester reduction clicker question—Spring 2017

TOTAL RESPONDENTS: 185 of 212 active participants (212 enrolled students)	
Answer Submission	**Student Percentage**
J *correct*	49.7%
D	22.2%
G	7.57%
C	5.95%

Observation of results from the implementation of the question shown in Figure 24 showed that the majority of second semester organic chemistry students in spring 2017 successfully identified the given functional group interconversion as a reduction. The question was designed to emphasize chemoselective reagents with limited reactivities; lithium diisobutylaluminum hydride, commonly referred to as DIBAL, was the expected correct answer. However, when a large group of students chose the reagent known for use in limited reduction of acyl chlorides to aldehydes, this prompted a unique discussion regarding the difference in utility between the two partially deactivated reducing agents. Although DIBAL is specifically associated with esters in textbooks and other resources and lithium tri-tert-butoxyaluminum hydride is associated only with acyl halides, the more sterically hindered reagent would still successfully accomplish the limited reduction of the ester. By contrast, DIBAL is still too reactive to accomplish the limited reduction of an acyl chloride and therefore the two are not interchangeable. This distinction was emphasized with students and then accuracy credit was awarded for both (D) and (J). The implementation of this question prompted a necessary comparison of the two chemoselective reagents that is not addressed in the text nor readily available via an internet search, and more importantly, a discussion of the determining factors that govern the unique chemoselectivity of these distinct reagents. Discussions like these move students away from sheer reagent recognition and encourage them to apply critical thinking and chemical intuition to draw logical conclusions.

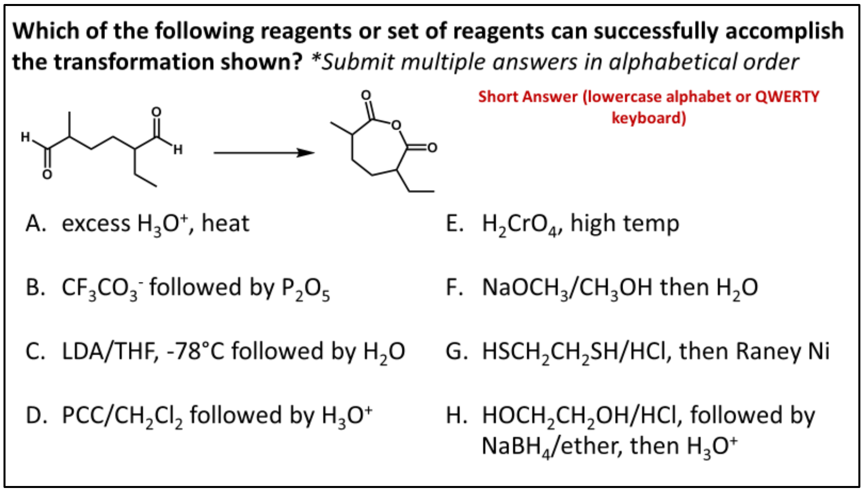


Figure 25. Clicker question exploring anhydride formation for second semester organic chemistry

Table 12. Top student responses to anhydride formation clicker question—Spring 2017

TOTAL RESPONDENTS: 227 of 230 active participants (230 enrolled students)	
Answer Submission	**Student Percentage**
BE **correct**	48.5%
B	15.9%
E	8.37%

The clicker question given in Figure 25 specifically explored student understanding of multiple synthetic strategies for the formation of a single product. In solving this problem, students must apply retrosynthetic analysis to recognize that the cyclic anhydride product is formed via dehydration of a 1,6-dicarboxylic acid. Because the starting material is a 1,6-dialdehyde, it follows that oxidation of this species would form the necessary 1,6-dicarboxylic acid. A large group of students (48.5%) in the spring 2017 second semester organic chemistry course recognized that Baeyer-Villager oxidation of the dialdehyde to form the dicarboxylic acid followed by dehydration with phosphorous pentoxide, or alternatively, chromic acid oxidation of the dialdehyde to the dicarboxylic acid followed by dehydration at high temperatures, could successfully accomplish the given synthetic transformation. In terms of student comprehension, instructors were pleased to see that an additional 24.3% of the class were able to recognize at least one of the two pathways for product formation. To reinforce diagnostic analysis, brief emphasis was placed on the importance of having multiple reagent possibilities for synthetic transformations to accommodate other functionalities that may already exist in the given starting material (i.e. acid sensitive functionalities would be affected by H_2CrO_4 oxidation, but not by basic Baeyer-Villager oxidation).

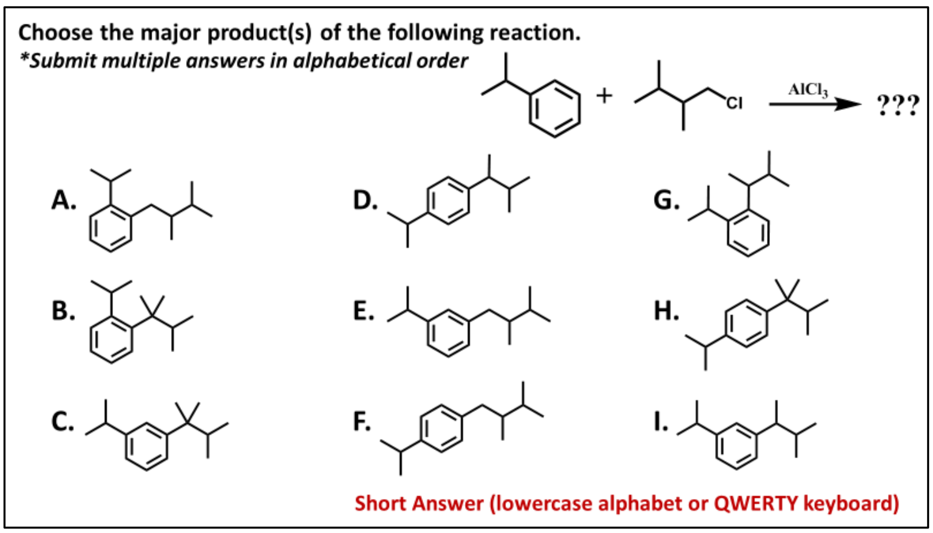


Figure 26. Clicker question exploring Friedel-Crafts alkylation reaction for second semester organic chemistry

Table 13. Top student responses to Friedel-Crafts alkylation clicker question—Spring 2017

TOTAL RESPONDENTS: 194 of 194 active participants (194 enrolled students)	
Answer Submission	**Student Percentage**
AF	36.1%
BH	28.4%
A	5.70%
H *correct*	5.70%

The Friedel-Crafts alkylation reaction given in Figure 26 explores student comprehension of carbocation rearrangements, directing effects, and steric hindrance. Results from implementation of this question in spring 2017 indicated that at least 75.9% of students recognized the isopropyl substituent of the benzene starting material as an electron-donating ortho-para director. However, results also indicated that a large group of students failed to acknowledge the inevitable carbocation rearrangement observed commonly in benzene alkylation reactions. A brief review of electrophile formation and the mechanism of rearrangement resulted. Because steric effects on the ortho-para ratio had not yet been fully explored in lecture, credit was awarded for responses indicating equal formation of (B) and (H) and the opportunity to fully develop this discussion was seized.

