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Developing and Implementing an Assessment Technique To Measure Linked Concepts

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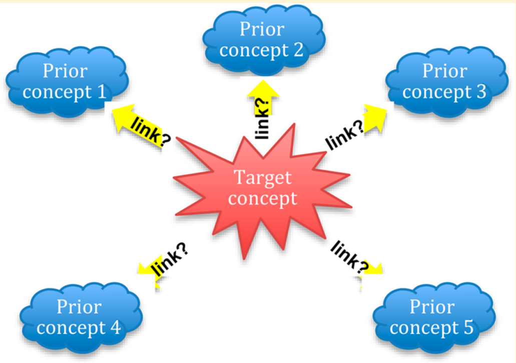
Ⓢ *Supporting Information*

ABSTRACT: The links students make among chemistry content is considered essential for a robust, enduring understanding in multiple learning theories. This article describes the development and implementation of an assessment technique, termed a Measure of Linked Concepts, designed to inform instructors on students' understanding of linking content throughout General Chemistry. Student performance on the assessment technique has provided unique insights relevant for instruction. For example, a substantial proportion of students could not identify when a model was used beyond its intended limit or show proficiency in tasks that the course assumed was prior knowledge. The use of these assessments also provides a means for instruction to show the relevance for topics such as periodic trends or ionic/molecular classification in a variety of subsequent topics throughout the course.



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■ INTRODUCTION

Student learning is aided by the conceptual links that can be made between newly learned content and students' existing conceptual knowledge. Ausubel's Assumptive Learning Theory describes meaningful learning as when the learner actively incorporates new knowledge to prior knowledge.[1] This is in contrast to rote learning, where new knowledge is memorized in isolation and not connected to other related content. Meaningful learning is further characterized by long-term retention of concepts, whereas rote learning would only yield short-term retention. In considering lasting impact, efforts in education should be directed toward facilitating meaningful learning while minimizing any emphasis on rote learning. Other learning theories or perspectives also emphasize the importance of making connections within course content. First, the Knowledge Integration Perspective emphasizes the importance of developing a coherent view of scientific phenomena versus the transmission of fragmented scientific knowledge.[2] Second, deep learning has been operationalized as holistic where knowledge is understood within its context as compared to surface learning, which is described as atomistic.[3] Finally, the description of constructivism emphasizes the match of new concepts with the learner's previous conceptual knowledge.[4] Returning to Assumptive Learning Theory, efforts to promote meaningful learning are supported by assessments that measure students' understanding of the context of content.[1] This paper introduces an attempt to build an assessment designed for large lecture General Chemistry classes that emphasizes the linking of content within General Chemistry.

This work is also informed by diSessa's contention that students' knowledge is fragmented and heavily dependent upon context.[5] The assessments proposed seek to provide a method for revisiting prior concepts in different contexts that can allow instructors insight into these perspectives. Also, by placing concepts in different contexts, students can begin to demonstrate a more sophisticated understanding of concepts beyond application in the scenario as presented by instruction and begin to consider application throughout the diverse range of concepts in General Chemistry. This development of a more sophisticated conceptual understanding is in line with Stevens et al. model of learning progression by further exploring the utility of prior concepts.[6]

■ BACKGROUND

Developing assessment techniques to match educational goals is an important area for multiple reasons. First, students direct their efforts toward how they are assessed.[7] Thus, an assessment technique that emphasizes linking new concepts with existing concepts has the potential to promote students' efforts to do the same while reinforcing an instructor's efforts to facilitate such linking. Second, assessments serve as the primary vehicle by which instructors learn about students' conceptions.[8] By building an assessment that emphasizes linking concepts,

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instructors can better understand the effectiveness of their instructional efforts to achieve this goal. Third, assessments provide feedback to the students regarding their progress in the course. By incorporating questions related to the linking of concepts, students can better understand their own progress on building these links.

