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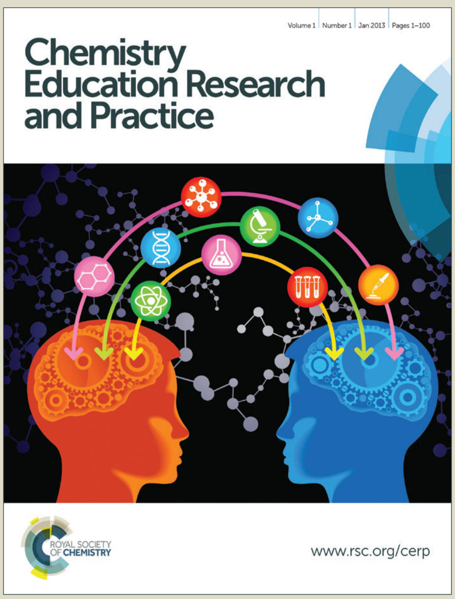

Looking for Links: Examining Student Responses in Creative Exercises for Evidence of Linking Chemistry Concepts

Abstract

Assumptive Learning Theory values the active process of linking concepts to promote meaningful over rote learning. To promote meaningful learning, assessment practices that encourage the linking of concepts needs to be developed and utilized. Creative Exercises (CEs) have the potential to encourage such links. CEs are an open-ended assessment technique where students are given a single prompt and are asked to describe, as many statements as they can that are distinct, correct, and relevant to the prompt. This study describes a qualitative investigation into student responses to CEs for evidence of students linking concepts throughout the course and the nature of the linked concepts. The findings indicate considerable interconnections of content in student responses. Further, students' efforts toward making connections revealed several misconceptions regarding their understanding of the limits of models. CEs are therefore proposed as a means to encourage students to link concepts and to inform instructors about the links made, both correctly and incorrectly. Finally, to determine the prevalence of the incorrect links, a novel assessment technique is proposed based on students' responses to CEs.

Introduction

A key decision a chemistry instructor makes is in deciding how to assess student knowledge. The assessments used play the primary role in providing feedback to students and guiding future instructional decisions. Further, the assessments used convey to students which information and level of understanding the instructor deems important and as a result serves to direct students' academic efforts. Despite the importance of classroom assessment practices, they have received relatively little attention in the research literature, compared to, for instance, the sizable literature on developing, implementing, and evaluating alternative practices for introducing content to students (Holme *et al.*, 2010).

This study seeks to investigate the potential for a novel assessment technique, termed Creative Exercises, to promote students' linking of concepts within General Chemistry. These efforts are born out of a concern that students memorize information, without assimilation into students' existing frameworks, and therefore do not develop or retain a conceptual understanding (Nyachwaya *et al.*, 2014). Additionally, there is a concern that students view the General Chemistry curriculum as a disjointed set of topics, a perception that would further hamper efforts to link concepts (Francisco *et al.*, 2002).

Creative Exercises

Creative Exercises (CEs) are an open-ended assessment practice that does not have a single or small set of possible correct answers. In essence, a CE provides students a prompt that describes an idea relevant to the course, such as "a million molecules of SO_2" and students are asked to describe as many statements as they can that are distinct, correct, and relevant to the prompt. Generally speaking, the prompt is designed to match content that is currently being assessed in the course. Credit is awarded for each statement that a student can list which satisfies the criteria of distinct, correct, and relevant. Students are informed in each CE how many statements are needed for full credit to provide a cap on the amount of credit students can receive on an individual assignment. To promote creativity, students are also informed there is no penalty for incorrect statements. To score a CE, an instructor brainstorms a list of likely answers prior to grading. Usually the maximum statements required by students for full credit is determined by taking one-third to one-half of the number of statements the instructor brainstorms. In grading CEs if an unanticipated statement arises, the instructor makes a decision using the distinct, correct, and relevant criteria. If the statement satisfies the criteria, it is added to the list of potential answers to ensure consistent grading with subsequent students. Examples of CEs that have been used in General Chemistry along with detailed information on the scoring process can be found in Lewis, *et al.* (2010). Evidence for the validity of CEs as a student assessment practice in a General Chemistry classroom has been collected through examining the content coverage, scoring structure, inter-rater reliability, and correlations with a traditional chemistry assessment (Lewis *et al.*, 2011). As a measure of chemistry knowledge stronger evidence for validity was available when CEs were used in-class as opposed to given as homework. Homework CEs still have the potential to offer students' preparation with the assessment technique and can serve as formative feedback to the students.