<u>Spectroscopy and Structure Elucidation</u>

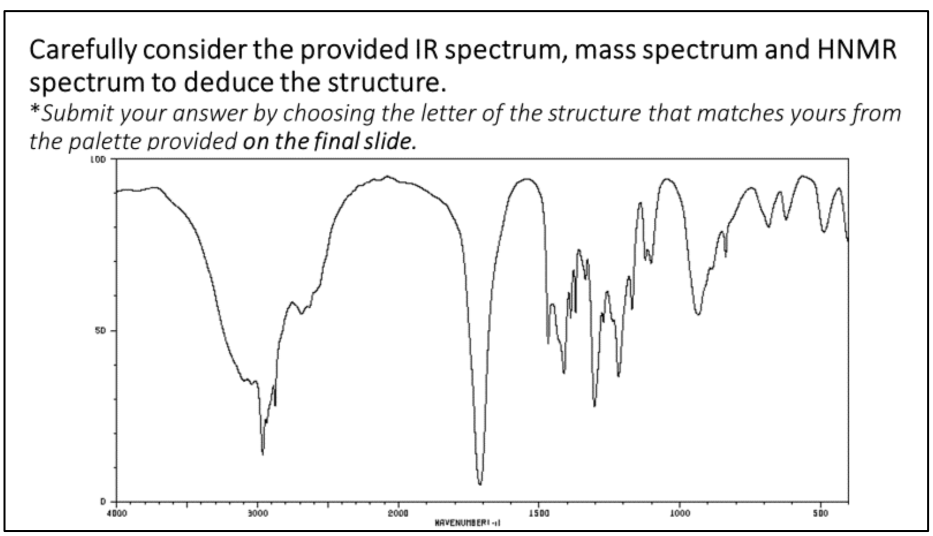


Figure 27. Clicker question exploring integrated spectroscopy—IR spectrum

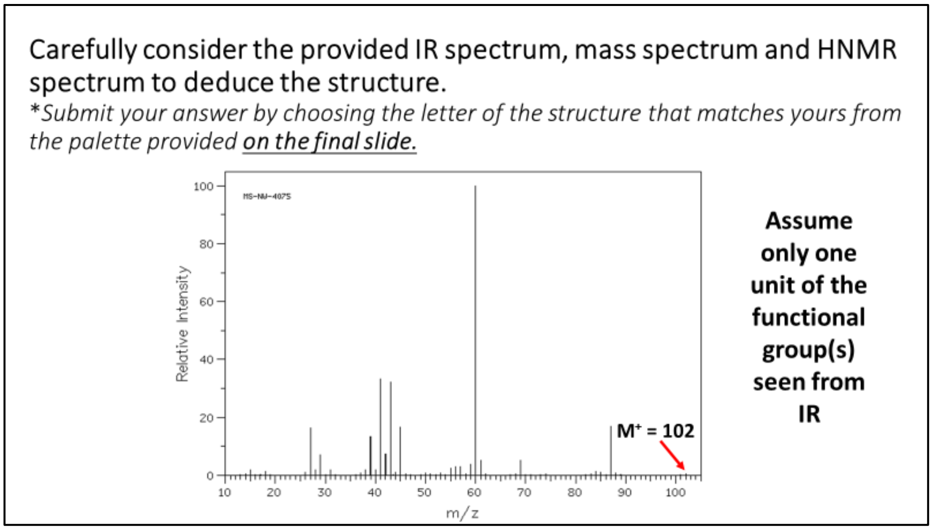


Figure 28. Clicker question exploring integrated spectroscopy—mass spectrum

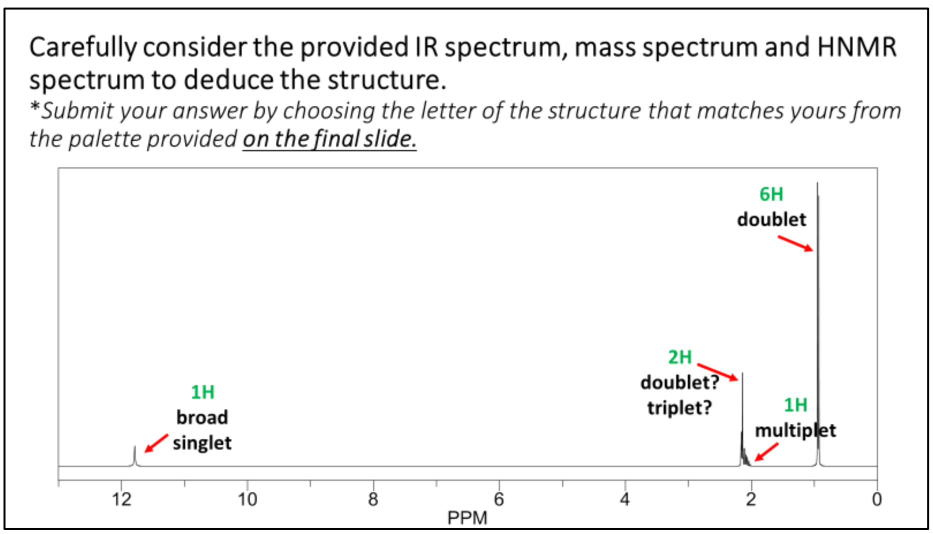


Figure 29. Clicker question exploring integrated spectroscopy—^{1}H NMR spectrum

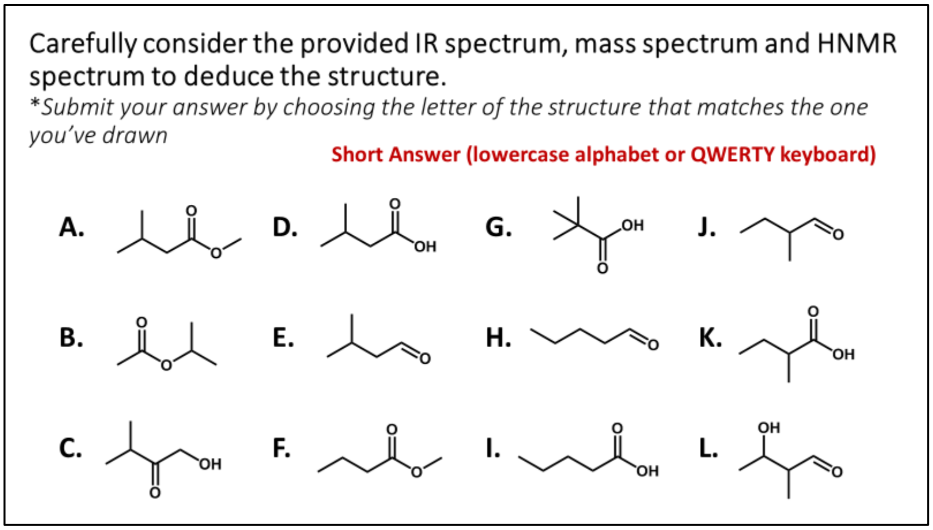


Figure 30. Clicker question exploring integrated spectroscopy—answer palette

Table 14. Top student responses to integrated spectroscopy clicker question—Fall 2016

TOTAL RESPONDENTS: 236 of 237 active participants (266 enrolled students)	
Answer Submission	**Student Percentage**
D *correct*	43.6%
K	19.1%
C	13.6%

Integrated spectroscopy problems, like the one explored in Figures 27-30, are essential in developing and probing students' diagnostic skills in first semester organic chemistry. As evidenced by the series of slides that comprise the overall question, students must gather key points from each individual spectrum and rationalize all of these observations to elucidate an appropriate structure. Popular response statistics revealed that a majority of students were able to establish the unknown structure as a five-carbon carboxylic acid. This information is gleaned from quick observation of the IR and mass spectrums. The representative IR absorptions for carboxylic acids were pointed out and emphasized for the notable group of students who chose structure (C). Subsequent explanative discussion focused on interpreting the provided ^{1}H NMR spectrum. For students who chose the incorrect isomer (K), attention needed to be drawn to the 6H doublet at ~1.0ppm; this signal is a quintessential indicator of an isopropyl group and cannot be rationalized by isomer (K).

Although these integrated spectroscopy problems require relatively more time to administer in class than some of the other types of questions discussed, they are incomparable in their incitement of peer discussion and investigative analyses. Students gain confidence through paced practice while developing diagnostic skills that are essential for their future endeavors; and instructors gain valuable insight into students' abilities to interpret the various types of spectra used for organic structure elucidation.

Synthesis

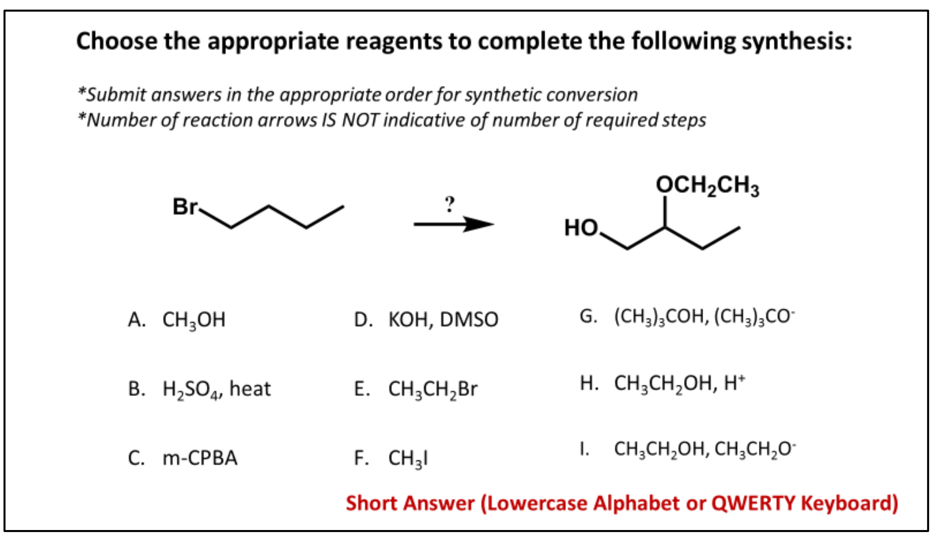


Figure 31. Clicker question exploring synthesis of an alkoxyalcohol for second semester organic chemistry

Table 15. Top student responses to alkoxyalcohol synthesis clicker question—Spring 2015

TOTAL RESPONDENTS: 251 of 285 active participants (318 enrolled students)	
Answer Submission	**Student Percentage**
dch	17.5%
bch	10.0%
dg	10.0%
dbch	8.37%
gch **correct**	0.80%

As is often the case with these string-of-character syntheses questions, the majority of student responses are not encompassed by the popular answer statistics displayed following implementation. In these cases, more insight into student comprehension is gleaned via post-lecture analyses of responses, where answer submissions can be categorized based on partial commonalities instead of complete agreement. However, in noting that 36.7% of students responding to the synthesis question in Figure 31 were correct in identifying the final two steps of the synthesis, instructors turned instructional attention to the first step. Despite recognizing the need to form an epoxide that would then undergo nucleophilic attack under acidic conditions, students struggled to determine the appropriate conditions for elimination to form the necessary alkene. For students who reacted the primary alkyl halide starting material with KOH in DMSO, a review of the competition between substitution and elimination reactions was necessary. Students were reminded that strong nucleophiles promoted S_N2 reactions of primary alkyl halides and that this process was even more favored in a polar, aprotic solvent like DMSO. Students were then prompted to explore the conditions under which primary halides can undergo elimination and were led to the bulky base alkoxide given in option (G). Results from this clicker question suggested students' need for increased practice with multistep synthetic transformations, specifically those involving reactions from first semester organic chemistry.

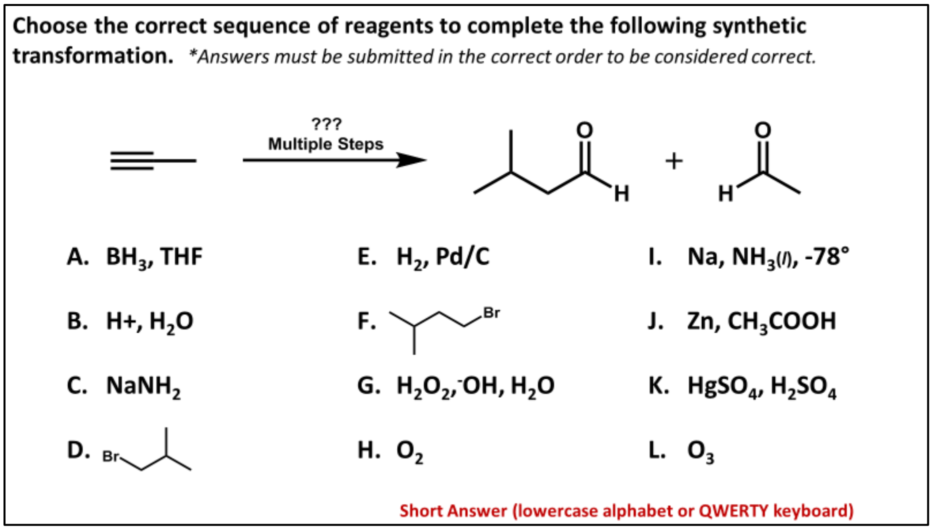


Figure 32. Clicker question exploring synthesis of two carbonyl compounds for first semester organic chemistry

Table 16. Top student responses to carbonyl synthesis clicker question—Fall 2014

TOTAL RESPONDENTS: 193 of 207 active participants (260 enrolled students)	
Answer Submission	**Student Percentage**
cdilj **correct**	29.0%
cdil	24.9%
cdl	7.25%
cdel	6.22%

The synthesis question given in Figure 32 was one of the first opportunities students had outside of the textbook to practice synthetic planning, as they had just recently been exposed to alkyne extension reactions. A significant group of students (29.0%) were able to determine the complete synthetic process necessary for successful transformation of the alkyne starting material to the carbonyl products. In fact, a fairly comparable number of students (24.9%) were able to accurately determine the first four steps of this five-step synthetic transformation. The cause of missing just the last step of the synthesis was easy for instructors to determine because it relates directly to the original intentions of question construction. In the textbook and associated lecture presentations of the ozonolysis process, students are taught two different reductive workup methods: $(CH_3)_2S$ and Zn in CH_3COOH. Being aware of students' natural inclination toward recognizing and using the dimethyl sulfide reduction, the question was constructed with specific intention to highlight the zinc reduction instead. Students who suggested the synthetic pathway (CDIL) were likely unable to recognize the alternative reagents for reduction and, being unable to locate $(CH_3)_2S$ on the palette, stopped their synthesis after introduction of O_3. Similar conclusions were drawn for the students proposing the (CDL) and (CDEL) syntheses, but there were other missteps that also required attention.

The question was also designed to highlight the use of the dissolving metal reduction over H_2 and Lindlar's catalyst for alkyne reduction. Because both the cis and trans alkene isomers give rise to the same carbonyl products upon oxidative cleavage, students could use either sets of reagents in a free-response answer submission. For this question, students were provided with only the dissolving metal reduction reagents. According to student feedback, unfamiliarity with the utility of these reagents may play a role in the submission of the (CDL) and (CDEL) synthetic schemes. Other clicker questions could have been designed and implemented to further probe these hypotheses.

Summary

The use of these strategic and targeted clicker questions for real-time assessment of students increases the formative value of student response analyses, essentially allowing wrong answer submissions to be just as informative, if not more so, than correct answer statistics in the identification of students' concept mastery and problem-solving strategies. Analyses of these common aggregate statistics immediately following class survey informed the course instructor and the researcher of students' unfamiliarity and missteps in problem-solving. This insight immediately suggested specific points of emphases for instruction. The distribution of correct response statistics provide instructors with guidance on how best to address student limitations in understanding. When the majority of the class indicates mastery of a given concept, instructors can be confident in moving forward with the presentation of more complex examples or introduction to new material. When large groups of students struggle with a specific aspect of a problem, instructors can determine whether students need to review on their own time or be led through an appropriate discussion based on a quick assessment of the factors influencing answer submissions. This formative analysis is incredibly valuable in guiding instruction and promoting student-instructor communication.

