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Encouraging Higher-Order Thinking in General Chemistry by Scaffolding Student Learning Using Marzano's Taxonomy

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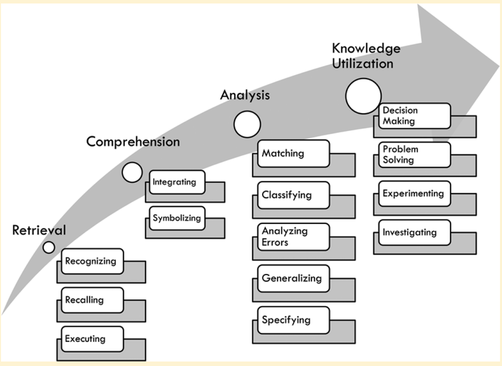
S *Supporting Information*

ABSTRACT: An emphasis on higher-order thinking within the curriculum has been a subject of interest in the chemical and STEM literature due to its ability to promote meaningful, transferable learning in students. The systematic use of learning taxonomies could be a practical way to scaffold student learning in order to achieve this goal. This work proposes the use of Marzano's Taxonomy of Learning. Because it offers a functional way to distinguish lower from higher-order thinking, the taxonomy is particularly useful to instructors interested in helping students develop these skills. We outline and provide examples of how it was used in constructing Student Learning Outcomes (SLOs), class activities, and assessments for a first semester general chemistry course. Preliminary observations of the impact of this methodology on student learning are presented.



KEYWORDS: *General Public, First-Year Undergraduate/General*

There is a strand of the literature in STEM education and chemical education that focuses on the intentional development of students' cognitive abilities.[1−9] The broader literature in teaching and learning has also underscored the importance of intentionally developing such thinking skills.[10−12] These higher-order skills are essential to enable students to more easily transfer their knowledge across courses and more importantly to apply chemistry to new situations.[10,13] In an increasingly complex, dynamic job market, both in chemistry and STEM in general, the ability to respond to new situations is in high demand.[14] After a few years of teaching college chemistry, we assumed we had a solid grip on what constituted higher-order thinking skills; our attempts at articulating what that meant and how to achieve it in the classroom led us to realize that we lacked a rigorous operational framework. One result of not having a framework was that we confused being an instructor that asked "hard" questions with one that developed higher-order thinking in students.

As we sought a way to build these necessary skills methodically in students, we explored the role of learning taxonomies. These can serve as an important tool to scaffold learning and reach higher-order thinking. There are a number of taxonomies that have been developed,[12,15−18] Bloom's as the most common.[15] The focus of the paper is to introduce Marzano's taxonomy, an alternative framework that has not yet made its way into higher education in chemistry. We report here the methodology to redesign a general chemistry first semester course according to the taxonomy in order to target higher-order levels of thinking systematically.

■ MARZANO'S TAXONOMY

Marzano's taxonomy proposes a full theory of learning that integrates the findings from the most recent brain-based learning literature.[17] Though there are three interrelated mental systems in the full theory, the focus of this paper is the cognitive system. Marzano outlines four hierarchically arranged cognitive levels (*retrieval*, *comprehension*, *analysis*, and *knowledge utilization*, Figure 1). *Retrieval* tasks ask students to access information exactly as it was originally presented. *Comprehension* requires that they interpret the information and work to internalize only the most essential/important elements. *Analysis* involves extending their knowledge as they discover new relationships and applications. *Knowledge utilization* focuses on using the knowledge to address more authentic tasks.

There are two key features of Marzano's taxonomy that make it practical and useful for instructors in designing courses. First, the cognitive levels are differentiated based on the degree of cognitive control or intentionality of thought processes needed to complete a task. At one end of the spectrum, *retrieval* tasks require little to no processing as students simply access information from working memory; at the other end, *knowledge utilization* invokes the most significant intentional effort. Marzano's taxonomy is beneficial in the sense that it helps us think about the intrinsic cognitive load[19] we place on our students when asking questions. This puts the idea of asking "hard" questions in a different light. It is not about how hard the question appears (as it is in Bloom's),[15,20,21] it is about how intentional the thought process is as students answer a