One strong advantage to using CEs is that they incentivize students to link prior concepts in the course with concepts currently presented. Students who can draw on past content and link it to the prompt given will have more chance to succeed on a CE. However, there is also the possibility that students can find sufficient information on a single topic that directly pertains to the prompt and therefore succeed without linking content. The over-arching goal of this study is to explore student responses to CEs for the extent and nature of their efforts to link prior concepts.

Theoretical Frameworks

The theory base that guides this work is Ausubel's Assumptive Learning Theory (Novak, 2010). In this theory, learning is placed on a continuum between meaningful and rote. Rote learning is where the learner makes no effort to incorporate new information into existing knowledge structures. Rote learning is often characterized as efforts in direct memorization. Examples of tasks that use rote learning are memory tests where individuals are asked to remember a sequence of unassociated letters. A chemistry example would be to ask a first year chemistry student to recall the color of a particular metal when it is put in a flame test. As the information that is being recalled has no meaningful association with existing content knowledge, the information must be learned through rote learning.

Meaningful learning, in contrast, is characterized by incorporating new information into an existing knowledge structure. The process for meaningful learning is interactive. Both the new information and the existing knowledge structure become slightly modified to facilitate the interconnection between the two. A chemistry example would be for a first-year student learning the solubility of ionic compounds and covalent compounds, to recognize that the different solubility processes can be added to their prior understanding of the differences in physical properties between ionic and covalent compounds.

Emphasizing meaningful learning is essential in students' conceptualizing chemistry as a framework of linked concepts that offer explanatory value instead of a discrete set of factors to be memorized (Taber 2014).

Rote and meaningful learning are differentiated by how they play a role in concept retention (Novak, 2010). Concepts that are learned by rote learning typically feature very limited retention and are simply forgotten. There is the potential for overlearning, where material is restudied well past recall has been achieved, which can lead to longer retention. Remembering one's own phone number would be an example of such overlearning. In contrast, meaningful learning will generally lead to a longer retention of new concepts. Owing to the interactive nature of meaningful learning, the new concept is modified to incorporate with the existing knowledge structure. Over time the learner will be able to retrieve the general attributes of the new concept as they pertain to the now modified knowledge structure, however the learner will not be able to recall exact details of how a concept was presented. One key difference between rote and meaningful learning, then, is the ability to recall information verbatim. Rote learning would be ideal for the direct recall of verbatim information; meaningful learning would struggle with this owing to the modification of the new information. Meaningful learning would be ideal for longer-term retention of the use of the concept.

The concept of rote versus meaningful learning have similarities with other established educational theories. Novak (2010) points to the similarities between this framework and Marton and Saljo's (1976) work on surface versus deep learning. In surface learning, students are described as focusing on the text as written and this learning can be characterized by direct recall of the text. Students using deep learning focus on the intentional content of the text and can be characterized by comprehension of the text. Later work found that deep learning could be described as holistic, where students related content to a larger context (Marton and Saljo, 2005). In contrast, surface learning was atomistic, focusing on the sequence of the text and details within the text.

The description of meaningful learning as an interactive process is also compatible with constructivism's account of accommodation (Tsaparlis 2014). As Staver (1998) writes, in constructivism the learner evaluates new concepts based on the concept's ability to fit into the learner's existing conceptual network. When a concept leads to an unexpected result, termed a perturbation, it is a sign that the concept does not fit within the existing conceptual network. Modifying the existing conceptual network to accept the new concept eliminates the perturbation, a process termed accommodation. Thus, similar to Assumptive Learning's meaningful learning, the existing conceptual scheme is modified when learning the new concept. More broadly, the importance and characterization of linking new concepts to existing concepts is a central theme in at least three widely used educational theories.

Returning to Assumptive Learning Theory, there are actions teachers can take to emphasize meaningful learning. One of the most important actions is the nature of how students are tested. Testing the recall of definitions or principles in verbatim emphasizes rote learning. However, testing the linking of new information with existing information, would emphasize meaningful learning. Novak (2010) prescribes concept maps as an assessment technique to measure students' linking of concepts, and therefore encourage meaningful learning. Concept maps as an assessment technique require students to create a map that link separate concepts within a course with a brief phrase termed a proposition.

