

Homing in on the Capabilities That Are Most Predictive of Student Success in the First Semester of Organic Chemistry

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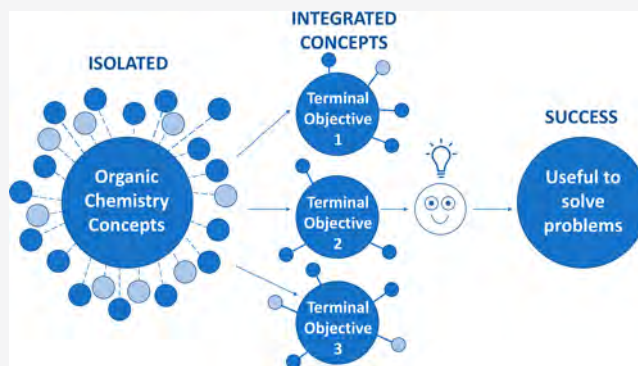


Supporting Information

ABSTRACT: The non-major's two-semester organic chemistry course at UPR-RP aims at developing a more integrated and meaningful understanding of the fundamentals of Organic Chemistry. To achieve this goal, we have implemented a novel instructional design that focuses on nine terminal objectives. The nine terminal objectives describe what students should be able to do with the knowledge they gain in the course. They describe capabilities that expert organic chemists master and that novice students need to solve problems in organic chemistry. Through the development of the capabilities described by terminal objectives, we aim at getting students to observe, connect, and understand the structural similarities of functionalities. Moreover, we aim at getting students to look for underlying concepts to explain the effects of differences in structure. By integrating the terminal objectives into class delivery, we intend to communicate to students what is important, the types of problems they should be able to solve, and where the course is going. This paper presents the nine terminal objectives and the curriculum design that supports their development. It also informs on a study that evaluated student performance on final exam multiple-choice items that were prepared to test for the capabilities described by the nine terminal objectives. Data collected from 400 to 500 students each year for 2 consecutive years was statistically analyzed using a linear regression analysis. The study found that success on certain final exam items, associated with three of the nine terminal objectives, was most predictive of students' success in the course as determined by the final course grade.

KEYWORDS: Chemical Education Research, Second-Year Undergraduate, Organic Chemistry, Testing/Assessment, Learning Theories, Minorities in Chemistry, Student-Centered Learning

FEATURE: Chemical Education Research



INTRODUCTION

Teaching organic chemistry is a challenge.^{1,2} The subject demands complex intellectual processes such as the visualization of spatial relationships, the understanding of abstract concepts, the capacity to solve multiple-variable problems, and the use of specific symbols and drawings to convey ideas.³ The course covers a lot of material in a short period of time and requires long hours of study and practice. The increase in the size of the organic textbooks makes it difficult to decide which reactions to keep in the curriculum.¹ There is an increase in the learning resources that are available for students, both digital and printed. So much information makes it tough for students to focus on what is important. Students learn in individual ways and could benefit from improving their metacognitive knowledge.⁴ Due to the cumulative nature of the material, those who resort to extensive memorization without understanding do poorly.⁵ The task gets tougher in the non-majors course where most of the audience is not genuinely interested in the subject and only takes the course because it is required.

Efforts to improve teaching and learning in the organic course have included the introduction of student-centered learning techniques, changes in the curriculum, and the identification of the problems students have with the subject. A format called the flip classroom has been implemented with observed increments in student success.⁶ A highly structured active learning format also reports an increase in student final course grades.⁷ The use of a Peer-Led Team Learning instructional approach (PLTL), instead of traditional lectures, also showed improvement in students' final course grades.⁸

Changes in curriculum have also been associated with student success. Most organic chemistry textbooks are organized around functional groups, and consequently, most curricula are based on this approach and it is up to the