CHAPTER 4

FORMATIVE INSTRUCTION: MODIFYING LECTURE PRESENTATIONS TO ADDRESS IDENTIFIED LIMITATIONS IN STUDENT COMPREHENSION

The use of these advanced clicker questions in the large-enrollment organic chemistry classes at the University of Georgia allowed for prompt analyses of top response statistics to indicate more precisely what students in that given class knew and what required further clarification. The resultant improvements in class performance observed from the aforementioned formative analysis efforts prompted the researcher to consider general strategies to garner more comprehensive and lasting insight about student comprehension of organic chemistry concepts.

Top response statistics proved useful for immediate interpretation and response, but more precise and comprehensive insight could be gathered from post-lecture analyses of all response statistics. This insight along with semester-to-semester comparison of results from same or similar questions revealed some commonalities in student problem-solving and train of thought that were over-arching and common across semesters. These discoveries were further reinforced by observations made in grading free-response exams or with deliberate implementation of clicker questions to test hypotheses. And, these discoveries provided forethought for the shaping of original presentations of material. That is to say, certain points were emphasized in the initial lecture presentation of the material instead of after they were manifested in assessment results in hopes of precluding student misconceptions and misapplications of trends. Some examples of these discovered trends and the impact of reformed preemptive instruction on student comprehension follow.

Observing and Addressing Trends in Student Comprehension

In fall 2013, when implementation of these advanced clicker questions first began, the question shown in Figure 33 was administered in the high-enrollment first semester organic course. As evidenced by the results provided in Table 17, students struggled to correctly identify the configurations at both chiral centers present in the given structure.

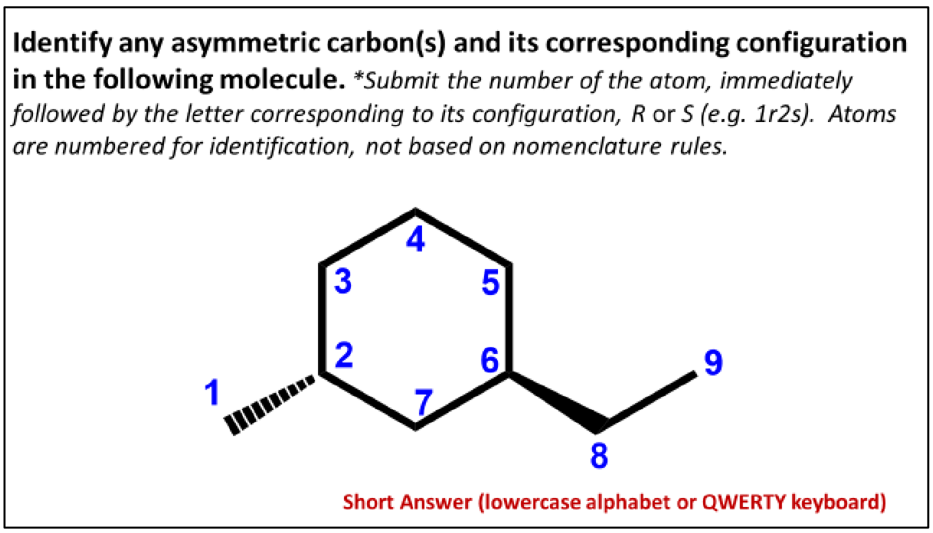


Figure 33. Clicker question exploring chirality in cyclic systems for first semester organic chemistry

Table 17. Top student responses to chirality in cyclic systems clicker question—Fall 2013

TOTAL RESPONDENTS: 277 of 280 active participants (342 enrolled students)	
Answer Submission	**Student Percentage**
2S6R	33.2%
2R6S	29.2%
2R6R **correct**	14.1%
2S6S	5.42%

Continued probing of student comprehension and problem-solving for chiral carbons over the course of the semester revealed that, in general, students struggle more in assigning priorities and confirming correct perspective when assessing chiral centers that are in a ring structure than those in a chain. This suggested that instructors should incorporate more examples of chiral centers in ring structures in the initial presentations for chirality and assigning configurations in future semesters, which was heeded for the initial presentation of this material with the fall 2014 group. Implementation of the same clicker question following the lecture presentation afforded improved results, as shown in Table 18.

Table 18. Top student responses to chirality in cyclic systems clicker question—Fall 2014

TOTAL RESPONDENTS: 202 of 265 active participants (307 enrolled students)	
Answer Submission	**Student Percentage**
2R6R **correct**	38.6%
2R6S	27.2%
2S6R	13.9%
6S	3.47%

This trend demonstrating increased student comprehension of chiral configuration assignment continued in subsequent years (Table 19), even when an alternative, but analogous clicker question was implemented (Figure 34, Table 20).

Table 19. Top student responses to chirality in cyclic systems clicker question—Fall 2016

TOTAL RESPONDENTS: 210 of 232 active participants (258 enrolled students)	
Answer Submission	**Student Percentage**
2R6R **correct**	42.4%
2R6S	28.6%
2S6R	12.4%

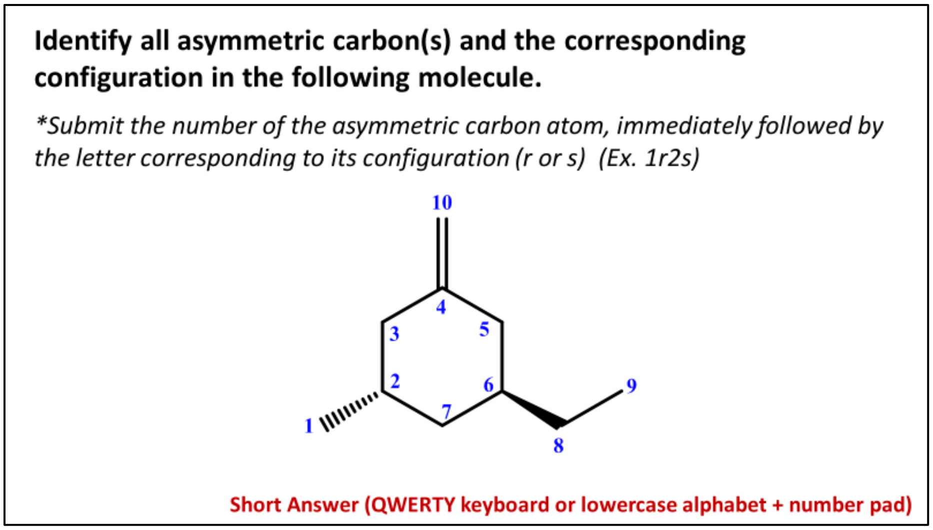


Figure 34. Clicker question exploring chiral configurations in cyclic systems for first semester organic chemistry

Table 20. Top student responses to chirality in cyclic systems clicker question—Fall 2017

TOTAL RESPONDENTS: 167 of 207 active participants (230 enrolled students)	
Answer Submission	**Student Percentage**
2S6S **correct**	54.4%
2S6R	16.8%
2R6S	11.8%
2R6R	3.99%

According to this trend of results, by addressing chiral recognition and prioritization for ring carbons more frequently in the initial presentation of asymmetric centers and configurations, instructors are steadily improving students' abilities to recognize and assign configurations for chiral carbons.

Similarly, student response statistics from multiple-semester implementations of questions regarding transition states indicate an improvement in overall understanding as a direct result of targeted initial instruction. The question given in Figure 35 was first implemented in fall 2015 to assess student understanding of transition state representations. This question was specifically designed as a leading question after noticing a general lack in comprehensive discussions of transition states and their two-dimensional representations in the course textbook.

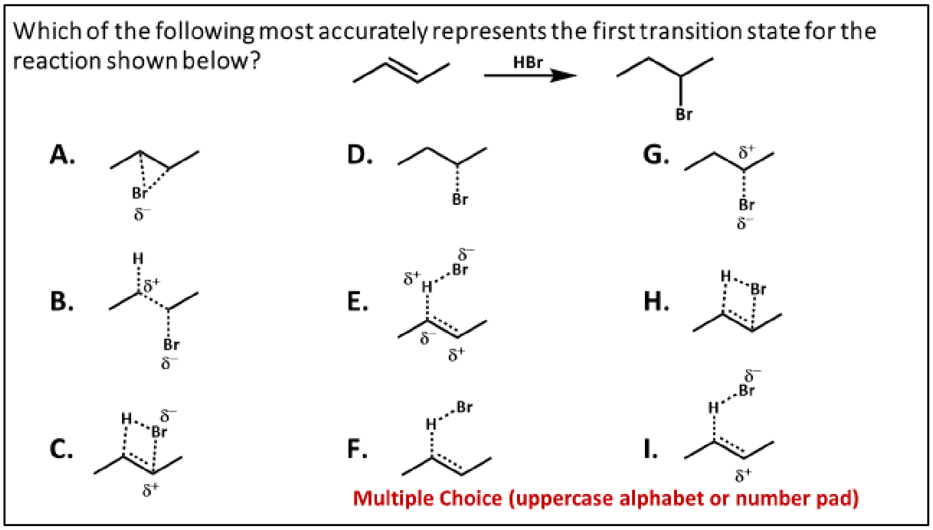


Figure 35. Clicker question exploring transition states for hydrohalogenation of alkenes for first semester organic chemistry

Table 21. Top student responses to transition state clicker question—Fall 2015

TOTAL RESPONDENTS: 219 of 219 active participants (270 enrolled students)	
Answer Submission	**Student Percentage**
A	39.5%
E	25.7%
B	13.8%
G	13.2%
I *correct*	0.00%

From these results, it is clear that students in the fall 2015 class had no conceptual understanding of the transition state representing the high energy first step of hydrohalogenation of alkenes, despite having had prior exposure to the mechanism for the reaction. Recognizing that textbooks typically lack a sufficient discussion of transition states and that understanding the transition state is important for a complete understanding of relative reaction rates, intermediate stabilities and reaction progress, instructors began emphasizing transition states and their significance with initial discussions of reaction profiles. Noticeable improvements in student command over transition state representations were afforded as a result.

Table 22. Top student responses to transition state clicker question—Fall 2017

TOTAL RESPONDENTS: 152 of 204 active participants (204 enrolled students)	
Answer Submission	**Student Percentage**
I *correct*	43.4%
E	21.2%
F	10.7%
G	2.2%

Table 23. Top student responses to transition state clicker question—Fall 2018

TOTAL RESPONDENTS: 191 of 194 active participants (280 enrolled students)	
Answer Submission	**Student Percentage**
I *correct*	67.0%
E	17.8%
C	5.24%
H	3.14%

One final example of the improvements in student comprehension observed as a result of focused initial instruction involves carbohydrate chemistry from second semester organic chemistry. Carbohydrates and their reactions are some of the last topics covered in the organic chemistry curriculum. At that point, students have honed their chemical skills so well that the simple and familiar reactions carbohydrates undergo present little challenge. The one aspect of carbohydrate chemistry that does pose some difficulty for students, however, is disaccharide formation, likely due to the fact that navigating the formation of a given disaccharide requires the convergence of multiple individual points of understanding about carbohydrates: cyclization and appropriate stereochemistry of monosaccharide units; glycosidic bond linkages; and orientation about anomeric carbon. As is the case with other multi-faceted topics in organic chemistry like integrated spectroscopy and synthesis, students improve with increased exposure and practice. Given this, it was suggested that instructors spend time walking through disaccharide formation with students after background information on carbohydrates had been briefly covered. Student comprehension of disaccharide construction was then probed during the fourth exam review session using the question posed in Figure 36.