Students may be provided with a list of concepts, asked to generate their own concepts or a combination of both (Stoddart 2000). Multiple scoring schemes have also been developed for concept maps, each of which necessarily makes an assumption regarding the nature of a correct mapping of concepts, which is problematic as multiple organization schemes may lead to successful understanding (Lewis *et al.*, 2011, Ruiz-Primo and Shavelson, 1996). CEs are proposed as an alternative assessment technique to concept maps that still intends to promote students' linking of concepts. The use of CEs as a classroom assessment may be preferable to concept maps as CEs have a simpler scoring method that does not require an assumption regarding appropriate organization schemes. The overarching hypothesis tested here, then, is that CEs can serve as an alternative assessment technique that can inform instruction by compelling students to link concepts throughout chemistry.

Research Questions

To explore this hypothesis the following research questions guided this study:

1. How frequently do students link chemistry concepts when responding to CEs?
2. How do student responses to CEs inform the nature of linked concepts throughout a General Chemistry course?

Methods

CEs were incorporated into the homework and in-class exam assignments at two large, primarily undergraduate institutions in the southeast United States. CEs from three classes were selected to be coded. The classes were chosen to ensure variety in terms of institution and sufficient class size (N > 30) to provide ample variety of student responses for analysis. Within each class, CEs were chosen to have variety in terms of whether the CE was given as homework or in-class as part of an exam and the extent they provided mathematical information. The inclusion of a homework CE, despite the weaker evidence for validity, was chosen to determine if this method of using the assessment could also provide information to the instructor regarding students' efforts to link concepts. At one institution, the content covered up to the CEs examined were in sequence: conversions, atomic structure, compounds, stoichiometry, solution chemistry, gas laws, and thermodynamics. For this institution, two CEs were examined, one that followed gas laws and one that followed thermodynamics. At the other institution, the content sequence up to the CE was: conversions, atomic structure, compounds, stoichiometry, electronic structure of atoms, periodic trends, models of chemical bonding, Lewis structures, and molecular shapes. The CE examined followed the molecular shapes topic. All of the CEs analyzed came after students experienced at least one homework CE and one in-class CE. IRB approval was obtained at both institutions to conduct this study.

This research employs a qualitative approach. Two researchers independently coded the student responses from each CE. The initial code list was the rubric of correct answers that instructors used to grade the CEs. The code list was expanded as unexpected correct answers or incorrect answers appeared, in congruence with an open coding scheme. Once complete, the researchers compared codes and discussed any discrepancies until they reached a consensus. The resulting consensus codes were next characterized as correct, incorrect or irrelevant statements. Irrelevant statements were those statements that were correct but were statements that restated the prompt (e.g. the reaction given is balanced), restated information from the periodic table or well known constants, used a negative statement to exclude general categories (e.g. this is not a redox reaction), or were not relevant to the content in the course (e.g. $FeCl_2$ is a yellow solution, where qualitative chemistry was not presented). The codes were then organized based on major chemistry topic as suggested by the chapter titles in common chemistry textbooks (Silberberg, 2008, Brown *et al.*, 2008). The complete code list, including frequency of responses and classifications by correctness and topic, are included as an appendix.

Results

Gas Laws Topic

The Gas Law CE (Figure 1) was given in-class and described an acid-metal reaction in solution to evolve a gas with the volume and molarity of the acid and the reaction pressure and temperature given. Students needed seven statements with this CE to receive full credit and could get extra credit for two additional statements.

Reacting 1.45 L of 0.41 M of HBr with excess Calcium
Ca (*s*) + 2 HBr (*aq*) → H_2(*g*) + $CaBr_2$(*aq*)
This reaction occurs at 1.61 atm and 45 degrees Celsius

Figure 1: CE Prompt used with Gas Laws

There were 67 students who completed the Gas Law CE and their responses are categorized by topic and correctness in Table 1. Statements categorized as irrelevant were not considered in the analysis. In Table 1, the number of students who attempted to incorporate each chemistry topic in their response is indicated. These responses are also delineated in terms of how many made correct statements and incorrect statements. Note, the number correct and number incorrect are not mutually exclusive as a student could make both a correct description of a topic and incorrect description of the same topic within their responses. For example, under the topic of Compound in Table 1, ten students provided information related to compounds. One student described $CaBr_2$ as a salt and HBr as a salt where the first statement was categorized as correct and the second as incorrect, and therefore this student was counted under each column. Tables 2 and 3 can be interpreted in a similar fashion.