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instructor to establish connections between functional groups.^{5,9} There is a general belief that when students do not establish connections across functional groups they have a higher tendency to resort to mastering the subject through memorization.^{1,10} In an effort to integrate knowledge across functional groups, some textbooks have included chapters that present the similarities in structure of functional groups with similar reactivity.^{11,12} Other efforts include the development of curricula that differ from the functional group approach and address relating structure to chemical properties.^{10,13,14} One of these new curricula introduces mechanisms and electron pushing formalism (EPF) before reactions. This curricula has been implemented and recently analyzed with positive findings and interesting implications for instruction.^{10,13} Among the findings was that all students in the study used the EPF formalism correctly. Also, since every participant struggled with an acronym, they recommend drawing out structures instead of using acronyms to emphasize the importance of connecting structure to reactivity over memorizing. More recently, an interesting curriculum has been designed (OCLUE) which connects all topics to four core ideas (structure–property relationships, bonding and interactions, energy and stability and change) by using scientific practices, such as constructing models, analyzing and interpreting data, and emphasizing causal mechanistic reasoning. OCLUE is relevant to non-majors because it focuses on biologically prevalent reactions.¹⁴

The difficulties that students have with organic chemistry are well documented and include the following: working with multiple styles of representation of organic molecules;¹⁵ distinguishing between nucleophiles, electrophiles, acids, and bases;^{16,17} using mechanisms to explain the product(s) of reactions;^{18–22} establishing differences in the stability of intermediates;²³ ordering acids according to their strength using structure–property relationships;^{24,25} establishing the relative reactivity of species;²³ predicting the principal products of reactions;^{22,26} generating potential energy diagrams;²⁷ proposing synthetic pathways for molecules.^{28,29}

THE TERMINAL OBJECTIVES

The need for terminal objectives (TOs) arose in the early 2000s when professors started making changes in the course design for the development of more meaningful learning. Large lectures were substituted by 12–13 sections of 35–40 students to increase interaction with students. Class periods were increased by 30 min to accommodate new active teaching/learning methods. Despite these changes, there was still too much material to “cover” in class, and to make more efficient use of class time, it was necessary to identify important capabilities to develop and to concentrate on. In the analysis of the course’s operational objectives, it was found that nine objectives were common to all functional groups. Since the nine common objectives were also more comprehensive, all of the course’s objectives were regrouped under these more inclusive objectives. This regrouping resulted in the identification of the nine terminal objectives and the capabilities they describe (see Table 1).

The terminal objectives are relevant because they describe capabilities the expert organic chemists have and the novice students need to solve problems in the introductory organic chemistry course. The TOs describe desired performance in areas where students have difficulties with organic chemistry.¹⁴ *Some concepts span more than one TO.* For example, the concept

Table 1. Terminal Objectives

Upon Completion of the Course, the Student Will Be Able to Perform the Following Tasks:
1. Given the drawings of several isomers, classify each as either constitutional or stereoisomers. If stereoisomers, classify each as either conformational isomers, enantiomers, or diastereoisomers.
2. Given reactants, intermediate species, and products of a reaction, classify species as either acids, bases, nucleophiles, or electrophiles.
3. Given the reactant, the conditions, and the product, propose a mechanism for a chemical transformation.
4. Given the structures of several intermediate organic species, compare and classify them in terms of their relative stability, based on steric and electronic effects.
5. Given the structures of various acids or bases, arrange according to strength.
6. Given several organic species, compare them in terms of their relative reactivity under the conditions of the fundamental organic reactions. ^{a,b}
7. Given the reactants and the conditions, predict the principal product(s) of fundamental organic reactions. ^{a,b}
8. Given an organic reaction, generate its potential energy diagram based on the relative stability of species and relative rate of reaction steps.
9. Given a chemical transformation, design a possible synthetic (or retrosynthetic) pathway.
^a Semester 1: acid–base, electrophilic addition, and electrophilic aromatic substitution. ^b Semester 2: nucleophilic substitution, elimination, nucleophilic acyl substitution, nucleophilic addition, oxidation–reduction, and α carbon chemistry.

of electronic substituent effects applies to various TOs: the relative stability of intermediate species (TO#4); the relative strength of acids and bases (TO#5); the relative reactivity of species (TO#6); and the principal product(s) of reactions (TO#8). *Each TO requires a different combination of concepts.* For instance, TO#6 (relative reactivity) requires the combination of the concepts students use for TO#4 (stability of intermediate species) with other concepts (e.g., rate-determining step, free energy of activation, Hammond’s postulate). *Not all problems that could test for a TO require the same combination of concepts.* To give an example, there are problems that test for TO#4 (stability of intermediate species) that can be solved with the concept of electronic inductive effects (e.g., relative stability of tertiary carbocation > secondary carbocation > primary carbocation) and there are problems for TO#4 that require the consideration of both inductive and resonance electronic effects as well as hybridization (e.g., relative stability of benzyl carbocation > allyl carbocation > vinyl carbocation).