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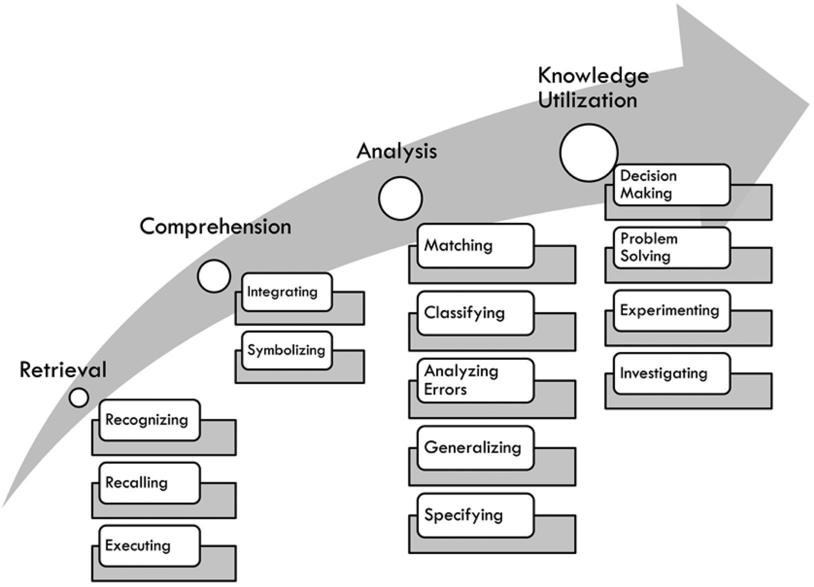

Figure 1. Graphical representation of the cognitive levels in Marzano's Taxonomy arranged hierarchically according to level of cognitive control.

question. If thinking skills is what we are aiming for, by focusing on the thought process Marzano fits this criteria. Complexity does not necessarily imply cognitive control and may thus not be considered higher-order thinking. In a general chemistry course, for instance, a student may be asked to solve a limiting reactant problem and determine the yield of a reaction. While there are many components to accomplishing this task (making it complex according to Bloom), a student solving this question can simply remember an algorithm on how to solve a limiting reactant problem. Because the task is asking them only to reproduce exactly the same algorithm they might have used previously in class (albeit with perhaps different numbers and compounds), it does not require significant cognitive control and is thus lower-order (retrieval) according to Marzano. This taxonomy allows us to classify thinking skills more accurately.[17]

A second key feature of the taxonomy is based on the idea that Marzano designed the cognitive levels to be arranged hierarchically. Not having the ability to retrieve, for instance, will preclude students' ability to successfully address *comprehension* tasks. Looking at the hierarchy more broadly yields an additional benefit to support the use of Marzano. The lower two levels require accessing and making sense of *existing* knowledge, while the upper two levels involve creating *new* knowledge. This serves as a clear, consistent, and straightforward functional delineation between lower and higher-order thinking skills. Thus, Marzano's taxonomy addresses the criticism associated with other taxonomies with a looser hierarchical structure.[18,20,21] These two features made the adoption of Marzano's framework practical to achieve our goals.

■ IMPLEMENTATION

Building Scaffolded Student Learning Outcomes

Course design, instruction, and assessment should aim to target these skills strategically and intentionally by providing the proper scaffolding for students, a key characteristic that has been shown to enhance learning.[11,22−30] Here we describe the process of designing a course with Marzano's taxonomy as a scaffolding framework. The resultant course was taught in two sections of a first-semester general chemistry class (75 min, 2 days a week) using an Atoms First book with a total of 37 students combined in the fall of 2014. Note that the demographics of the course mirror those of the institution (Supporting Information Document 4). Our redesigned course began with the drafting of student learning objectives (SLOs), written using a structure similar to the one presented by Marzano.[31] Initially, we crafted benchmark goals, broad descriptions of what students should understand. For instance, in the general chemistry curriculum, one of our benchmark statements read "Students will be able to understand the concepts associated with molecules and ions (mono atomic and polyatomic); and symbolically depict them using commonly used chemical models." This type of statement is not intended to be measurable and it clearly includes a broad number of topics. The benchmark statement is then broken down into essential topics necessary to achieve the benchmark. In this context, we refer to these as knowledge foci (KF). A couple of KF associated with the benchmark above were the following: KF1, *Symbolic representations of ions, ionic and molecular compounds*, and KF2, *Polarity and electronegativity*. Now that the benchmark was not so daunting, the KF was used to guide the drafting of the specific SLOs. Each KF was then broken down for each of Marzano's cognitive levels into measurable objectives, referred to as SLOs. Table 1 captures an example of SLOs for KF-1.