Table 1: Topics Used with Gas Laws CE

Topic	Students attempting	Number correct (%)	Number incorrect (%)
Conversions	43	42 (98%)	1 (2%)
Compound	10	9 (90%)	3 (30%)
Stoichiometry	62	57 (92%)	36 (58%)
Solution Chemistry	48	41 (85%)	34 (71%)
Gas laws	40	13 (33%)	35 (88%)

The most common response among the students was the use of stoichiometry calculations with this problem. Of the 67 students, 51 correctly converted the molarity and volume of HBr into moles. Calculations based on this figure were less common as only 23 students solved the moles of other components in the solution and 21 students found the mass of the same. Other stoichiometry calculations involved 25 students determining the molecular mass of a compound in the reaction and one student determining the percent composition of a compound. Surprisingly, 22 students used the ideal gas law and the values given in the prompt, mistakenly attributing the volume of solution as the volume of a gas, to solve for moles.

Solution chemistry had considerable variety among student responses. Numerous students identified factors relevant to a reduction-oxidation reaction, where 14 student responses assigned oxidation numbers to the chemicals, nine students identified Ca as being oxidized or HBr as being reduced and six students identified the respective oxidizing and reducing agents. Five students identified the reaction as either single replacement or reduction-oxidation. Eleven students described the solubility of either $CaBr_2$ or HBr and seven students identified HBr as an acid. Twelve students used terms to identify the situation as a limiting reagent or excess of calcium. In terms of common errors, 11 students incorrectly attempted to identify an ionic equation to represent the reaction and seven students described calcium as a precipitate despite its placement as a reactant.

This prompt was timed to match the presentation of gas law content and is evidenced by the 40 students who attempted to use gas laws. Of those 40, only 10 students successfully determined the volume of gas created. One student expanded on this by describing the density of the hydrogen gas created. Fourteen other students attempted to solve for density but did so incorrectly. The other common mistake was the aforementioned use of the volume of the solution into the Ideal Gas Law. Four students solved for the volume of gas but used the moles of the reactant, without taking into account the mole ratio to the hydrogen gas produced.

In terms of the remaining topics in Table 1, the majority of students (42) were able to use the common conversion from Celsius to Kelvin. Nine students used content related to the introduction of compound, by either describing $CaBr_2$ as an ionic compound or salt, applying the nomenclature to name a compound in the reaction correctly or identifying cations and anions in the reaction.

Thermodynamics Topic

The CE presented in Figure 2, described a dissociation reaction in water with information on the amount of reactant and water, initial water temperature and heats of formation. This CE models a calorimetry type problem and was given as a homework assignment following the introduction of Thermodynamics. Students received credit for up to seven distinct statements with this CE.

In the reaction, below 23.0 g of $FeCl_2$ undergoes the reaction in 5.15 L of water initially at 25.0 Celsius (assume 1.0 g / mL).
$FeCl_2(s) \rightarrow Fe^{2+}(aq) + 2\ Cl^{-}(aq)$
$H_f(FeCl_2) = -341.8$ kJ/mol
$H_f(Fe^{2+}) = -87.9$ kJ/mol
$H_f(Cl^{-}) = -167.46$ kJ/mol

Figure 2: CE Prompt used with Thermodynamics

There were 31 students who completed the Thermodynamics CE and their results are summarized in Table 2.