THEORETICAL FRAMEWORK

The strategy of focusing the non-majors organic chemistry course on the development of specific capabilities students need to solve problems (TOs) is guided by the current understanding of how people learn. Research in educational psychology tells us that students’ knowledge will be more organized, accessible, and useful if students connect it to the solution of problems.³⁰ Educational research also informs that knowledge gains relevance when it is connected and beneficial in a new problem solving context. Consequently, returning to the TOs in the study of different functional groups could help students understand how the same concepts might be used to solve problems in different situations. According to Grove and Bretz, metacognition plays a crucial role in helping students become meaningful learners.³¹ Going back to the TOs when solving problems could also help students create awareness of the capabilities they are developing and motivate them to connect new concepts to concepts they already know.³² This

strategy could also help students organize their ideas around the solution of problems so they can see how the subject fits together.

METHODS

Research Questions

The non-majors' organic chemistry course focuses on developing the capabilities that are described by nine terminal objectives. The goal of this study was to identify the capabilities that are more closely related to student success in organic chemistry. The research questions addressed by this manuscript are

1. Do all of the terminal objectives (the capabilities they describe) contribute equally to student success?
2. Are one or more terminal objectives (one or more capabilities) more closely related to student success?

Participants and Setting

The participants in the study were students taking the first semester of the two-semester sophomore non-majors organic chemistry course at the University of Puerto Rico, Rio Piedras Campus (UPR-RP). Participants were all Hispanics, and Table 2 includes the gender and year at the university. The mean of

Table 2. Participant Gender and Year in University

Year	Gender		Year in University			Total
	Male	Female	2nd	3rd	4th+	
2012	181	325	145	176	185	506
2013	195	337	156	195	181	532

the general admission index (GAI) of both groups of students was compared using a *t* test. The *t* test results suggest that the mean of GAI was not significantly different between year 2012 and year 2013 (see the Supporting Information). Therefore, both groups are similar and can be compared. This study was granted exempt status from IRB at UPR-RP.

The non-majors organic chemistry course curriculum at UPR-RP is organized into 12–14 topics per semester (see Table 3 and the Supporting Information). Each topic has a distinct and long list of detailed operational objectives. The

Table 3. First Semester Curriculum^a

Hours	Topics
6.0	Structure and bonding
4.0	Resonance
4.0	Acids and bases
4.0	Nomenclature and conformations of alkanes and cycloalkanes
5.0	Stereochemistry
7.5	Reaction energetics and regioselectivity of electrophilic addition of alkenes
4.0	Stereochemistry of electrophilic addition of alkenes
2.5	Infrared spectroscopy (IR)
4.0	Electrophilic addition of alkynes
4.0	Electrophilic addition of dienes
2.5	Aromaticity
4.0	Electrophilic substitution of benzene
4.0	Electrophilic substitution of substituted benzenes
4.5	Proton nuclear magnetic resonance (¹ H NMR)

^aIn addition, five (3 h) laboratory sessions are dedicated to molecular models, infrared and ¹H NMR.

course requires two semesters of general chemistry and is a requisite for students majoring in biology and chemical education. It also supports students who will pursue careers in health care such as pharmacy, dentistry, nutrition, and medicine and prepares them for subsequent courses such as biochemistry and medicinal chemistry. The course is taught in Spanish, the textbook is in English, and all of the exams are in Spanish. At the time of the study, the textbook used was the sixth edition of *Organic Chemistry* by Bruice.³³ Students had educational materials in Spanish to support their learning. Both semesters are taught in 12–13 sections of 35–40 students. Students attend two classes a week (1 h 50 min each) and one 3 h laboratory. The course is coordinated so all sections are taught by professors who meet weekly to coordinate their teaching and to prepare exams. All sections follow the same teaching program and use the same textbook. All students take the same semester exams and final exam and are graded with the same grading scale.