The *retrieval* and *comprehension* SLOs are statements that refer to students making sense of existing knowledge provided by either the text or the instructor. In contrast the *analysis* SLO qualifies as creation of new knowledge (higher-order skill) when students are not merely repeating a Lewis dot structure of a substance they had already been exposed to and also explaining how they went about constructing such structure. As we drafted the SLOs for the course we had to remain aware of Marzano's way of distinguishing lower vs higher-order objectives. For a comprehensive list of benchmarks, KF and SLOs for this general chemistry course see Supporting Information Document 1. After drafting SLOs at each cognitive level for each KF, we identified the most appropriate cognitive level to target. Not all targets in our class aimed at higher-order analysis and/or knowledge utilization, though we are aware the transfer of knowledge is more likely when students engage in

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Table 1. Sample Student Learning Outcomes Structure

Benchmark statement: *Students will be able to understand the concepts associated with molecules and ions (mono atomic and polyatomic); and symbolically depict them using commonly used chemical models.*
KF-1 *Symbolic representations of ions, ionic and molecular compounds*

Cognitive Levels	SLOs: Students Will Be Able To···
Retrieval	list the rules for drawing Lewis dot structures of ions/compounds
Comprehension	explain the reasoning behind each of the rules for drawing Lewis dot structures
Analysis	draw an accurate Lewis dot structure of a substance starting from either its chemical formula or its chemical name by giving consideration to the octet rule, its exceptions, the rules to draw Lewis dot structures, and explain the reasoning for their answer.
Knowledge utilization	Not applicable[a]

[a] For this class, some of the KF did not include *knowledge utilization* SLOs. This was a choice based on the nature of an introductory course, but this is a matter of instructor discretion.

higher-order thinking.[13] This is a matter of instructor discretion. Comparing our taxonomy-driven SLOs to our loosely formed notions of learning objectives from before, we realized we often miscategorized lower-order objectives as higher-order and vice versa.

Marzano's taxonomy helped us develop SLOs systematically, so we ended up with a roadmap that consisted of target SLOs and supporting SLOs that underlie those targets. Intentionally thinking about what students should know at a foundational cognitive level and the specific steps they had to take to reach the desired level of mastery changed how we approached instruction, forcing us to think about the scaffolding. When we looked back at our instruction prior to having this roadmap, we realized how often we skipped instruction of the supporting SLOs (those at the *retrieval* and *comprehension* levels of understanding) when targeting *analysis* levels. When we jumped directly into *analysis* and/or *knowledge utilization* goals without the baseline understanding, it became clear why students rarely achieved success on those tasks.

Scaffolding Instruction

The roadmap was used to plan daily activities to maintain proper scaffolding. The first day of class typically involved consolidating students' understanding at the *retrieval* and *comprehension* level with an emphasis on *comprehension*. The second day on the chapter/unit consisted primarily of constructing *analytical* knowledge by students, though there was usually some cleanup on *comprehension*. Each activity was explicitly mapped to a particular SLO at a specific cognitive level. The taxonomical distinction allowed us to realize that some instructional practices were well-suited to develop certain cognitive levels, while other practices were more effective when used to target a different cognitive level. A one-size/one-type instructional method simply did not work. For instance, the *retrieval* SLO (Table 1) was targeted via short multiple choice quizzes or prompts focused on listing the rules for drawing Lewis dot structures. When developing *comprehension* for the same KF students refined their understanding of the reasoning behind the rules of Lewis-dot structures via interactive lecture. The *analytical* SLO in this KF required more cognitive control and thus extended processing time as students struggled with applying their understanding to a new context they had not seen before. Because interactive lecture does not typically allow sufficient individual and collective processing time, other methods such as jigsaw (students are put in groups and asked to develop expertise on one component of a topic and then each group explains their assigned component to the rest of their classmates), or similar collaborative learning exercises coupled to peer-reviews of each other's work were better suited for this task. There were also times when class activities worked more effectively for certain groups. Another benefit of having the roadmap was that we now had the ability to push these groups beyond the original desired target outcome, harnessing the benefits of differentiated instruction.[10,11,32]

Scaffolding Assessments

The fully articulated list of SLOs were used as a guide to prepare the corresponding formative and summative assessments. We mapped each question/exercise/problem in these assessments to the corresponding KF and cognitive level. This ensured our assessments were aligned with the expectations set forth in the SLOs, and thus kept us honest and transparent in expecting of students only what we had told them we expected.