Table 2: Topics used with Thermodynamics CE

Topic	Students attempting	Number correct (%)	Number incorrect (%)
Conversions	13	11 (85%)	2 (15%)
Atomic Structure	1	1 (100%)	0 (0%)
Compound	6	6 (100%)	1 (17%)
Stoichiometry	21	19 (90%)	6 (29%)
Solution Chemistry	13	11 (85%)	6 (46%)
Gas laws	5	0 (0%)	5 (100%)
Thermodynamics	25	16 (64%)	19 (76%)

The most common response to this CE targeted the intended topic of Thermodynamics. Nine students correctly calculated the enthalpy of the reaction. Ten students identified the reaction as exothermic, surprisingly only four of those students also identified the correct enthalpy of reaction. Two of the students that identified an exothermic reaction incorrectly solved the enthalpy of reaction yet still arrived at a negative number. One other student arrived at a positive number for enthalpy but described the reaction as exothermic. This highlights the potential for some links to appear meaningful even with an incorrect student understanding and represents a limitation of CEs (that is similar to traditional multiple choice assessments). To minimize this impact, CEs require students demonstrate multiple links for successful completion, with the scoring structure set-up to provide more credit for demonstrating a correct understanding (e.g. a correct value for enthalpy and exothermic determination results in two correct statements).

Only two students successfully determined the energy released by the reaction, while seven other students incorrectly attempted to do so. Overall, eight students miscalculated the enthalpy of reaction, with four students subtracting reactants from products, two students missing the coefficient from chlorine and two students combining both mistakes. Three students attempted to solve for the energy associated with each chemical in the reaction by multiplying the number of moles by the heat of formation for each chemical. One other student compared the heats of formation and concluded that $FeCl_2$ releases the most energy and Fe^{2+} releases the least.

In the stoichiometry topic, 13 students successfully converted the mass of the reactant into moles, while seven other students only described the molar mass of the compound. Of the 13, seven went on to determine the moles of other components. Interestingly, three students described the percent composition by mass of the $FeCl_2$ compound. In terms of incorrect responses, two students incorrectly solved for the moles of the reactant. Two other students took the moles of $FeCl_2$ and used Avogadro's number with one description of the resulting value as "atoms of $FeCl_2$" and another description as "molecules $FeCl_2$".

In solution chemistry, nine students recognized the reaction as a dissolution or dissociation reaction. Eight students described $FeCl_2$ as soluble. Two students correctly determined the molarity of $FeCl_2$ in the situation while three other students incorrectly calculated molarity. Similar to the previous CE, two students described the reactant as a precipitate and one other student described $FeCl_2$ as insoluble. Also similar to the above was the misapplication of gas law relationships to a reaction in solution. Four students attempted to use the volume of the solution in the Ideal Gas Law to solve for the resulting pressure. One of the students also employed Avogadro's Law and the moles before and after to determine the new volume of the solution. A separate student described: "When (sic) the information that the water is 1.0 g/mL and at 25^0 C, we know that it is in (STP) standard temperature and pressure. And so the pressure = 1 atm."

In the remaining topics in Table 2, eleven students showed conversions of the temperature or volume of water into other units. One student correctly described the number of protons and electrons present in Fe and Cl separately. Four students correctly identified characteristics of a compound such as naming $FeCl_2$ as Iron(II) chloride, identifying the compound as ionic or identifying the cation and anion present. One student described the charge incorrectly, labeling chlorine as a -3 charge.

Molecular Shapes CE

The Molecular Shapes CE, presented in Figure 3 describes a single molecule with one central atom and the electronegativity values for each atom. This CE was given in-class as part of an exam on molecular geometries and bonding theories. Students received credit for up to five distinct statements with this CE.

COH_2 where C is the central atom Electronegativity values: C = 2.5, H = 2.1 and O = 3.5

Figure 3: CE Prompt used with Molecular Shapes

There were 31 students who completed the Molecular Shapes CE and their results are summarized in Table 3.

Table 3: Topics used with Molecular Shapes CE

Topic	Students attempting	Number correct (%)	Number incorrect (%)
Atomic Structure	1	1 (100%)	0 (0%)
Compound	1	0 (0%)	1 (100%)
Stoichiometry	8	7 (88%)	1 (13%)
Periodic Trends/ Electron Configuration	3	3 (100%)	3 (100%)
Lewis Structure	31	27 (87%)	17 (55%)
Geometry/Shape	28	28 (100%)	9 (32%)
Valence Bond Theory	10	9 (90%)	5 (50%)

The student responses to the CE on Molecular Shapes featured less variety of topics than the other CEs. Every student except one attempted to draw a Lewis structure. The other student provided a written description of the carbon atom in the Lewis structure. There were 21 students who were able to correctly draw the Lewis structure and nine students who drew an incorrect Lewis structure. Students indicated a variety of descriptions regarding the structure, such as the molecule satisfies the octet rule (4 students), carbon obeys the octet rule (3 students), carbon has no lone pairs (3 students) or there are 12 valence electrons (3 students). There were also descriptions of properties that expand on the Lewis structure. Two students determined the electronegativity differences in the bonds, one student followed by stating "polar bonds between each element" and the other student assigned polarity incorrectly, labeling the carbon to oxygen bond nonpolar and the carbon to hydrogen bond polar.