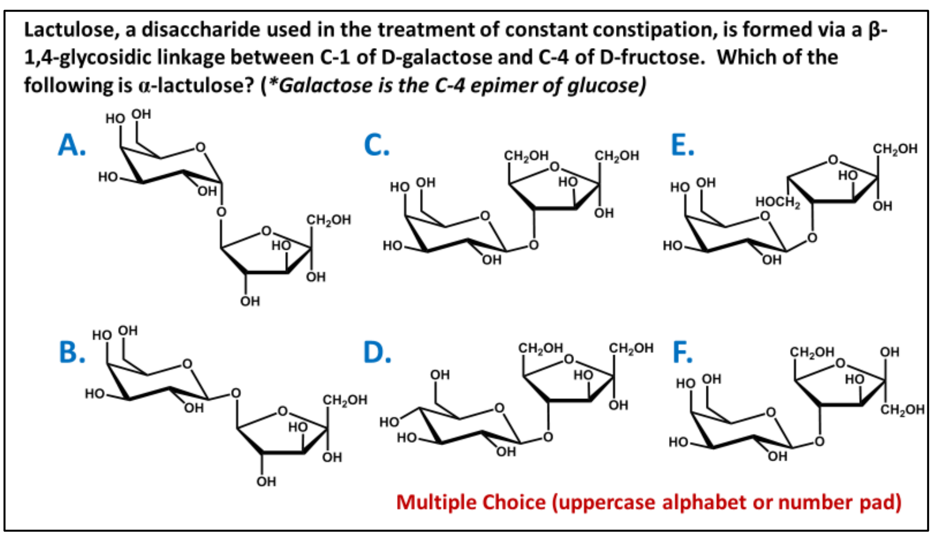


Figure 36. Clicker question exploring disaccharide construction for second semester organic chemistry

This question was first implemented with the second semester organic group in spring of 2015 (Table 24). Increased practice and guided instruction was introduced with the spring 2016 group and continued with the group in spring 2017 (Tables 25 and 26, respectively).

Table 24. Top student responses to disaccharide clicker question—Spring 2015

TOTAL RESPONDENTS: 243 of 246 active participants (282 enrolled students)	
Answer Submission	**Student Percentage**
B	48.2%
C *correct*	20.1%
A	9.05%
D	8.64%

Table 25. Top student responses to disaccharide clicker question—Spring 2016

TOTAL RESPONDENTS: 254 of 259 active participants (288 enrolled students)	
Answer Submission	**Student Percentage**
B	37.4%
C *correct*	31.1%
D	9.84%
A	9.06%

Table 26. Top student responses to disaccharide clicker question—Spring 2017

TOTAL RESPONDENTS: 204 of 210 active participants (210 enrolled students)	
Answer Submission	**Student Percentage**
C *correct*	43.6%
F	18.6%
B	16.2%
A	8.33%

These few presented cases involving preemptive instructional efforts based upon previous student results and observed improvements in student performance are representative examples of the informed modifications that have been made to lecture presentations for organic chemistry at the University of Georgia. Collective observations garnered from years of clicker response data and years of experience in grading and instruction has afforded the researcher unique insight into the specific aspects of each topic in the organic chemistry curriculum that challenge students. These observations were communicated to instructors who modified lecture presentations to address these points of difficulty beginning with introductory discussions of given material. By introducing more complex examples as part of the initial presentation of material, the instructor decreases opportunities for students to misinterpret trends or misapply strategies for problem-solving because they have been engaged in the solution process and have seen the appropriate applications firsthand. Working more complex examples during initial presentations also allows students to generate questions and have them answered immediately rather than when they are working on their own without reliable resources to turn to for clarification.

Teaching Problem-Solving Strategies

While some lapses in student comprehension are addressed by increased exposure to and practice with examples pertaining to the topic, like constructing disaccharides or applying Cahn-Ingold-Prelog rules of prioritization in ring structures, others stem from issues with problem-solving. If students do not know how to begin to approach a problem or if they are unknowingly incorporating flawed logic or incorrect assumptions into their problem-solving strategy, it is unlikely that exposure to more practice problems will improve their understanding. In these situations, students need more practice, but first, they need more thorough and accurate exposure to the problem-solving strategy one must invoke to arrive at the correct answer. For the types of problems that require a series of considerations to arrive at the correct answer, the researcher developed problem-solving guides to accompany post-polling explanations of challenging clicker questions. These slides are designed to guide students through problem-solving by posing and answering a series of necessary questions. As students provide answers to the given questions or draw expected conclusions from prompting information, the answers are made visible on the slides. In this way, students receive verbal *and* visual confirmation of correct responses which minimizes the likelihood of incorrect insertions into notes. The following are examples of topics for which students responded positively to problem-solving guidance and the resultant improvements observed.

Acid-base chemistry is a general chemistry topic with which incoming organic students consistently struggle, but a fundamental understanding of the electron movements and the factors governing these simple reactions can create a substantial foundation upon which to build understanding of more complex organic chemistry phenomena. Observations in instruction and assessment indicate that incoming organic students are often comfortable with trends (electronegativity, pKa and acidity) and memorized lists (strong acids/bases, oxidation states) from general chemistry, but lack the understanding to adequately explain these trends with chemical logic. These conclusions are corroborated by the results of implementing the question shown as Figure 37 in the general chemistry review clicker sessions for incoming students in fall 2016 and fall 2017.

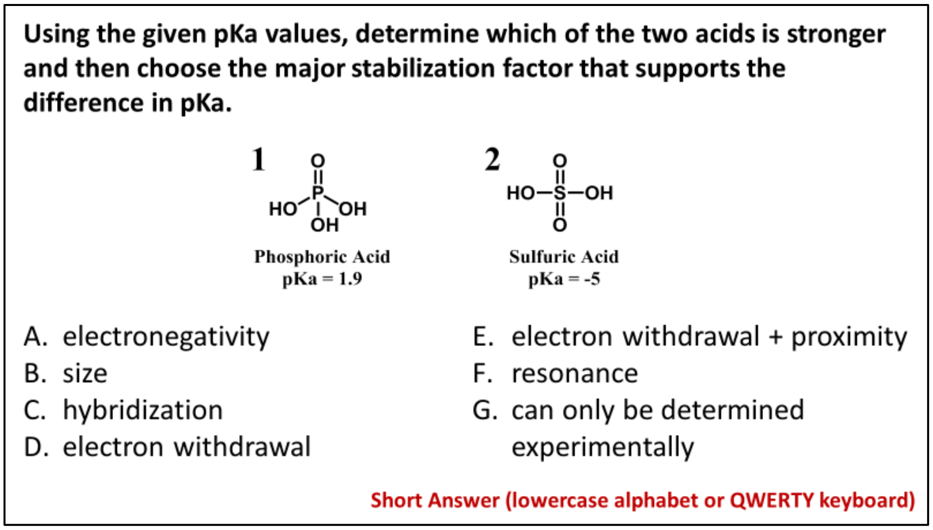


Figure 37. Clicker question exploring relative acidities and supporting stabilization factors

In this two part question, students were asked to first determine which of two species was the stronger acid, based on given pKa values, and to then choose a stabilization factor that most adequately supports the observed difference in acidity. Results from the two semesters are provided below (Tables 27 and 28).

Table 27. Top student responses to relative acidities clicker question—Fall 2016

TOTAL RESPONDENTS: 249 of 257 active participants (284 enrolled students)	
Answer Submission	**Student Percentage**
2A	34.98%
2C	18.47%
2F **correct**	12.45%
2E	8.84%
2D	6.02%
Identified stronger acid	90.8%

Table 28. Top student responses to relative acidities clicker question—Fall 2017

TOTAL RESPONDENTS: 244 of 252 active participants (263 enrolled students)	
Answer Submission	**Student Percentage**
2A	33.25%
2C	21.36%
2F *correct*	14.98%
2E	9.70%
2D	6.61%
Identified stronger acid	93.1%

Correct response statistics vary slightly between semesters but this is not surprising given that students in different semesters are not guaranteed to have the same general chemistry background. What does remain consistent between the groups, however, is that an overwhelming majority of students are able to correctly identify the stronger acid, but are unable to identify the correct stabilizing feature. Additionally, a comparable and considerable percentage of students across all three semesters chose electronegativity (A) as their designated answer, with hybridization (C) being the second most popular choice. These trends suggest that students are not familiar with the considerations necessary to delineate differences in acidity and therefore look to physical differences in structure to hint at the correct answer. Students citing electronegativity differences appear to be considering the phosphorus atom in phosphoric acid versus the sulfur atom in sulfuric acid and students citing differences in hybridization are observing the different bonding patterns in the two species. The fact that phosphorous and sulfur have comparable electronegativities and that they are both sp^3 hybridized only confirms that students, in general, lack the ability to qualitatively assess acid strength.

Students in the fall 2018 incoming class were even less successful than their predecessors in navigating the necessary considerations to arrive at the correct answer, but response statistics support the same general conclusions about students' abilities for qualitative analysis of the factors affecting acidity (Table 29).

Table 29. Top student responses to relative acidities clicker question—Fall 2018

TOTAL RESPONDENTS: 236 of 237 active participants (237 enrolled students)	
Answer Submission	**Student Percentage**
2A	38.1%
2C	16.5%
2D	11.9%
2E	11.9%
2F **correct*	4.24%
Identified stronger acid	87.3%

To potentially address the observed shortcomings in student understanding of relative acidities, the researcher constructed a problem-solution guide to aid in the explanation that typically follows polling. The developed guide is animated to work in conjunction with a series of questions that prompt and engage students through the problem solving process; this guide was first implemented following polling of the fall 2018 class. Because students were unfamiliar with where to begin analysis for a problem like this, the researcher first emphasized the connection between acid-strength and conjugate base stability and then prompted students to draw conclusions based on this information (Figures 38 and 39). This led to the physical depiction of the conjugate base species for comparison (Figure 40).

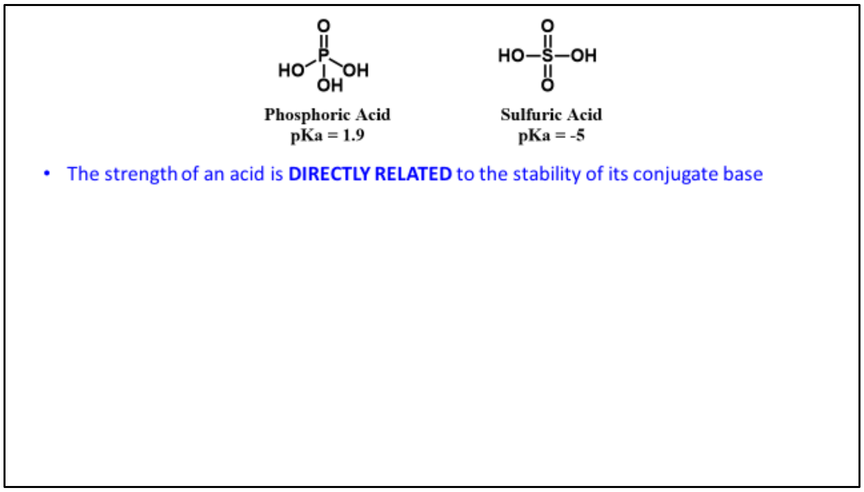


Figure 38. Problem-solving guide for comparative acidity clicker question—initial prompt