In this course, formative assessments consisted of short weekly quizzes (2−3 constructive response questions) graded for purposes of feedback only to give students a sense of how well they understood the material at any given cognitive level. Summative assessments (unit/final exams) were explicitly divided into three sections according to the first three cognitive levels of the taxonomy. Questions covered supporting SLOs or target SLOs, but nothing at a cognitive level higher than the target. In this course, a 1 h and 15 min exam included three retrieval questions, four comprehension questions, and five or six analysis questions (constructed response). To emphasize higher-order thinking skills, the number of questions on any given exam was skewed toward those that required higher-order thinking. Additionally, lower cognitive level questions (*retrieval* and *comprehension*) were given less weight than higher-order questions (*analysis* and *knowledge utilization*). Supporting Information Document 2 provides a sample unit exam. When writing these exams we had to keep in mind that higher-order questions must involve creating *new* knowledge. If a question asked students to explain/reproduce the analysis done by the instructor or the textbook, it would no longer be classified as an *analysis*-level question.

Feedback for Students and Faculty

In addition to intentionally targeting higher-order thinking, the use of this exam structure also generated valuable results to improve instruction. For example, when a student was unsuccessful answering an *analysis* question over a specific concept, we could see if *comprehension*-level questions on the same concepts were successful. If they were successful, it could be taken as an indication that there was a gap in analytical thinking. However, when the *comprehension* question is also incorrect, it could imply a more significant deficiency in understanding. Using this information, we had the ability to potentially diagnose student learning more precisely, either individually or as a class, and subsequently design more targeted interventions or revisions to teaching strategies within the semester. This information was also aggregated for all exams and used to uncover themes regarding student struggles on content and/or thinking skills for use in redesigning or refining future courses.

Students also had access to this rich feedback, and could use it to see where their understanding broke down for a given SLO (i.e., monitoring their success/failure at each cognitive level).

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Students quickly realized that learning strategies necessary to master a concept at *retrieval* are fundamentally different from those required to master a concept at the *analysis* level. Students could then adapt their learning strategies in order to develop proficiency when given such feedback. This made for more productive conversations between us and the students when trying to help them achieve their goals for the course.

■ EARLY OBSERVATIONS

The type of data and the methods for data gathering for this section of the paper were examined by our institutional review board (IRB) as to whether it appropriately followed all guidelines related to human subject research. IRB approval was obtained for the work described herein. It is important to note that data presented here corresponds only to students that completed the course and therefore took all the unit exams and the final exam. All formative and summative assessments were graded using a 4-point rubric that indicated if a student was correct, had a minor error, a major error or showed multiple major errors. The grades presented in this section are according to the scale in Table 2. Note this is not a GPA based scale and was used for internal purposes in the class only. All grades from Tables 2 and 3 correspond to grades as assigned and not converted from a letter grade.

Table 2. Average Performance on Exams by Cognitive Level

Cognitive Level	Unit Exam 1[a,b]	Unit Exam 2[a,b]	Unit Exam 3[a,b]	Final Exam[a,b]
Retrieval	3.13	1.84	2.32	2.72
Comprehension	2.27	1.82	1.87	2.52
Analysis	1.84	1.78	1.48	2.08

[a]Scores are based on a 4-point grading rubric where a grade of A = 3.2−4.0, B = 2.5−3.19, C = 1.8−2.49, D = 1.30−1.79, F = <1.30. [b]N = 37.

Student Performance on Summative Assessments

If Marzano's model holds and cognitive levels are hierarchical based on cognitive control, one would expect to see better performance on summative assessment questions for lower cognitive levels relative to higher cognitive levels. Because each question on each exam was mapped to specific cognitive levels (as described in the previous section), the average student performance for both sections of the course can be calculated for the first three cognitive levels for each unit exam and the final exam (Table 2). Note that knowledge utilization was not part of this analysis since it was only applicable in certain SLOs and was not part of all the exams. The data suggests this to be true: students on average perform better at *retrieval* questions, and that on average they perform better on *comprehension* questions than *analysis* level questions. This is consistent for all exams.