Among the nine incorrect Lewis structures, five students did not record the total number of valence electrons. Of the four with the total number of valence electrons, two students had the correct structure except each placed both a single bond and three lone pairs of electrons on oxygen atom. The remaining incorrect structures used the wrong number of valence electrons. Two students made a similar incorrect structure as before, with three lone pairs of electrons on oxygen and a double bond. One student placed a single bond between C and O, with one lone pair of electrons on C and three lone pairs of electrons on O. Two other students used only 10 valence electrons and fell short of the octet; one of the students placed the oxygen as the center atom.

Building on Lewis structures, 24 students either drew a trigonal planar shape, described the electron geometry or molecular geometry as trigonal planar or just wrote the words trigonal planar. Building on the shape, 15 students described the bond angle as 120^0 and 14 students described the molecule as polar. Four students described the shape as tetrahedral, with only one student having a Lewis structure that would lead to the tetrahedral shape. In addition, one student each described the shape as T-shaped or bent.

Valence bond theory was also used to describe the Lewis structure, with eight students identifying sigma or pi bonds in the structure and two students identified sp^2 hybridization without attributing it to the central atom. Incorrect applications of the valence bond theory were two students who described the double bond as a pi bond, one student that described the CO bond as sp^2 and the CH bond as sp and one student who described "the hydrogen bonds are weak and are in s orbital. The double bond is in the p-orbital."

There were minimal instances of relating this topic to other topics in the course. The most common, seven students correctly identified the molecular mass of the compound. Two students correctly described the electron configurations for individual atoms. Both students also made incorrect electron configurations along with one other student. One of these students attempted an electron configuration for the entire molecule, working with the sum of electrons in the molecule. Using atomic structure, one student correctly described the number of protons and electrons in hydrogen, though described an incorrect number for oxygen. Another student used periodic trends to correctly describe the relative electron affinity and ionization energy of the atoms in the molecule but incorrectly labeled oxygen as the smallest atomic size. Finally, one student attempted to classify the compound, but incorrectly described it as an ionic compound.

Discussion

In response to the first research question, students' appear to make a considerable attempt to link chemistry topics in their responses to CEs, particularly between the first two prompts analyzed here. In the first prompt described, each of the categories: stoichiometry, solution chemistry concepts, and gas laws, were well represented in over half of the student responses. There was less use of the nature of chemical compounds. Within each of these broad topics, students used a diverse range of topics, particularly among solution chemistry. In the second prompt described, the majority used thermodynamics and stoichiometry as expected. Nearly half the students used topics in solution chemistry and nearly a quarter used gas laws and the nature of chemical compounds. As the second prompt was a homework CE, which can be thought of as more formative in nature, there is evidence of students frequently linking concepts which can then provide an opportunity for feedback to students on their efforts to link concepts. The CE on molecular shapes featured less variety, as much of the information in General Chemistry on covalent compounds is clustered together in Lewis structures, shapes, and polarity. Still, nearly 1/4 of the respondents used stoichiometry concepts in responding, and by placing a mass of the compound in the prompt it may have spurred greater use of linking these topics.

That students use a wide range of topics in responding to CEs indicates that students can make connections in content throughout the course. That the efforts to link concepts are in response to an open-ended format and not a targeted question indicates that the connections displayed are of the students' choosing and not an artificial contrivance to address a particular, targeted question. Whether such links are sufficient to enable meaningful learning as described in the Assumptive Learning Theory is yet to be determined. Evidence of long-term retention of the linked concepts would be necessary to claim meaningful learning. This research provides the first step by demonstrating an in-class assessment technique that can serve to identify the links made. Further, the results indicate the potential for future investigations into the use of CEs as an intervention tool to promote greater linking of concepts.