The course's instructional program (see the Supporting Information) combines short lectures with active and group learning activities, where students have time to work problems and receive feedback. Educational materials have been developed in Spanish to guide students in the process of problem solving using the construction of molecular models and the analysis and interpretation of data. Interactive chemical demonstrations are used to introduce and clarify concepts. The course employs former students to assist instructors in class activities and to tutor students at the faculty's learning center. Tutors' responsibilities include the correction of quizzes and homework assignments.

The final grade is based on three open-response exams (300 points, 53.1% of grade), a laboratory grade (115 points, 20.4% of grade), and a multiple-choice final exam (150 points, 26.5% of grade). Short quizzes are given once or twice a week to help students monitor their learning, and they contribute 10 bonus points. The three open-response exams have problems that elicit reasoning, and they also include problems to challenge students with new reactions and different reaction outcomes. Students can use the molecular models in exams. Exams include tables with relevant data such as electronegativity and bond enthalpy values and spectroscopic data for IR and ¹H NMR.

Course Curriculum

The course design (Table 3) uses teaching strategies that have been successful, is consistent with fundamental ideas that have guided changes in curriculum, and addresses difficulties students have with learning organic chemistry. What is novel with this design is that it explicitly focuses on the development of nine capabilities that are described by the terminal objectives. The TOs are introduced to students the first day of class, are included in the course syllabus, and are integrated in class delivery and activities. Students know that terminal objectives guide teaching and the preparation of exams. The TOs are developed through the causal analysis of problems related to the reactions that are taught. Since the TOs apply to both semesters of the organic chemistry course, they are developed in the contexts of all of the functional groups. Focusing on the development of the TOs supports students in noticing conceptual similarities and differences in the structures of functional groups which they might otherwise overlook. Returning to the TOs as often as possible is important to help students realize how concepts may be

combined differently in different situations. In the process of solving problems in class, students are reminded that they are applying and practicing the capabilities described by the TOs.³¹ The explicit development of the TOs intends to help students organize their learning in preparation for quizzes and exams. Through this approach, all of the TOs are equally developed in terms of class time, student tasks, and quality of resources.

The first semester curriculum initiates with bonding, molecular representations, hybridization, resonance, conformations, and stereoisomerism. In addition to the programmed classes, three laboratory sessions are dedicated to teaching the initial topics with the aid of molecular models. The molecular models used are the ball and rod with sp, sp², and sp³ centers and p orbital plates. When resonance is discussed, students represent the delocalized pi systems of resonance hybrids with molecular models. Students construct potential energy diagrams to show energy changes due to steric strain. Students also analyze the relationship between stereoisomers.

Only three types of reactions are covered the first semester: acid–base, electrophilic addition, and electrophilic aromatic substitution. Acid–base reactions are covered first, and students bring knowledge of these reactions from general chemistry. Mechanistic arrows are introduced in the context of acid–base reactions. Students solve problems that develop and integrate the concepts of proton transfer equilibria, conjugate acid–base pairs, the position of equilibrium, and free energy diagrams. Students are required to explain why one compound is more acidic or basic than another based on the molecular structure and the relative stability of the conjugate base or acid, considering factors such as electronegativity, resonance, and inductive effects.

The electrophilic reactions covered are those that will be built on later in the course. The electrophilic addition of alkenes, alkynes, and dienes includes the addition of hydrogen halides, water (acid catalyzed), alcohols (acid catalyzed), halogens, and hydrogen (metal catalyzed). In the addition of borane to alkenes and alkynes, the mechanism of oxidation is not discussed. Class activities require students to reflect on how structural differences in the π nucleophile and in the electrophile affect the mechanism, relative rates, and outcomes of these reactions.

Aromaticity is covered to introduce benzene and its derivatives before electrophilic aromatic substitution. Students use molecular models to establish the structural similarities and differences between compounds that are aromatic and nonaromatic. The electrophilic aromatic substitution reactions that are included are halogenation, nitration, sulfonation, Friedel–Crafts acylation, and Friedel–Crafts alkylation of benzene and substituted benzenes. Electrophilic aromatic substitution reactions are compared to electrophilic addition reactions. Class activities help students reflect on the relative rate and regiochemistry of the reactions.