To assess improvement in higher-order thinking skills upon completion of the course, each question on the cumulative final exam was also mapped to specific cognitive levels. Table 3 reports average student score by cognitive level on all the unit exams versus the cumulative final exam. The data shows an improvement on student performance regardless of cognitive level with statistically significant gains at all levels, including *analysis* in spite of the increased cognitive load associated with such questions. A rough translation from the rubric-based scoring to a traditional scoring method suggests that students showed a 4.1 absolute percentage point gain (nearly 1/2 a letter grade) in *retrieval*, a 7.7 absolute percentage point gain in *comprehension*, and a 6.9 percentage point gain in *analysis*. Normalized learning gains (NLG), which represent the percent total possible gain that students could have had in the course [(%post − %pre)/(100 − %pre)], are also reported.

Table 3. Improvement in Student Performance by Cognitive Level

Measure	Scores[a,b] by Cognitive Levels[a]		
	Retrieval	*Comprehension*	*Analysis*
All unit exams (average)	2.43	1.99	1.70
Final Exam (average)	2.72	2.52	2.19
Absolute Gain	0.29[c]	0.54[d]	0.48[c]
NLG	0.18	0.27	0.21

[a]N = 37. [b]Scores are based on a 4 point grading rubric where a grade of A = 3.2−4.0, B = 2.5−3.19, C = 1.8−2.49, D = 1.30−1.79, F = <1.30. [c]$p < 0.1$. [d]$p < 0.01$.

Prior to teaching our courses without using this assessment model, only one aggregate number was identified to capture student performance: an overall exam score. This ignored the multitude of SLOs assessed as well as the cognitive level evaluated. Analyzing data according to the new model generates much richer insight. For SLOs that were tested on the unit exam and retested on the final, students improved on 50% of the SLOs tested at the *retrieval* level, as well as the *comprehension* level. Student performance improved on 91% of the SLOs that were retested at the *analysis* level. This allowed us to identify which specific SLOs required adjustment in instructional strategies. For instance, in *analysis* level SLOs, the SLO with the largest improvement was on the topic of bonding suggesting that no major adjustments were needed for the next semester version of the course. Meanwhile performance actually regressed on the SLO that focused on molarity and serial dilutions. This opened up a series of question regarding the treatment of this SLO: did we spend enough time on it? Were the instructional strategies the most appropriate? Were there gaps in the feedback?, etc. Simply mapping exam questions results in more actionable data that helped us be more effective as instructors.

Student Performance Pre/Post Intervention

As a robustness check, students were also administered a pre/post multiple choice exam, a selection of questions from the ACS "First-Term General Chemistry" exam (Form 2012), chosen based on SLOs. For the pre-test, students were given 60 min of class time to complete the exam on the first day of the semester. The time was chosen proportionally to the number of questions using the guidelines given for the original ACS exam. The same exam was administered again immediately after students have taken a comprehensive final exam designed by the instructor as a post-test with a 60 min time limit.

As reported in Table 4, the data shows statistically significant absolute and normalized learning gains from pre- to post-test. However, looking only at statistical significance ignores any practical impact of the course design inspired by Marzano's taxonomy.[33] The magnitude of the improvement matters, and is widely measured using Cohen's D effect size.[34] The effect size is 1.48 for both sections combined, meaning that the mean of the post-test was 1.48 standard deviations above the mean of the pre-test. Another way of looking at this is 92% of student scores in the pre-test would be below the average student score in the post-test.[34] While the ACS exam questions were not

Table 4. Summary Exam Data on Learning Gains

Measure	Results, $N = 33$
Pre-test	25.28%
Post-test	43.98%
Gain	18.70%[b]
NLG	25.14%
Effect Size[a]	1.34

[a] Effect size measured using Cohen's D. [b] $p < 0.01$

separated or mapped by cognitive level, this preliminary examination shows clear gains, consistent with the comparison between unit and final exam scores. Unfortunately, the practice of administering ACS exams was not in place prior to the implementation of this new course design so we were unable to do a comparison with "regular" courses. Another important thing to note is that, although gain is evident, the raw performance is below 50%. Note that this is a percent of correct answers not a percentile. Possible reasons for this poor overall performance could be attributed to the particular demographics of the sample of students in the course or due to fatigue based on the timing of the post-test. Without a rigorous analysis of these elements and a norming of the administered test, conclusions are difficult to make.