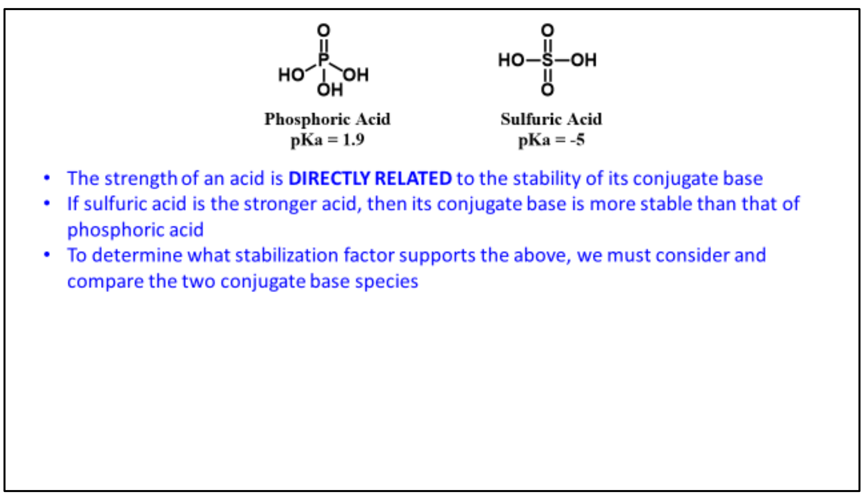


Figure 39. Problem-solving guide for comparative acidity clicker question—conclusions drawn

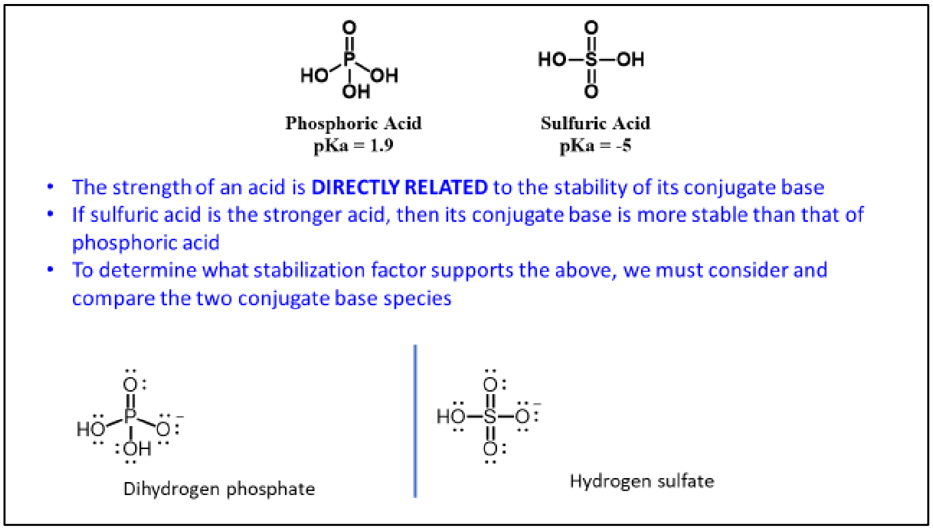


Figure 40. Problem-solving guide for comparative acidity clicker question—conjugate bases shown for comparison

Based on verbal feedback, it was at this point in the analysis that many students begin to rethink their initial responses. Even if students were still not completely confident in their ability to determine the correct stabilization factor, it was a significant point of progress that they were reassessing their initial considerations based on new information. Continuing the discussion by comparing the two conjugate base species side by side drew students' attention to the atom bearing the negative charge; this led them further away from their initial conclusions about the roles of electronegativity and hybridization in species stabilization and toward that of electron delocalization. Ultimately, students recognized that electron delocalization was prominent in both species, but that electron density was distributed across more atoms in hydrogen sulfate than in dihydrogen phosphate. Therefore, hydrogen sulfate was more stable due to resonance.

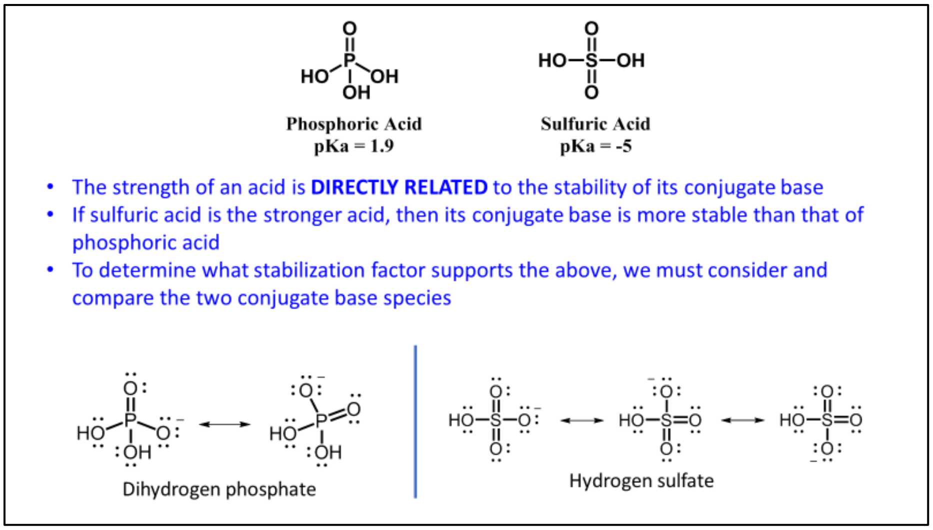


Figure 41. Problem-solving guide for comparative acidity clicker question—complete

This problem-solving guide focuses on conceptual analysis to support a trend and directs students to the use of logic and chemical intuition to explain how certain species tend to behave. This general understanding of stability and the related factors aids in later discussions regarding relative reactivities, reaction rates, chemical equilibrium, and a number of other concepts supporting the organic reactions to which students are exposed in the course.

Several weeks following the implementation of this question (Figure 37) and its post-polling explanation with the fall 2018 group, student comprehension was reassessed using a different question probing the same topic (Figure 42).

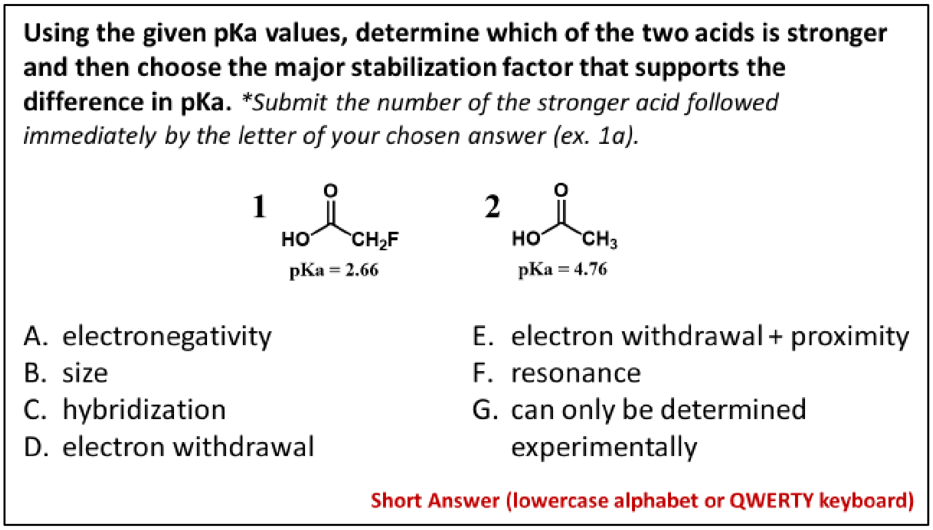


Figure 42. Follow-up clicker question exploring relative acidities and supporting stabilization factors

Table 30. Top student responses to follow-up stabilization factors clicker question—Fall 2018

TOTAL RESPONDENTS: 239 of 245 active participants (245 enrolled students)	
Answer Submission	**Student Percentage**
1D **correct**	64.5%
1A	14.1%
1E	8.37%
1F	6.69%

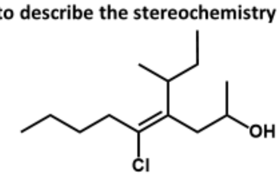
Student response statistics indicate a significant improvement in student comprehension of the factors affecting differences in acidity. During post-polling discussion, students were significantly more confident in suggesting the necessary considerations for problem-solving and in answering the series of questions that led to the correct response.

Student comprehension for identification and assignment of stereochemistry is also positively influenced by exposure to an accurate and methodical problem-solving strategy.

Through data analyses, it was found that students often struggle to identify or assign stereochemistry because they fail to precisely analyze the series of atoms bonded to a given center. In general, students either focus only on the groups directly connected to the center being considered or on differences beyond the first point of difference when assigning stereochemistry to chiral carbons or about double bonds. An example of the former was described in conjunction with the question identifying chiral carbons (Figure 19) where some students failed to identify a center as chiral because the groups immediately bonded to that center were the same.

In consideration of these identified issues, a detailed problem-solving guide for correct assignment of alkene stereochemistry was used in the fall 2016 class following question polling (Figure 43).

Choose the best answer to describe the stereochemistry of the alkene below:



A. **The above compound is the *cis* isomer of that alkene**
B. **The above compound is the *trans* isomer of that alkene**
C. **The above compound is the *E* isomer of that alkene**
D. **The above compound is the *Z* isomer of that alkene**
E. **The above compound cannot exist as *cis/trans/E/Z* isomers**
F. **The stereochemistry cannot be determined without more information**

Multiple Choice (uppercase alphabet or number pad)

Figure 43. Clicker question exploring alkene stereochemistry for first semester organic chemistry

Table 31. Top student responses to alkene stereochemistry clicker question—Fall 2016

TOTAL RESPONDENTS: 204 of 221 active participants (271 enrolled students)	
Answer Submission	**Student Percentage**
D	37.3%
C *correct*	28.4%
E	18.1%
B	6.90%
A	6.37%

A majority of students recognized that the given alkene exhibited stereochemistry *and* that the stereochemistry of that tetrasubstituted double bond could not be accurately described by the *cis*-*trans* system. Therefore, the decrease in correct assignment of the recognized stereochemistry is associated with the application of Cahn-Ingold-Prelog rules of prioritization. Hence, it was assumed that a problem-solving guide showing successive comparison of bonded atoms would aid in clarifying the strategic approach necessary for analysis. Again, animations were employed in conjunction with guided questioning to engage students and lead them through problem-solving. The slide given in Figure 44 is the end result of the series of animations.

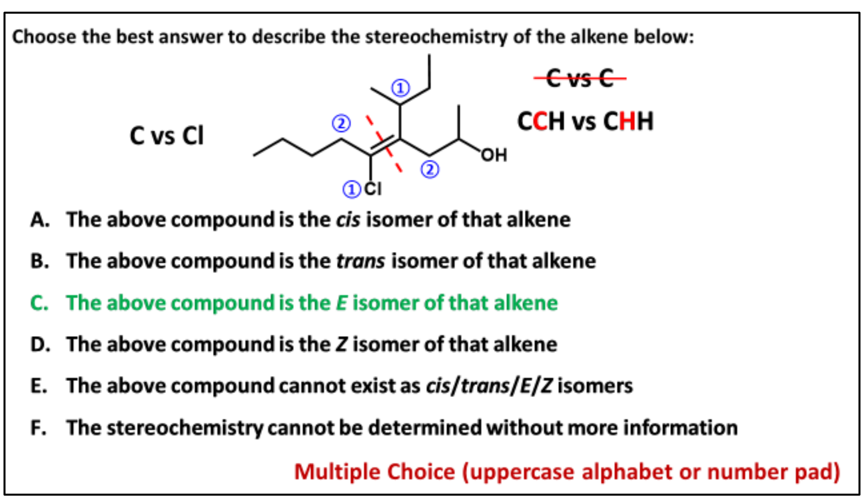


Figure 44. Problem-solving guide for alkene stereochemistry clicker question—complete

Again, students showed immediate progress in understanding as they were guided through the problem-solving strategy with an emphasis on precision and bond-by-bond analysis. To investigate the lasting impact of this progress, students were asked a follow-up question regarding alkene stereochemistry (Figure 45).