IR spectroscopy is introduced in the middle of the semester when students are already familiar with some functional groups, and ¹H NMR spectroscopy is taught at the end of the semester. Spectroscopy is further developed the second semester. The second semester curriculum is included in the [Supporting Information](#).

Electrophilic addition reactions and electrophilic aromatic substitution reactions both have rate-determining steps where a π nucleophile reacts with an electrophile. Acid–base reactions are present in mechanisms of both types of reactions.

The second step of electrophilic aromatic substitution is an (acid–base) elimination reaction that regenerates the aromatic system. Elimination reactions are covered during the second semester. Including and comparing fewer and somewhat related reactions and organizing concepts by the terminal objectives early in the course intends to move students away from rote memorization to more meaningful learning techniques. Through the simplicity of this approach, we also seek to help students monitor their own thinking.

Alignment of Terminal Objectives with Final Exam Items

Different final exams were prepared for each year by a group of six to seven professors who were currently teaching the non-majors' organic chemistry course. Each final exam had 40 multiple-choice items designed to test for the TOs with at least 2 items for each TO. Only items that the course professors considered relevant and of adequate difficulty were included.³⁴

All course sections took the final exam simultaneously. Students marked their answers on Scantron sheets, and the campus technology division (CTD) corrected the exam and performed the initial statistical analysis of the results. As is standard in psychometric measurement, the initial statistical analysis determined the upper and lower 27% of students based on their overall performance on the final exam.³⁵ The discrimination index for each item was determined using the results of the upper and lower groups. The discrimination index is a measure of how well an item is able to distinguish between examinees who are knowledgeable and those who are not. According to the range presented by Linn and Gronlund,³⁶ the magnitude of the discrimination index goes as follows: larger than 0.40, very good discrimination; from 0.39 to 0.30, good discrimination; from 0.29 to 0.00, poor discrimination. Test items with negative indices do not discriminate. An item will have a low discrimination if it is so difficult that everyone gets it wrong or so easy that everyone gets it right. Most items in both final exams were discriminatory (see the [Supporting Information](#)).

The final exams for years 2012 and 2013 were also good predictors of students' final course grades. Most students in the upper 27% of the final exams passed the first semester with A or B. Conversely, a large percentage of students in the lower 27% failed the first semester ([Table 4](#)).

Table 4. Student's Final Grade in the Course vs Grade in the Final Exam

Course Grade	Upper 27%		Lower 27%	
	2012	2013	2012	2013
	Frequency		Frequency	
A	74	48	0	0
B	43	59	0	0
C	0	7	3	20
D	1	0	30	27
F	1	0	85	67
Total	119	114	119	114

Linear Regression Analysis

A linear regression analysis was performed each year with the exam results of all students to determine which of the nine TOs best predicted the final grade in the course. The predictors (independent variables) were the composite scores calculated by adding the corresponding items related to each of the nine TOs. The criterion (dependent variable) was the final

grade obtained in the semester. The “stepwise” variable selection algorithm was chosen to determine the optimal combination of predictors to include in the regression model. Stepwise selection initially includes only an intercept term in the model and recursively adds or subtracts variables one at a time to determine if model fit improves. The Akaike information criterion (AIC) was used to indicate model fit.³⁷ The AIC statistic uses the maximized log likelihood value as a baseline for model fit and adds a penalty for estimating additional parameters (see the [Supporting Information](#)).

For the linear regression analysis, two items were linked to each of the nine TOs. When the exam had more than two items for a TO, those with the best discrimination indices were selected. [Table 5](#) includes the discrimination indices of the

Table 5. Results of the Prediction Model^a

Final 2012			Final 2013		
TO	Item (DI)	% V	TO	Item (DI)	% V
2	35 (0.559)	24.8	6	6 (0.698)	40.8
	39 (0.423)			7 (0.731)	
1	30 (0.542)	11.5	2	10 (0.549)	8.2
	31 (0.517)			11 (0.621)	
3	12 (0.426)	9.1	3	31 (0.453)	5.5
	14 (0.398)			32 (0.619)	
6	9 (0.702)	4.9	4	28 (0.619)	3.7
	24 (0.358)			9 (0.580)	
4	25 (0.297)	3.4	8	26 (0.321)	2.1
	20 (0.484)			27 (0.425)	
7	18 (0.105)	2.4	7	34 (0.578)	1.5
	22 (0.573)			35 (0.629)	
9	19 (0.226)	1.7	5	3 (0.402)	0.9
	21 (0.496)			4 (0.422)	
8	34 (0.328)	1.1	1	19 (0.506)	0.7
	17 (0.230)			20 (0.423)	
5	36 (0.506)	0.4	9	16 (0.244)	0.4
	37 (0.465)			17 (0.498)	

^aDI, discrimination index; V, variance.

items included in the linear regression analysis and the percent variance of each TO. Only three items with poor discrimination were used in the regression analysis, and all were difficult for both groups (2012 items #18 and #19, 2013 item #16).