Student Perceptions

Student perceptions of the course were measured at the end of semester with an anonymous survey administered prior to the final. While the survey contained numerous questions, those pertaining to the learning gains associated with elements of course design with Marzano's taxonomy are presented in Table 5. Students chose among five responses: no gain, little gain, moderate gain, good gain, and great gain. As it relates to the use of SLOs, a vast majority of students perceived that the use of SLOs and the alignment of these SLOs to all course materials positively impacted their learning (questions a and b in Table 5). Students could optionally add short responses to justify their choices. Many remarked on the helpfulness of the approach generally, and often stressed the value of the SLOs as a study guide and a tool that helped clarify expectations for the course (see a selection of comments on Supporting Information Document 3).

Table 5. Results from an Anonymous Survey of Student Perceptions

	Degree of Gain, % ($N = 27$)	
Survey Statements for Student Response	Gain[a]	High Gain[b]
a. How much did having SLOs to guide your studying impact your learning?	81%	52%
b. How much did the alignment of SLOs, in-class activities, assignments and exams impact your learning?	74%	48%
c. How much did the emphasis on scaffolding learning—moving from retrieval to comprehension to analysis to knowledge utilization (Marzano's Taxonomy) impact your learning?	70%	44%

[a] Corresponds to the percentage of students that marked their learning gain as moderate, good, or great. [b] Corresponds to the percentage of students that marked their learning gain as either good or great.

Students were also asked to rank and discuss the effectiveness of scaffolding. Again, a vast majority found it to be helpful (question c in Table 5). The comments further emphasized the overwhelming support from students toward the use of SLOs and Marzano's taxonomy to scaffold their learning. A student highlighted the usefulness of scaffolding by saying "...the scaffolding helped to build a topic starting basic and expanding, leading to a better understanding. The emphasis on mastery allowed opportunity to reevaluate problems and see my own mistakes as well as learn how to fix them." Another student commented on the use of Marzano's by saying "...I also liked having the scaffolding because if I couldn't do a higher level problem, I could go back to retrieval or what not and figure out where I went wrong."

When students were asked to choose the three elements of the course (out of nine possible choices) that most contributed to their learning, use of SLOs and alignment of SLOs were frequently chosen (48% and 41% of the time respectively, Table 6). While the emphasis on scaffolding and the emphasis on mastery did not rank as often in the top 3 (11, 33%, respectively), this could be due to the more abstract nature of these elements when compared to other elements such as the use of rubrics. Further work must be done in this area to find out how to help students find further relevance on these interventions. Nonetheless, the results are encouraging.

Table 6. Results from an Anonymous Survey of Students' *Ranking* on the Perceived Impact on Their Learning of Certain Aspects of the Course Design

	Course Elements Selected as Most Helpful[a], % ($N = 27$)			
Which of the Following Elements of the Course (Maximum of 3) Were the Most Helpful for Your Learning?	Use of SLOs	Alignment of SLOs to Activities, Assignments and Exams	Emphasis on Scaffolding	Emphasis on Mastery
1. Use of SLOs	48%	41%	11%	33%
2. Alignment of SLOs to activities, assignments, exams				
3. Emphasis on scaffolding				
4. Active learning				
5. Emphasis on mastery				
6. Descriptive grading scale				
7. Use of rubrics				
8. Pace of class				
9. Grade updates				

[a] Corresponds to the percentage of students that included the given item as one of their top three choices from a list of nine possible options of course elements.

The data presented above summarizes the outcomes of the initial implementation of Marzano's taxonomy and is not intended to be a rigorous statistical analysis to evaluate the efficacy of the intervention. Future work will aim at refining the methodology and performing statistical investigations on its efficacy and test the broad applicability of this methodology across other types of institutions.

■ CONCLUSIONS

A search for a framework that allowed us to properly scaffold instruction and intentionally target higher-order thinking skills culminated in the adoption of Marzano's taxonomy. We designed a first-semester general chemistry course using this research-based framework that we found to be intuitive. It provided a clear delineation between lower and higher-order thinking that then informed the development of scaffolded SLOs, class activities and assessments. By mapping assessments using this framework, students and faculty were able to get more actionable feedback. Preliminary observations with respect to exam results and student perceptions suggest this is a promising framework.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00184.

Document 1, sample Student Learning Outcomes (SLOs) (PDF, DOCX)

Document 2, sample exam (PDF, DOCX)

Document 3, selection of students' comments (PDF, DOCX)

Document 4, brief description of the institution's profile (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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