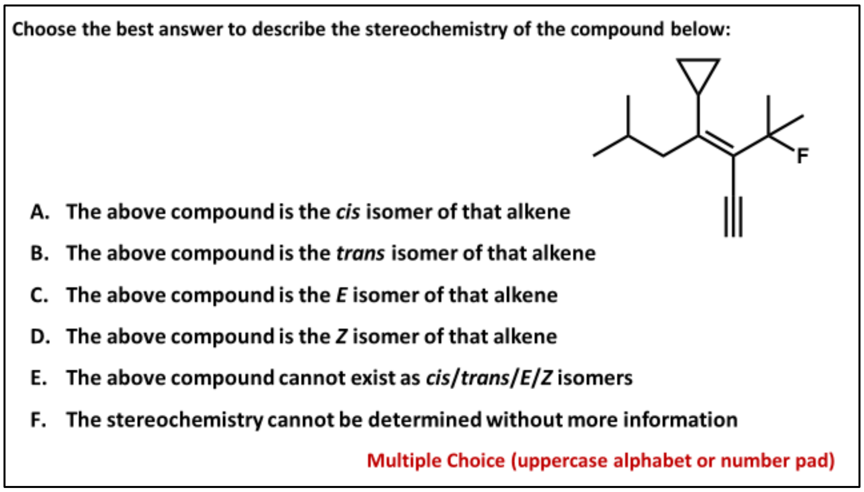


Figure 45. Follow-up clicker question exploring alkene stereochemistry

Table 32. Top student responses to follow-up alkene stereochemistry clicker question—Fall 2016

TOTAL RESPONDENTS: 204 of 221 active participants (271 enrolled students)	
Answer Submission	**Student Percentage**
D *correct*	70.1%
C	20.6%
B	6.54%
E	1.40%

Once again, a significant increase in student performance was observed. By comparison to the first question addressing alkene stereochemistry, student recognition of stereochemistry about the double bond increased by 19.2%; application of the correct system for expressing the stereochemistry of a tetrasubstituted double bond increased by 25.0%; and assignment of the correct configuration increased by 41.7%. Furthermore, student feedback indicated that the implementation and corresponding explanation of the first clicker question dealing with alkene stereochemistry played an integral role in their improved understanding.

Follow-up questions are not always used to assess student understanding following the use of these problem-solving guides but positive student feedback and data from various summative assessments (clickers, free response exams, etc.) indicating increased student comprehension encouraged the continued development and use of these guides for questions requiring more methodical analyses. These types of questions include, but are not limited to, those regarding stereospecific product formation and electrophilic addition to conjugated dienes.

Students consistently struggle with stereospecific reactions like electrophilic additions to alkenes for two observed reasons: 1) alkene reactions are the first organic reactions to which students are exposed and they are still familiarizing themselves with the associated mechanistic theories, relative stabilities of reaction intermediates and regiochemical considerations; and 2) introduction to stereochemistry occurs just a few weeks prior to the discussion of alkene reactions so students are often still developing their recognition skills with regard to *E*/*Z* isomerism and chirality. To aid students in rationalizing the various considerations necessary to determine products from electrophilic additions, these clicker questions are often accompanied by a problem-solving guide. This guide begins by prompting students through a series of questions assessing the functionalities produced via reaction and the regiochemical and stereochemical consequences of the mechanism by which the given reaction proceeds. Then, students are guided through a stepwise strategy that preserves the existing stereochemistry of the starting alkene while also introducing the stereochemical consequences of reaction (Figures 46-48). This is of particular import because the strategies textbooks present for predicting the stereochemistry of products often rely on memorization rather than application of logic. Therefore, the problem-solving guide is also employed to reinforce the more helpful strategy previously illustrated by the professor during lecture.

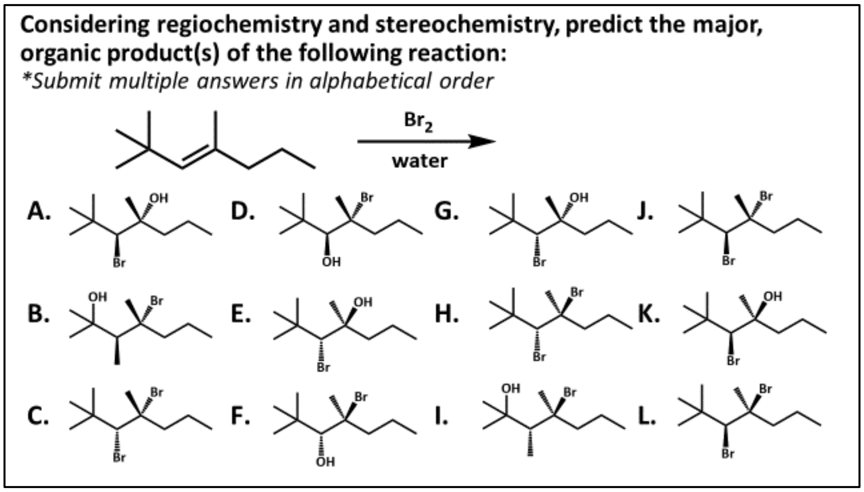


Figure 46. Clicker question exploring stereospecific bromohydrin formation

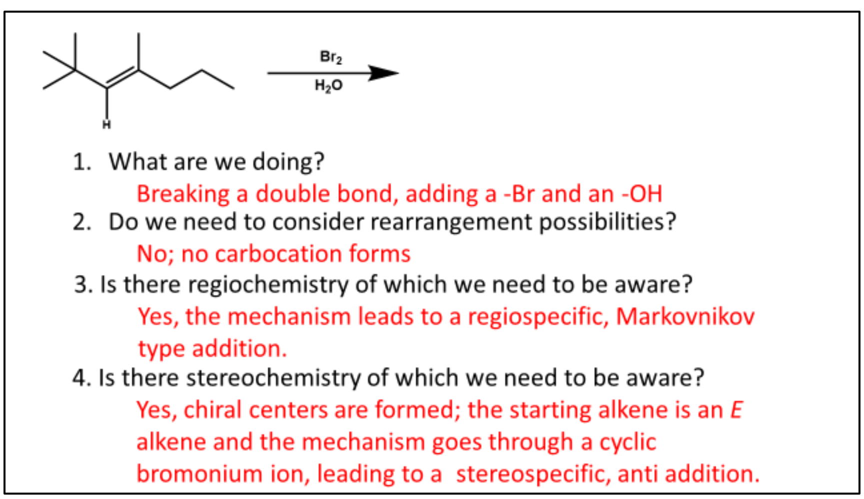


Figure 47. Problem-solving guide for bromohydrin formation clicker question—initial prompts

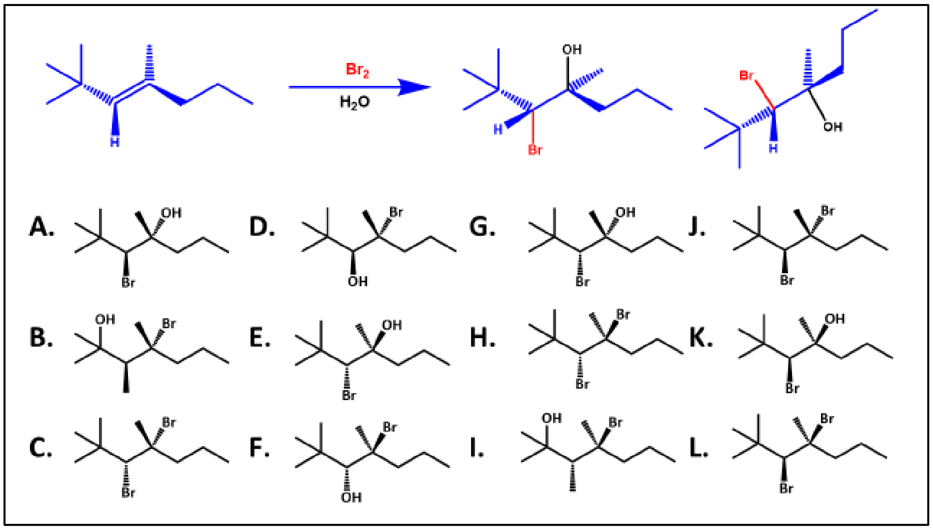


Figure 48. Problem-solving guide for bromohydrin formation clicker question—application of instructor illustrated strategy

<u>Generation of a "Clicker Bank"</u>

Over the course of five years, over two hundred clicker questions were developed encompassing all topics traditionally covered in the University of Georgia organic chemistry curriculum. These questions promote and facilitate formative assessment strategies because they were designed to elucidate specific aspects of student comprehension. Additionally, because most of these questions have been employed at least once, their potential for elucidating student comprehension has already been confirmed. The questions in this bank are especially unique in construction, unlike those provided in any other clicker repository currently available, including those that require purchase and those that claim to be impactful for student comprehension[61].

Because the burden of creating summative assessment items that effectively elucidate student comprehension is often the hindering factor to instructor employment of formative assessment[11], the researcher has compiled the developed clicker questions into an organized repository for distribution to University of Georgia organic chemistry faculty. It is the researcher's hope that providing instructors with this resource will enhance or incite their passion for formative assessment and instruction. Each question is given with clear directions for submission to promote statistics that are actually representative of class performance. Also provided for each question are: the correct answer slide; the associated explanation slide, complete with animations designed to promote student engagement in problem-solving after polling is complete; and an analysis slide indicating question objective, past year statistics and formative conclusions drawn from past data analyses. As an example, Figures 49-52 show this series of slides for one of the available questions addressing structural relationships.

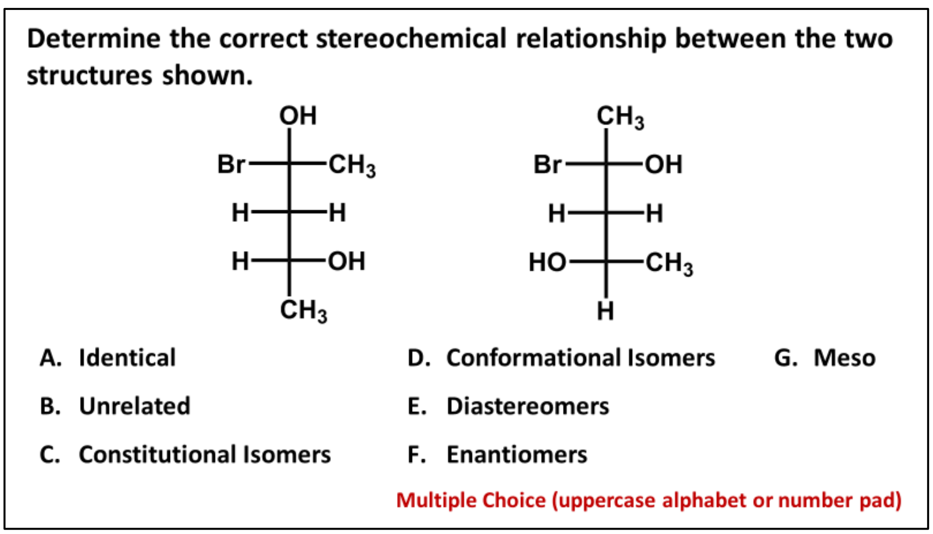


Figure 49. Clicker question exploring structural relationships with Fischer projections for first semester organic chemistry