The most widely known assessment technique for linking concepts is concept maps. Concept maps were originally proposed by Novak as a research tool to investigate student conceptions, and they have subsequently been used as a classroom assessment technique.[9] In a concept map, students are tasked with linking two concepts with an arrow and a proposition, a single word or short phrase that describes the nature of the link of the two concepts. As an assessment technique, there is considerable variety in terms of administration methods and scoring techniques.[10] Some scoring techniques emphasize the organization of concepts and the extent hierarchies are present, whereas others focus primarily on the validity of the propositions presented.[9,11]

Another assessment technique designed to promote linking of concepts is Creative Exercises.[10,12] Creative Exercises involve providing a prompt to students that describes a chemical situation, such as the "oxidation of 25.0 grams of iron." Students are encouraged to write down as many statements as they can that are relevant to the prompt and the material covered in class. Students are scored based on the number of correct and distinct statements they can create. Investigating student responses to a set of Creative Exercises showed that student responses were able to describe a wide range of chemistry content related to each prompt.[13] It is inferred that students' ability to do so is representative of the links they form among the content in General Chemistry.

Concept maps and Creative Exercises are necessarily open-ended assessment techniques, defined as assessments that have more than one or a small set of possible right answers. Students respond to open-ended assessment based on the information they deem most relevant and each student can have drastically different responses to a single prompt and each may score well on the assessment. There are many advantages with an open-ended setup that include learning the information that the student deems most relevant and providing the student the opportunity to organize information in the student's response to the assessment.

However, there are some drawbacks to open-ended assessments. First, they cannot target a particular concept. If, for example, an instructor wanted information on students' understanding of electron configurations as they relate to quantum numbers, an open-ended assessment can provide some evidence for those students who chose to show this link. For students who choose to provide alternative information (e.g., relate electron configurations to chemical reactivity instead), little can be concluded regarding these students' understanding of the link to quantum numbers. Second, open-ended assessments cannot provide information on the prevalence of concepts. For example, in Creative Exercises it was found that students would incorrectly use the ideal gas law on chemicals that were not in the gaseous state.[13] Although a subset of students indicated this incorrect link of concepts, it is not known how widespread this incorrect link is among students. Finally, as an open-ended assessment, grading can become logistically problematic for very large classes or assessing multiple classes, in particular, when the assessment technique is regularly used.

Creating a series of closed-ended assessments that measure students' abilities to assess the linking of concepts within a course can address these drawbacks. Such a closed-ended assessment loses the student generation of links, which can only be achieved with open-ended assessments. Closed-ended assessments also have limitations in that students can be scored correctly through chance, by guessing the correct answer. Additionally, in closed-ended questions, students may identify a correct answer through test-taking strategies unrelated to conceptual understanding or select a correct or incorrect answer for a different reason than the instructor's intent.[14,15] However, closed-ended assessments can target specific concepts and thus have the ability to determine the prevalence of students' understanding of these concepts. Closed-ended assessments can also benefit from automated grading that facilitates implementation in large classes or across multiple classes and minimizes the potential for grader error. The goal of this article is to present closed-ended assessments designed to measure the linking of concepts as a potentially useful instructional tool in chemistry. Toward that end, this article will describe the methodology in developing and administering the assessments and discuss student results from the assessment in terms of instructional implications.

■ METHODOLOGY

To develop an assessment that measures the prevalence of students' abilities to link specific concepts, a series of closed-ended assessments, termed Measure of Linked Concepts (MLCs), have been developed. In this work, the term *concept* follows Taber's perspective of conceptual knowledge as any knowledge that is meaningful.[16] Meaningful knowledge has an explanatory value that is often shown by describing the relationships to other content and is opposed to learning facts in isolation. In this method, stoichiometry can be learned in isolation as a memorized algorithm, but becomes conceptual when students can understand the value of stoichiometry in a range of situations. The term *linking* then is used to describe the relationships between concepts. In this case, the linking occurs in content throughout the course of General Chemistry, though linking with students' everyday experiences and content knowledge in other courses are certainly fruitful areas for researchers to explore. The MLCs then are designed to measure the extent students can link a newly learned target concept with prior concepts throughout the course.