Prior to conducting the linear regression, the assumptions of normality of residuals, homoscedasticity of residuals, variance inflation factors (absence of multicollinearity), and the lack of outliers were examined (see the [Supporting Information](#)).

The *R*-square change criterion was used to select the “best prediction model”. This criterion establishes that, when the introduction of a next variable does not account for a significant change in variance for that model, that variable can be dropped from the model. When analyzing the results, we considered two-, three-, and four-variable prediction models (see [Tables 6](#) and [7](#)). The two-variable prediction model accounts for 36.3% of the variance in 2012 and 49.0% in 2013. Common to both of the two-variable prediction models is TO#2. The three-variable prediction model accounts for 45.4% of the variance in 2012 and 54.5% in 2013. Common to both of the three-variable prediction models are TOs #2 and #3. The four-variable prediction model accounts for 50.3% of the variance in 2012 and 58.2% in 2013. Common to both of the four-variable prediction models are TOs #2, #3, and #6.

Table 6. 2012 Prediction Model Summary

Model TOs	<i>R</i> ²	Change Statistics				
		<i>R</i> ²	F	df1	df2	Sig. F
2	0.248	0.248	142.934	1	434	0.000
2, 1	0.363	0.115	78.062	1	433	0.000
2, 1, 3	0.454	0.092	72.511	1	432	0.000
2, 1, 3, 6	0.503	0.049	42.508	1	431	0.000

Table 7. 2013 Prediction Model Summary

Model TOs	<i>R</i> ²	Change Statistics				
		<i>R</i> ²	F	df1	df2	Sig. F
6	0.408	0.408	283.152	1	410	0.000
6, 2	0.490	0.081	65.358	1	409	0.000
6, 2, 3	0.545	0.055	49.250	1	408	0.000
6, 2, 3, 4	0.582	0.037	36.213	1	407	0.000

The proportion of variance for the four-variable prediction model indicates the percent of the variance in the final grade that is explainable by the set of three TOs identified by the model (50.3% in 2012 and 58.2% in 2013). The description and the results of this analysis are included in the [Supporting Information](#).

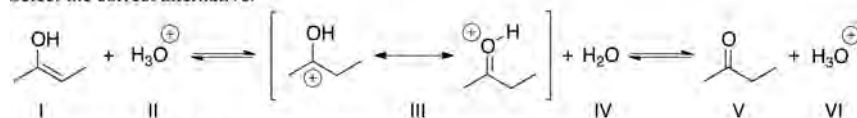
DISCUSSION OF THE RESULTS

To delve into why certain exam items predicted success, we analyzed one item linked to each of TOs #2, #3, and #6, to determine the combinations of concepts and underlying factors that students must weigh to solve them. Informed by other relevant studies, the discussion includes common student problems with these capabilities. The final exam items did not include the selection of appropriate reasoning, so we do not know how far along students were in the continuum connecting meaningful learning and rote learning when they took the final exam.³¹ However, since the instructional approach sought to move students toward meaningful understanding and awareness of their capabilities, we analyzed the results assuming that students’ answers reflect some understanding.