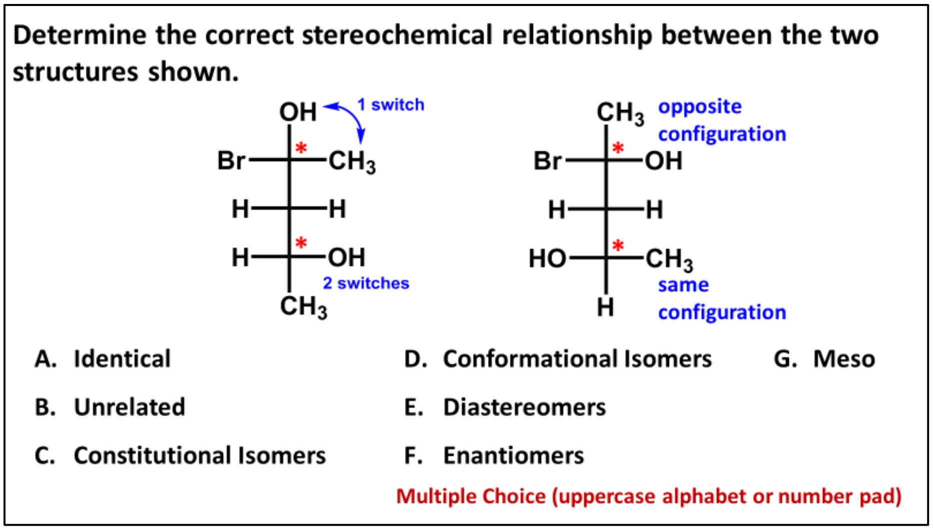


Figure 50. Problem-solving guide for Fischer structural relationships clicker question—complete

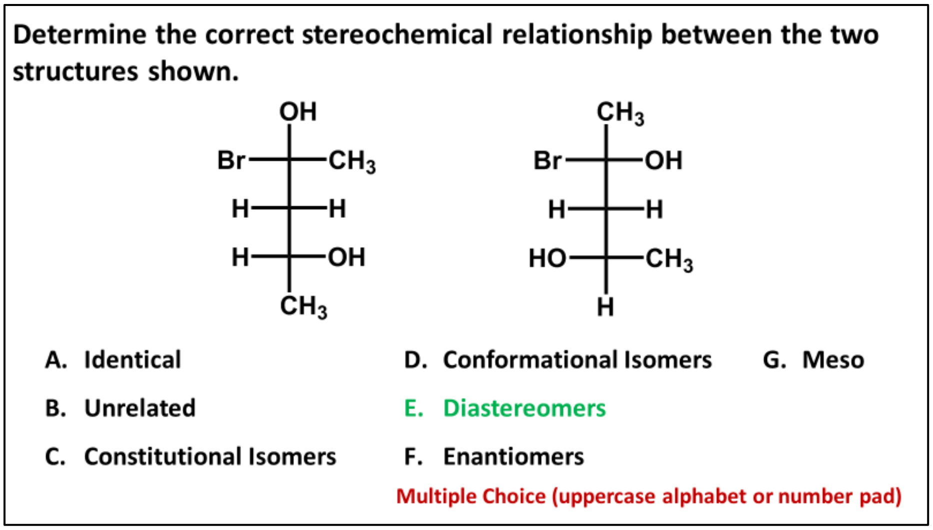


Figure 51. Correct answer slide for Fischer structural relationships clicker question

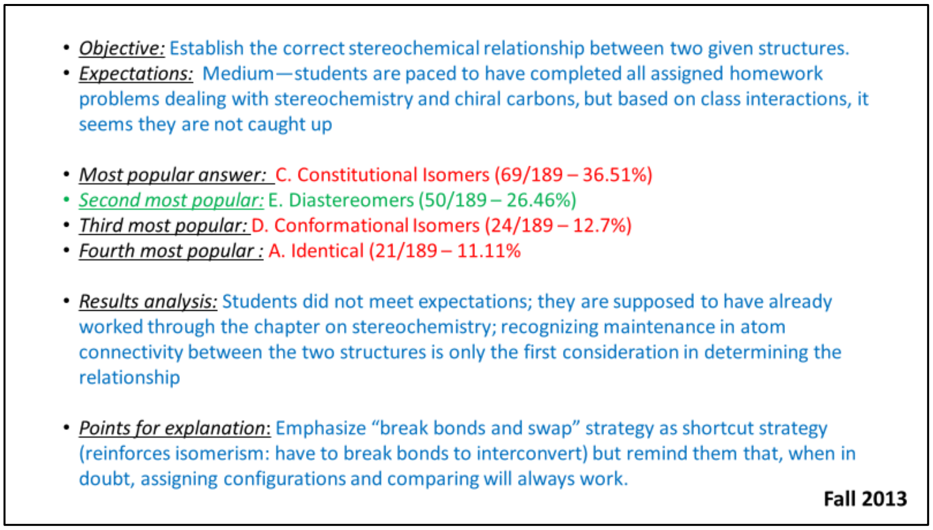


Figure 52. Detailed analysis slide from implementation of Fischer structural relationships clicker question in Fall 2013

Also interspersed throughout the bank are detailed explanation slides that were designed in specific semesters where the researcher observed students' needs for further guidance. These were made to display before class for review or as part of pacing assignments to reinforce concepts with which students seemed to struggle. An example of an explanation slide designed to elucidate the distinct utilities of the three alkene hydration reactions presented in first semester organic chemistry is provided below (Figure 53).

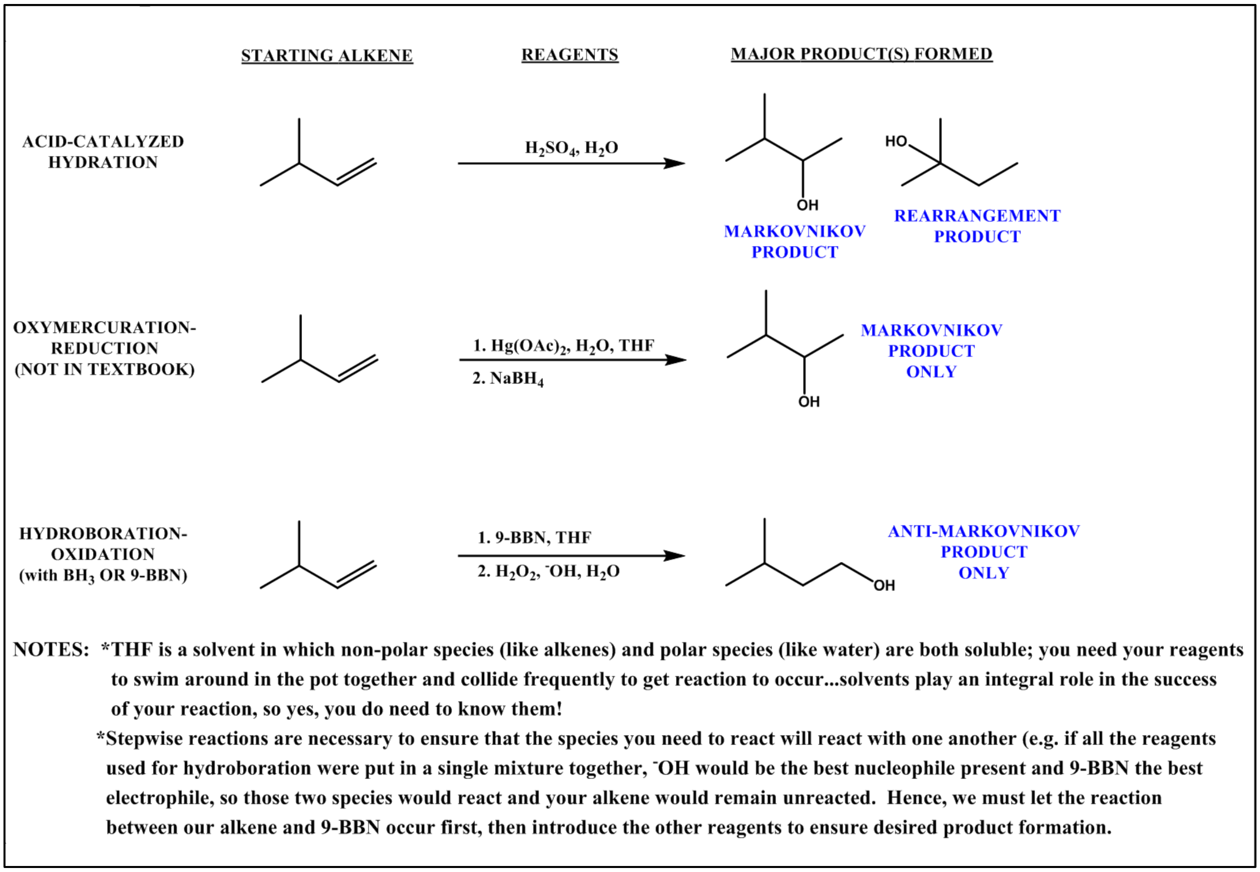


Figure 53. Explanation slide designed for concept reinforcement—alkene hydrations

Summary

In education, formative assessment is described as the process "to recognize and respond to student learning to enhance that learning during the learning" [62] which, in practice, describes the process of analyzing student response data from some summative assessment to elucidate the needs of the given student group and respond to those needs during instruction. For the researcher, it seemed that a natural extension of this type of assessment would be to draw comprehensive conclusions about students' understanding of organic chemistry concepts by comparing student responses across multiple semesters and assessments and identifying commonalities. Elucidation of misconceptions and struggles common to the average student in organic chemistry suggested specific modifications to instruction that could potentially preclude misapplications of theory and student confusion. The suggestions made for incorporation of more challenging examples into initial material presentations and the utilization of problem-solving guides to emphasize methodical analyses of multi-faceted questions have contributed to a recognizable improvement in students' retention and performance in organic chemistry.

CHAPTER 5

CURRICULUM CONSISTENCY: GENERATION AND IMPLEMENTATION OF MULTIPLE-CHOICE CUMULATIVE FINAL EXAMS

Based upon several years' experience heading construction, implementation, and explanation of clicker questions in first and second semester organic chemistry, the researcher developed an expertise in designing effective and elucidative assessment items. This expertise was recognized by multiple faculty members in the University of Georgia organic chemistry department for its potential in realizing a longstanding goal: the construction of cumulative multiple-choice final examinations for first and second semester organic chemistry that reflect the coverage, rigor level and learning objectives established within the department.

American Chemical Society National Exams for Cumulative Assessment in Organic Chemistry

Beginning in 2005, the organic chemistry division at the University of Georgia began the consistent implementation of the American Chemical Society standardized multiple-choice examinations for cumulative final assessment of first and second semester organic chemistry students. Prior to this, cumulative free response final examinations were constructed by course instructors and graded by graduate students according to a detailed rubric. Prompt and consistent grading became increasingly difficult to ensure with increasing enrollments, thus encouraging the move to multiple-choice examinations.

Employment of the ACS standardized exams afforded several immediate advantages. First, the Scantron® answer sheets associated with these multiple-choice exams ensured prompt and effortless grading via campus testing services. Second, the use of predesigned and edited exams relieved instructors of the burden of constructing new free response examinations each semester. Additionally, the availability of different exam versions allowed instructors flexibility and minimized concerns surrounding students' recall of questions from one semester to the next. The most significant advantage of using the ACS standardized examinations was the information afforded regarding University of Georgia students' performance compared to national norms. These data substantiated University of Georgia organic chemistry instruction and students' command of the material.

However, as organic chemistry instruction and assessment evolved within the department, the limitations associated with the ACS standardized exams became increasingly apparent. One of the observed challenges surrounding the use of national standardized exams is that coverage is determined by individuals who are not familiar with the scope and depth of organic chemistry coverage at the University of Georgia; this can lead to questions being designed based on material that is easily assessed via multiple-choice questions rather than being designed to assess student mastery of the discipline overall.[63] The ACS standardized exams are inconsistent with University of Georgia organic chemistry coverage, in terms of rigor and scope. Student feedback consistently indicated that the final exam was considerably easier than the free response exams given throughout the semester and comparative student performance data echoed this feedback. Questions associated with reactions that are not incorporated into the university's curriculum are present in all available versions of the standardized exam and topic coverage is inconsistent between the two semester exams. These inconsistencies often led to student frustration and in some cases, inspired differences among instructors' presentation of material. Some instructors encompassed these inconsistencies into the characteristic "guessing percentage" typically associated with multiple-choice exams, while others felt the need to briefly address these topics to give students fair exposure to the material over which they would be examined. Additionally, there are similar concerns regarding scope, content rigor and organization for the associated ACS exam study guide. The most significant concern surrounding the university's usage of these ACS standardized exams, however, is exam security and the costs associated with funding construction of a replacement exam. Accommodating mass examinations across the university's main campus while maintaining exam security has become increasingly onerous with increasing enrollments each year.