The design of an MLC is to provide an initial description of a chemical situation to students similar to the design of Creative Exercises.[10] Next, students are given a series of statements that are related to the prompt that span the content of the course. The statements are based on student responses to Creative Exercises that have been collected in previous research and can be either correct or incorrect links of content.[13] The statements are also designed to span the content of previous topics in the course. Six instructors of General Chemistry reviewed the MLCs presented here prior to their use in exams. Instructors who are interested in designing their own MLCs would be encouraged to use learning objectives associated with each major topic (e.g., chapter in the textbook) and attempt to have at least one statement per major topic. Students are given instructions to evaluate each link as either true or false, in essence providing students a task very similar to grading another student's response to a Creative Exercise. The MLC also has the benefit of incorporating material learned earlier in the course (e.g., before the previous test), which rewards students for retaining information throughout the course. MLCs can be used in a variety of instructional contexts such as activities within group work, as homework or part of an exam. When the MLC is incorporated within a traditional assessment it is recommended that each statement is given less weight than the conventional test questions owing to the higher likelihood of guessing correctly with true/false statements. In the results discussed below, each MLC statement is rated as either one-third or one-half the weight of a single multiple-choice question. Instructors who are concerned about the higher likelihood of guessing correctly may consider offering students a third answer choice of "I'm not sure" where students who select it receive partial credit on the question (e.g., one-third of the points possible).

An example of an MLC with the instructions given to students is shown in Box 1. One MLC each was incorporated into four homework assignments and four in-class tests throughout a semester of General Chemistry I at a large university. At the setting 1,653 students initially enrolled in General Chemistry I and the exams were administered at a common time for all students. For the homework assignments, an MLC was written into the Sapling Learning online homework system and the homework assignments were staggered such that students saw one MLC prior to each test. This was done to familiarize students with the assessment technique prior to seeing MLCs on the in-class tests, which serve as high stakes assessments in terms of course grades. Students were permitted up to ten attempts on each of the homework MLCs and received credit if they answered all of the prompts correctly. Alternatively, students could choose to view the solution to the homework MLC and would then not receive any credit.

Box 1. Example of an MLC Used within an Exam

Consider an atom of sulfur. Indicate whether each statement about an atom of sulfur is true (A) or false (B)

1. It is more likely to gain electrons than silicon.
2. Its last electron is found in an "s" orbital.
3. It has an electron in $m_s = +1/3$.
4. The greater number of protons in its nucleus causes a sulfur atom to be larger than an aluminum atom.
5. It has six valence electrons.
6. Has a higher tendency to lose electrons than magnesium.
7. Sufficiently bright light below the threshold frequency will cause an electron to be emitted.

Table 1. MLC1

Prompt: An Atom of Sulfur			
	Statements (Correct Answer)	Correct Responses, %[a]	Correlation with Total
1	It is more likely to gain electrons than silicon (True)	87%	0.600
2	Its last electron is found in an "s" orbital (False)	97%	0.297
3	It has an electron in $m_s = +1/3$ (False)	97%	0.230
4	The greater number of protons in its nucleus causes a sulfur atom to be larger than an aluminum atom (False)	72%	0.563
5	It has six valence electrons (True)	93%	0.432
6	Has a higher tendency to lose electrons than magnesium (False)	79%	0.580
7	Sufficiently bright light below the threshold frequency will cause an electron to be emitted (False)	69%	0.557
Total		85%	

[a] N = 1587.

Table 2. MLC2

Prompt: A Molecule of PCl_5			
	Statements (Correct Answer)	Correct Responses, %[a]	Correlation with Total
1	PCl_5 is phosphorus pentachloride (True)	96%	0.224
2	The molecule has sp^3 hybridization (False)	93%	0.375
3	When the preferred Lewis structure is drawn, no lone pairs appears on P (True)	93%	0.429
4	The bond between P and Cl is polar (True)	82%	0.360
5	Cl has a larger atomic radius than P (False)	67%	0.536
6	Its electron configuration is $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^2 4d^2$ (False)	52%	0.328
7	Its molecular geometry is trigonal bipyramidal (True)	89%	0.437
8	PCl_5 is a polar molecule (False)	59%	0.435
9	Cl has higher first ionization energy than P (True)	78%	0.382
Total		79%	

[a] N = 1533.