Success on Items Linked to Terminal Objective 2

Success on items linked to TO#2 was the best predictor of student success. This finding suggests that the capability described in TO#2 is fundamental and that students who do better in the course can identify nucleophiles, electrophiles, acids, and bases in reactions. Students’ difficulty with this capability has been previously identified. Anzovino and Bretz found that undergraduate students had fragmented ideas about the structure and function of nucleophiles and electrophiles.¹⁷ Bhattacharyya and Bodner found that students could define the concepts of Bronsted bases and nucleophiles but could not differentiate between the two when proposing a mechanism.²² Research by Cartrette and Mayo informs that students have a difficult time discriminating between a Lewis nucleophile and a Bronsted base and that students indiscriminately applied labels of nucleophile and electrophile to both Lewis and Bronsted–Lowry acid–base reactions.³⁸ The study by Anzovino and Bretz found that in the absence of a mechanism and/or reaction products students were unable to engage in the task of evaluating whether there was a nucleophile or electrophile involved in the reaction. They also observed that one significant impediment to students’ success in evaluating

Select the correct alternative.



- a. **I** is a nucleophile, **II** is an electrophile, **III** is an acid and **IV** is a base
 b. **I** is an acid, **II** is a base, **III** is an electrophile and **IV** is a nucleophile
 c. **I** is a nucleophile, **II** is an electrophile, **III** is a base and **IV** is an acid
 d. **I** is an electrophile, **II** is a nucleophile, **III** is a base and **IV** is an acid

Figure 1. Example of an item that tested for TO#2.

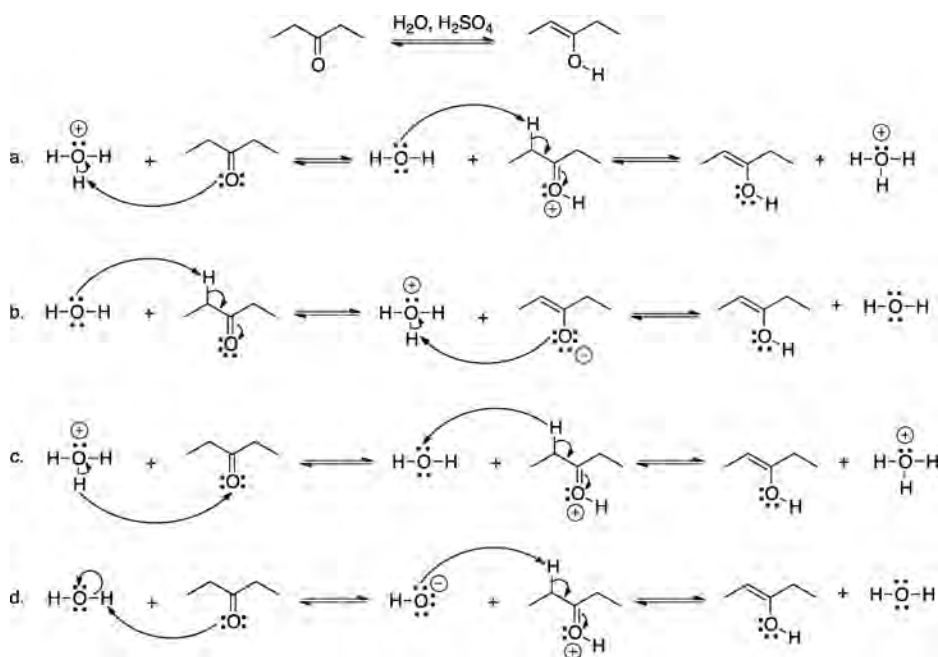


Figure 2. Example of an item that tested for TO#3.

reactions involved a conflation of the ideas of Bronsted acids/bases and nucleophiles/electrophiles.¹⁷

One of the items that tested for TO#2 is included in Figure 1. More examples are included in the Supporting Information. To solve the problem in Figure 1, students should combine the concepts of electronegativity, polarized bonds, formal charge, partial charge, nucleophile, electrophile, Bronsted–Lowry acid/bases, resonance, pi nucleophiles, and nonbonding electrons. Some underlying factors are the excess/lack of electron density; nucleophiles and electrophiles are not always charged; Bronsted–Lowry acid/bases have different functions than nucleophiles/electrophiles, equilibrium, and microscopic reversibility. To support the development of this capability, Anzovino and Bretz recommend discussing the ideas of nucleophiles and electrophiles in the context of function first, rather than emphasizing the structural features.^{16,17}

Success on Items Linked to Terminal Objective 3

Success on items linked to TO#3 turned out to be the second most predictive of success. Mechanisms are at the heart of organic chemistry, and according to these results, it is highly desirable that students develop this capability. Studies inform that students who engage in mechanistic reasoning with transfer of knowledge are better equipped to solve organic chemistry problems.³⁹ Unfortunately, many students have trouble with the electron pushing formalism (EPF)⁴⁰ and often

use this tool to illustrate the formation of a memorized product instead of an explanatory or predictive tool.^{18–21} For example, Battacharyya and Bodner found that graduate students' mechanistic reasoning only relied on a memorized sequence of events without any knowledge of the concepts that lie behind each step. One of the items that tested for TO#3 is included in Figure 2.