Given these concerns surrounding the use of ACS standardized exams for frequent assessment of University of Georgia organic chemistry students, the researcher was charged with the task of constructing a 70-question multiple-choice cumulative final examination to be administered for all first semester organic chemistry students in the fall of 2016.

Exam Construction and Implementation

The first semester organic chemistry final examination constructed in fall 2016 was designed with specific attention paid to the coverage and emphases given to topics in lectures throughout the given semester. Question stems were designed to be clear and precise in terms of language and objective and incorrect answer options were informed by observations made in assessing student responses to other summative assessments. Questions were vetted by instructing faculty members to ensure accuracy, precision and appropriate distribution of emphases.

In terms of implementation, the exams were treated with the same level of care and security required by the ACS standardized exams in prior years. Scratch paper and Scantron® sheets were placed before students entered the exam room to designate assigned seats. After students were seated and had filled out the appropriate information on the Scantron® sheets, exam booklets were distributed. A unique serial code was printed on each exam booklet to associate each student directly with their assigned test booklet and their answer sheet. Because the booklets were not intended for reuse from year to year and would eventually be destroyed, students were permitted to write in the exam booklets. Although no studies have been conducted to assess the validity of these claims, students consistently suggest that the ability to write directly on the exam booklet has a marked effect on their ability to problem-solve correctly and efficiently.

Results and Evaluation

Student results were collected and assessed for implications regarding appropriateness of rigor and to suggest adjustments for future versions of these department-generated final exams. Although the distribution of results from the fall 2016 implementation was Gaussian, the curve was shifted to the lower end and an average score of 32/70 was observed. The results suggested that the researcher, in an attempt to ensure the inclusion of questions that would challenge students to think critically, failed to strike an appropriate balance of rigor and assessment. Future versions called for a more balanced assessment of student skills, including basic recall and recognition. To account for the increased rigor and because the Gaussian distribution of results allowed for easy translation, student results were normalized using ACS standards. In doing so, overall student grades were not negatively affected by the introduction of a new exam.

Item analyses were provided by testing services and indicated the difficulty level and discrimination index for each question. Of the 70 exam questions, the discrimination index of 34 items was excellent (≥ 0.4), 12 were good (between 0.30 and 0.39), and 12 were fair (between 0.20 and 0.29).[64] Three questions returned discrimination indices of 0.00 and were singled out for evaluation. Of these three, one assessed student understanding of carbon-carbon bond formation using organometallic reagents, a topic that was covered in the days between the last in-semester exam and the last day of class. Students did not give as much attention or study time to material that was not assessed on in-semester exams, even when they knew the material will be represented on the final examination. The second question with poor discrimination dealt with a very specific instance of diastereotopicity for ^{1}H NMR and was expected to present a challenge. In the third question, it was discovered that one of the document translations between final editing and printing had incorrectly incorporated a hypervalent carbon atom in the reagent alcohol for the alkoxylation reaction. The question as printed in the fall 2016 exam booklet is shown in Figure 54 along with student response statistics.

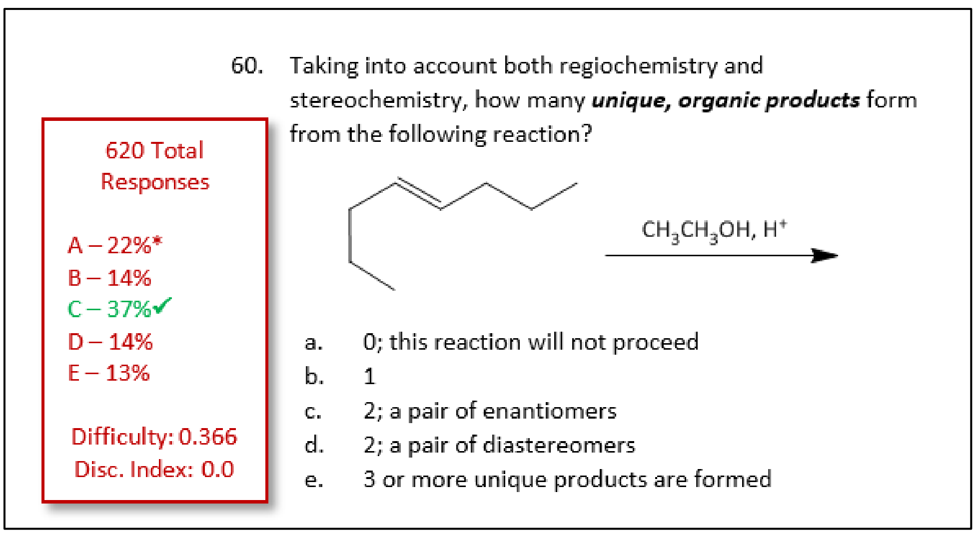


Figure 54. Final exam question with hypervalent carbon reagent—0.00 discrimination index

The observed discrimination index was assumed to be a reflection of the fact that some knowledgeable students who performed well in other parts of the exam chose that the reaction would not proceed because the given reagent does not exist while others either did not recognize the mistake, or chose to overlook the mistake, and selected the keyed answer (C). This problem was corrected for use in future exam versions.

Bearing in mind the need for a more balanced assessment of student comprehension, the first semester organic chemistry final was redesigned for the following semester to incorporate a more appropriate distribution of questions in terms of rigor. A second semester organic chemistry final was also designed. To avoid an overly rigorous construction, the researcher in conjunction with the director of organic chemistry and second semester organic instructor, reviewed each question and assigned a difficulty prediction (easy, easy/medium, medium, medium/hard and hard). This system predicted an average score of 40/70. The average score observed for the second semester organic chemistry final examination in spring 2017 was 41/70. The successful predictions of difficulty support the potential for eventual standardization of these exams.

The researcher-authored cumulative examinations have been implemented for first and second semester organic chemistry students in every semester since spring 2017. The researcher has compiled results from each semester's exam implementation noting average score, average difficulty, average discrimination and average class score as well as student response statistics for each question. Data for questions used in multiple semesters can be compared to elucidate standard difficulty assignments or to indicate differences in presentation based on individual instructors. Continued implementation and comparison of results will allow University of Georgia organic chemistry instructors to eventually compile a standardized exam where individual student performance relative to class performance can be used to suggest score assignments. Until then, student scores continue to be normalized using ACS standards. To ensure standards have been maintained or improved and to contribute comparative national data for the University of Georgia, ACS exams will be implemented every 4-5 years.

Question Bank Generation

One of the major motivating factors for constructing the departmental exam was to promote consistency in rigor and content. Because material presentation and emphases are not entirely uniform from semester to semester, the researcher wanted to give instructors the opportunity to construct their final exam to reflect presentation as accurately as possible. To provide instructors with flexibility in terms of both rigor and content emphases, the researcher generated a multiple-choice question bank. Currently, there are over 800 questions for first semester organic chemistry and over 200 questions for second semester organic chemistry, encompassing all covered material, including chapters that may or not be included in a given semester based on pacing. These questions are currently in the process of being vetted for technical accuracy, content level and language aspects.

Summary and Outlook

To ensure consistency in content coverage and assessment rigor and to circumvent overt risks to ACS exam security, a bank of carefully constructed and edited multiple-choice exam questions was created for continued use in the University of Georgia organic chemistry department. This bank provides instructors with a reliable source of questions to pull from for the construction of a cumulative final examination that effectively reflects their presentation of material within the given semester. Question specific results from previously implemented exams have been compiled for use in formative assessment strategies and eventual standardization. The creation of these department-specific multiple-choice final examinations opens a range of possibilities in terms of further academic investigation to elucidate student comprehension. Comparative analyses between in-semester free response questions and final exam multiple-choice questions on similar topics can elucidate key insights regarding students' retention and the influence of format on student response. The researcher is currently exploring these comparative considerations to provide commentary on the strength of different formats to effectively assess student comprehension.

CHAPTER 6

CONCLUSIONS AND FUTURE DIRECTIONS

The challenges that face instructors in piloting student mastery of the organic chemistry discipline involve a range of factors including students' academic maturity, students' diagnostic abilities and the detailed, visual nature of organic chemistry itself. To address each of these factors and ultimately improve student performance, careful consideration must be given to the design of assessment items, the recognition of student needs and the efficacy of instructional strategies.

Building upon a foundation of sound instruction and an esteem for the value of formative assessment, the researcher set about the construction of targeted and creative clicker questions to more effectively elucidate student comprehension in undergraduate organic chemistry at the University of Georgia. The researcher's efforts were motivated by the belief that effective teaching occurs when instructors precisely identify sources of student confusion and provide immediate corrective feedback.[26] This type of precise identification is simply not possible via analyses of traditional multiple-choice questions where student responses are influenced by the presence of prompts and the absence of options they might otherwise consider. To more effectively elucidate the series of logical decisions students must make to determine correct answers for many topics in organic chemistry, the researcher developed more creative, more challenging and more targeted clicker questions than have been previously designed for use in organic chemistry instruction. These advanced clicker questions afforded precise insight into students' pacing and concept mastery.

Real-time results from implementation of these advanced clicker questions suggested specific instructional strategies to appropriately address the shortcomings in understanding evidenced by response statistics. With a detailed understanding of the specific aspects of problem-solving that presented difficulties for students, instructors were able to suggest points of review for students, prompt in-class discussions for clarification or design subsequent assessments to precisely tackle these specific deficiencies. By using student feedback to inform instructional efforts, instructors engaged students in the teaching process and effectively addressed the specific needs of their students in real-time.

Increased exposure to student feedback via clicker assessments, instruction, and grading supported efforts to identify and preemptively address overarching misconceptions and difficulties common to organic chemistry students, in general. Applying formative assessment strategies to existing clicker response data elucidated commonalities in student interpretation and application of problem-solving strategies for specific topics. This insight was imparted to instructors to suggest specific examples that should be incorporated into initial presentations of material. Exposing students to more challenging applications of theory earlier on in presentation precluded misapplications of theory and in turn, improved student comprehension with regard to those specific topics. For concepts requiring more methodical considerations for correct answer elucidation, problem-solving guides were created to lead students through precise analysis of necessary factors. In this way, students' feedback guided the creation of a specific style of instructional tool to more effectively address their shortcomings in comprehension.

This continued vested interest in improving education and instruction of organic chemistry led to the development of cumulative multiple-choice final examinations for more precise assessment of students' long-term retention and development of diagnostic skills.

Collective data from the implementations of these final exams are used for continued formative analysis and further identification of the topics that present challenges for undergraduate students enrolled in organic chemistry. This insight informs the development of cumulative final exam study guides to reflect the increased rigor and comprehensive assessment given by the department-generated final exams at the University of Georgia.

In total, the present work describes the incredible wealth of knowledge and perspective one can garner from implementing successive strategies that are informed by prior efforts and recognizes the value of the formative approach as the ultimate instructional tool. Indeed, the approach requires a great deal of time, effort and motivation but implementation of this style of instruction is not only valuable, it is the ultimate nod to the methodology scientists apply every day in their experimental efforts; this should not be any different for instructional efforts.[40] It is the researcher's hope that the evident improvements to instruction and assessment accomplished in the organic chemistry department at the University of Georgia may inspire moves at other institutions to embrace a formative process for instructional improvement.

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