■ RESULTS AND DISCUSSION

The results from the four MLCs given as in-class tests are presented in Tables 1 through 4. The four homework MLCs are presented as Supporting Information. The curriculum follows an atoms-first approach where the content first introduces the structure of the atom, quantum numbers, electron configurations, and periodic trends for the first in-class test. On this in-class test, the corresponding MLC1 is presented in Table 1. In the content for the next in-class test, models of bonding are introduced with an emphasis on covalent bonds, Lewis structures, molecular shapes, and polarity, with the corresponding MLC2 described in Table 2. Following this are thermodynamics, the Born−Haber ionic bonding model, gas laws, and intermolecular forces (MLC3 in Table 3). The last topics covered are solid-state chemistry, units of solution concentration and colligative properties (MLC4 in Table 4). This curriculum assumes prior knowledge of atomic structure, nomenclature, stoichiometry, and reactions in solution from previous chemistry courses. MLCs could be developed for additional curricular models focusing on the content previously covered in the course at each assessment. Within each MLC, the intention was to link each statement with the prompt but to avoid statements that were dependent on other statements so that students missing one statement would not necessarily miss others.[15]

The content in MLC1 (Table 1) necessarily has less linked content throughout the course given its early placement in the semester, still as one assessment it can incorporate numerous concepts related to quantum numbers and periodic trends. Student results indicate high performance with many of the statements, but students had less success with the MLC1 statements related to periodic trends (statements 4 and

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Table 3. MLC3

Prompt: 20.0 g of $ZnCl_2$ dissolves in water as $ZnCl_2(s) \rightarrow Zn^{2+}(aq) + 2Cl^{-}(aq)$ in 5.25 L of water initially at 25.0 °C (assume the density is 1.0 g/mL). $H_f(ZnCl_2) = -415.1$ kJ/mol, $H_f(Zn^{2+}) = -152.4$ kJ/mol, and $H_f(Cl^{-}) = -167.46$ kJ/mol

	Statements (Correct Answer)	Correct Responses, %[a]	Correlation with Total
1	The reaction is exothermic (True)	76%	0.423
2	$ZnCl_2$ is zinc dichloride (False)	19%	0.298
3	$ZnCl_2$ is a covalent compound (False)	63%	0.437
4	ΔH for the reaction is −72.22 kJ/mol (True)	56%	0.441
5	The pressure determined by $PV = nRT$ is 0.684 atm (False)	31%	0.273
6	The electron configuration of Zn^{2+} is [Ar] $3d^{10}$ (True)	54%	0.361
7	Ion−dipole interactions are present in the products (True)	71%	0.339
8	The molar mass of $ZnCl_2$ is 136.3 g/mol (True)	95%	0.157
9	After the reaction, the temperature of the surrounding water will be less than 25.0 °C. (False)	66%	0.406
10	A neutral Cl atom has a greater atomic radius than a neutral Zn atom (False)	79%	0.368
Total		61%	

[a] $N = 1419$.

Table 4. MLC4

Prompt: A solution of 9.0 g NaBr and 74.8 g methanol (CH_3OH) at STP. Assume that NaBr completely dissociates in methanol. Boiling point of methanol = 64.6 °C; K_b(methanol) = 2.7 °C/m. Electonegativity values: C = 2.5, H = 2.1 and O = 3.5

	Statements (Correct Answer)	Correct Responses, %[a]	Correlation with Total
1	Ion−dipole interactions are present in the solution (True)	78%	0.304
2	The boiling point of the solution is 70.9 °C (True)	48%	0.259
3	The pressure equals 0.215 atm (False)	71%	0.493
4	The carbon in CH_3OH is sp^3 hybridized (True)	87%	0.367
5	In the preferred Lewis structure of CH_3OH, oxygen has a formal charge of −1 (False)	75%	0.461
6	NaBr dissociates to form Na^{2+} and Br^{2-} (False)	73%	0.480
7	CH_3OH contains nonpolar bonds but is a polar molecule (True)	68%	0.334
8	An atom of sodium has greater electron affinity than bromine (False)	69%	0.453
9	$\Delta H_{solvent}$ arises from the hydrogen bonding between methanol molecules (True)	71%	0.337
Total		71%	