To solve the problem in Figure 2, students should combine the following concepts: Bronsted–Lowry acid/bases; equilibrium; acidic and basic media; and EPF.⁴¹ An underlying factor students must consider is that proton transfer equilibrium is established quickly and it favors the formation of the weakest conjugate acid; thus, the hydronium ion is the acid. Also important is that strong bases (hydroxide ion) do not participate in the mechanisms of reactions that occur in acidic media. Grove et al. concluded in their study on mechanistic reasoning that many students are moving through (and passing) organic chemistry courses without learning to use mechanisms. To improve the development of this capability, they recommend that instructors focus on the tools that lead to mechanistic thinking and reinforce them during the course. They state that, if a student does not know what the curved arrows mean fairly early in the course, it is unlikely that he or she will be able to pick it up later.³⁵

Arrange the following substituted benzenes in descending order of reactivity towards a sulfonation reaction.

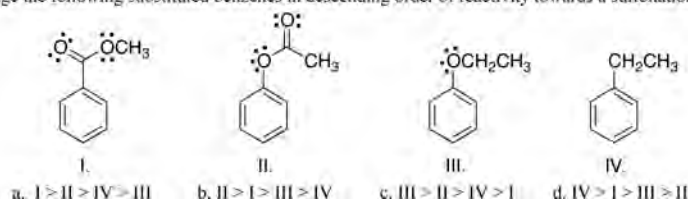


Figure 3. Example of an item that tested for TO#6.

Success on Items Linked to Terminal Objective 6

Success on items linked to TO#6 turned out to be the third most predictive of success. Graulich and Schween identify some difficulties that students may have in the development of this capacity. They state that, when comparing the relative reactivity of two substrates, students could have difficulty explaining the relative stability of the intermediates, but the most complicated step for students could be to rationalize the kinetics using Hammond's postulate.²³

One of the items that tested for TO#6 is included in Figure 3. The solution of this item requires the combination of the following concepts: nucleophile and electrophile; rate-determining step; relative stability of intermediates; resonance and inductive electronic effects; electronegativity; Hammond's postulate; and free energy of activation. One factor that students have to weigh is that the resonance effect of oxygen dominates over its inductive effect. Another factor is that the resonance effect of oxygen attached to the ring dominates over the inductive effect of the ethyl group.

LIMITATIONS AND FUTURE WORK

One of the biggest limitations of this study is that it is based on student answers to multiple-choice items that could have been answered with memorization instead of meaningful understanding. Future work could evaluate the construct validity of these items by requiring students to select the reason(s) for their answers. Another limitation could be that only two items were associated to each TO each year and maybe more items should be considered in future studies.

CONCLUSIONS

The most predictive items identified in this study can be associated with specific capabilities that other investigators deem as important.^{16,17,39,23} Analysis of most predictive exam items provided some insight for instruction into concept combinations and underlying factors that could be determinant of student success.

We believe that the strategy of focusing on the development of a small set of capabilities could lead to a more integrated expert-like organization of knowledge which could help students understand how organic chemistry fits together. Through this approach, we also intend to give students explicit insight into how to use their knowledge in the solution of problems to motivate them to aim for meaningful understanding.^{22,30} There are some indicators of success for this strategy which include student and instructor satisfaction, high class morale, and ease of implementation. Other indicators are the excellent retention of concepts and problem solving capabilities that former students that work as tutors exhibit and the fact that many students express that organic chemistry is their favorite course.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at <https://pubs.acs.org/doi/10.1021/acs.jchemed.9b00568>.

General admission index (GAI) two-tail independent samples *t* test, first semester instructional program, second semester curriculum, discrimination indices of final exam items, linear regression assumptions, linear regression results, final exam items used in assessment (PDF, DOCX)

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Notes

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