[a] $N = 1354$.

statement 6, abbreviated MLC1.4 and MLC1.6, respectively) and the photoelectric effect (MLC1.7). In Table 2, the building of the content becomes more evident as MLC2.5 and MLC2.9 relate to periodic trends and statement 6 relates to electron configurations. MLC2.6 describes an electron configuration for PCl_5 using the number of valence electrons. As 48% of students incorrectly assigned the statement as true, there is an indication that students do not understand the limits of the model for electron configuration. This phenomenon is analogous to the generalization heuristic where students recognize patterns but not the conditions in which the pattern is applicable.[17] It may be expected that the introduction of valence bond theory, in particular, orbital hybridization, may make the case, directly or indirectly, that electrons in molecules are not building within the same electron configuration. The results indicate this is not the case. In contrast, 93% of the students were able to correctly evaluate the hybrid orbital given in MLC2.2 regarding the same molecule. Thus, it appears students are able to employ the algorithm presented regarding orbital hybridization, but they are considerably less likely to understand the implications this model has for electron configurations. It is also worth noting that students saw a similar statement on electron configurations in molecules in the preceding Sapling HW assignment HWMLC2.5 (see Supporting Information).

The MLC presented in Table 3 occurs later in the term and targets a range of concepts including thermodynamics (MLC3.1, MLC3.4, and MLC3.9), nomenclature (MLC3.2), models of bonding (MLC3.3), gas laws (MLC3.5), intermolecular forces (MLC3.7), electron configurations (MLC3.6), stoichiometry (MLC3.8), and periodic trends (MLC3.10). The revisiting of multiple concepts within a single assessment given later in the term can reward students for retaining earlier information as described earlier. The percent correct on nomenclature (19%) is the lowest among any of the MLC statements. As mentioned, nomenclature was not covered specifically in this course; instead, it was assumed that students would enter the course with this knowledge well established from preceding courses. The low percent correct makes this assumption questionable and may call for revisiting it. MLC3.5 on gas laws further explores student understanding of the limits of models. The prompt provides information on volume and temperature of water and moles of a compound, though none of the compounds present are in the gas phase. The majority of students (69%) described this prompt as true, which matches the review of student responses to Creative Exercises where the use of gas laws in incorrect situations was prevalent. Past research has called for instruction to explicitly address the limits of models,[18] but it appears prudent to also recommend assessment practices, such as MLCs, that measure student understanding of the limits of models.

In Table 4, this MLC was given as part of a cumulative final exam in the course. The emphasis at the end of the semester was on colligative properties (MLC4.2) and the model for solution formation (MLC4.1 and MLC4.9). MLC4.6 was also related to colligative properties given the emphasis on writing dissociation reactions in understanding the van't Hoff factor. This MLC also covered gas laws (MLC4.3), Lewis structures (MLC4.5), polarity (MLC4.7), valence bond theory (MLC4.4), and periodic trends (MLC4.8). The use of gas laws was meant to further investigate the student performance on the previous MLC. Students performed better on this statement and the chi-square test showed no association between how students performed on MLC3.5 versus MLC4.3 ($\chi^2 = 0.896$, Cohen's $w = 0.03$ indicating a negligible effect size). This may be a result of the difference in prompts as the MLC4.3 prompt includes STP conditions and does not include a volume that may alter the response pattern.

Also present in Tables 1 through 4 are the correlations of students' responses on each statement (scored 0 for incorrect, 1 for correct) to the students' total score on the corresponding MLC. This correlation can be referred to as the discrimination index, which describes the extent student performance on a particular statement is related to their performance on the set of statements in the MLC. Of the 35 statements, nearly half (17 statements) had discrimination indices above 0.4 and the strong majority (28 statements) was over 0.3. Of the seven statements that were below 0.3, three statements approached or were below the 0.2 cutoff suggested for removing the statement (MLC1.3, MLC2.1, and MLC3.8).[15] Each of the three had percent correct greater than 95%, which is the likely reason for the low correlation value. The correlations overall indicate that the strong majority of statements are providing appropriate discriminatory ability, with the suggestion that future iterations may benefit by revising or removing the three statements indicated.

The use of MLCs also offers an opportunity for instructors to discuss well-known misconceptions that may be difficult to introduce with traditional assessment. For example, research has shown that students over rely on the octet rule as an explanation for ion formation instead of electrostatics.[19] In MLC4, statement 8 provides a means for considering periodic trends in electron affinity while describing a situation with an ionic compound. Follow-up instruction could describe why the relative ionization energy and electron affinity values for Na and Br are important considerations in an ionic compound to emphasize the importance of electrostatic interactions. Similarly, research has shown student confusion between molecular and ionic compounds, in particular ascribing molecular structure to ionic compounds.[20] This misconception is explored directly in the homework HWMLC3, statement 5. The importance of distinguishing between ionic and molecular compounds is present throughout the MLCs in terms of nomenclature (MLC2.1, MLC3.2, HWMLC2.2, HWMLC3.3, and HWMLC4.3,), structure of molecule or ion (MLC2.3, HWMLC2.1, HWMLC3.5, and HWMLC4.5) and in terms of classification (MLC3.3).

LIMITATIONS AND FUTURE WORK

This article is intended to present MLCs as a method of student assessment that can provide instructors information on the prevalence of linked concepts. At the current setting the incorporation of MLCs has provided insight into student understanding of a variety of concepts throughout the course such as student understanding of the limits of models. Toward that end, MLCs are recommended as a potential tool in the assessment toolbox for instructors to incorporate within their own assessment methods. However, it should be pointed out that each statement represents only a single measure of the relevant concept. Additionally, there is the potential that correct responses to the MLCs may reflect a heuristic or shortcut that the student is employing rather than a robust understanding of chemical principles.[14] For instructional purposes, it is therefore recommended that student assessments use a variety of assessment techniques where MLCs can serve as one such technique.

Ongoing and future work will investigate the ability of MLCs to achieve the goal of promoting and measuring the linking of content throughout the course. First, research investigating the validity of MLCs as a measure of linking content is necessary. Such research will involve investigating the response process of students undertaking MLCs and examining the relationship between MLCs and other measures of linked concepts such as Creative Exercises or Concept Maps. In particular some of the statements in the MLC can be evaluated without the original prompt (e.g., MLC2.5, MLC2.9, MLC3.2, MLC3.3, MLC3.6, and MLC4.5). It may be that students evaluating these statements within the broader context is sufficient to make the link clear to students or these statements may continue to be evaluated as independent statements and no linkage is made. Future research is needed to clarify the extent linking occurs with these statements. Also, validity would be aided by having subdiscipline content experts evaluate the phrasing of each statement.

Second, if sufficient evidence for validity is found, the ability of MLCs to promote linking of concepts can be explored. If successful, Assumptive Learning Theory suggests that the practice of assessing the linking of content can lead to more meaningful learning that would be demonstrated through greater long-term retention. Research into the role of these assessments in promoting long-term concept retention would serve to provide validity for the theory and offer greater utility to the assessment technique. Future work can also investigate the impact of incorporating MLCs into course assessments on students' efforts in course preparation or the impact of MLCs in cooperative learning on student group discussion.

CONCLUSIONS

The use of MLCs in the General Chemistry class has provided insight into the prevalence of students' concepts and has informed instruction at the research setting. The intent of this article is for instructors to consider students' efforts to link content, in particular, in the development of assessments, given the importance of these connections in learning theories. MLCs have the potential to serve as an assessment technique in this role and may be considered along with Concept Maps or Creative Exercises. Among these techniques, MLCs are unique in identifying the prevalence of student concepts by requiring each student to evaluate each connection and has the potential to meet the logistic demands of large classes, which are common in postsecondary introductory chemistry courses.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00161.

Tables describing the MLCs that were developed for the Sapling Learning homework system (PDF)

Tables describing the MLCs that were developed for the Sapling Learning homework system (DOCX)

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Notes

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