It is also of note that student responses show evidence that students successfully applied the prior and current presented topics in the course to CEs. For the Gas Law CE, among students who attempted to use the topics in terms of conversions, compounds, stoichiometry, and solution chemistry, at least 85% of respondents who attempted to do so, used these concepts correctly. For the thermodynamics CE, there were similar trends when students applied topics of conversions, atomic number, stoichiometry, and solution chemistry. With the molecular shapes CE, the students who attempted connections for topics including atomic number, stoichiometry, Lewis structure, geometry/shape, and valence bond theory were also largely able to make correct statements.

CEs also have the potential to identify students' misconceptions that can inform instruction during the course of a semester. The most common misconceptions for the Gas Laws CE were to use the ideal gas law to determine moles and to solve for the mass of an aqueous product. Also to incorrectly describe an ionic equation, to identify calcium as a precipitate, and to incorrectly ascribe simple gas laws to the situations. For thermodynamics, the misconceptions identified often involve mistakes in solving the enthalpy or energy change associated with the reaction, including omitting coefficients or reversing products and reactants when determining the enthalpy of a reaction from heats of formation. Additionally, though less common, students attempted to solve for the energy change of each component in the reaction. Misconceptions were also present in identifying a reactant as a precipitate, applying the Ideal Gas Law where the reaction occurs entirely in solution or attempting to solve the number of $FeCl_2$ atoms or molecules. In molecular shapes, the most common mistakes arise from not solving or incorrectly solving the total number of valence electrons. The resulting erroneous Lewis structure impacts students' geometry, shapes and polarity determinations. That said, other misconceptions also arose from students misuse of the valence bond theory terms of hybrid orbitals and bond type as well as misconceptions in the structure of the atom in terms of electron configurations or number of protons and electrons.

In response to the second research question, the nature of linked concepts is evident in the detailed description of student responses. One of the most consistent themes present in students' responses is the misapplication of content when it is applied to a new topic. In both of the first two prompts, a substantial portion of students used the volume of solution in the Ideal Gas Law. While less common in the responses, there is also evidence of applying gas law concepts such as standard temperature and pressure and Avogadro's Law to the second prompt, which described a reaction occurring entirely in solution. Similarly, students used the term precipitate to describe reactants, and one student response described the hydrogen gas evolved as a precipitate. Other examples of this misapplication were the creation of an electron configuration for an overall molecule by placing the sum of electrons present in the molecule into the electron configuration for an atom or solving for the atoms of $FeCl_2$.

These results call attention to the need for both instruction and assessment to examine students' understanding of the limits of models in chemistry. This call corresponds to past research findings that describe the need for incorporating limits of models in teacher preparation and textbooks (Van Driel and Verloop 1999, Justi and Gilbert 2002, Oversby 2000, Dreschler 2007). The student responses demonstrated here represent a possible outcome of failing to incorporate targeted discussions on the limits of models. Additionally, conventional assessment techniques, such as multiple-choice questions, typically do not examine students' understanding of the limits of models. In particular, designing multiple-choice questions to examine students' use of existing chemistry concepts with new topics, such as the appropriateness of gas laws for a reaction in solution, is problematic.

CEs can serve as an instrument for uncovering students' attempted use of concepts with novel topics, but they cannot determine the prevalence of misuse, as they are not directed questions. For example, in the data presented here, it is entirely possible that a large number of students believe the hydrogen gas emitted can be termed a precipitate, but only one student chose to provide that information in their response. One possible way to determine the prevalence of these links in an instructional setting would be to create an assessment similar to the Implicit Information from Lewis Structures Instrument (IILSI) developed by Cooper *et al.*, (2012). Students can be given a single prompt similar to the prompts described above and asked to mark all of the descriptions and procedures that the students believe could be applied. The prompt and student responses associated with Figure 2 were used to develop an example present in Figure 4.

Consider the below situation:

In the reaction: $FeCl_2(s) \rightarrow Fe^{2+}(aq) + 2\ Cl^-(aq)$

23.0 g of $FeCl_2$ undergoes the reaction in 5.15 L of water initially at 25.0 Celsius (assume 1.0 g / mL).

$H_f(FeCl_2) = -341.8$ kJ/mol

$H_f(Fe^{2+}) = -87.9$ kJ/mol

$H_f(Cl^-) = -167.46$ kJ/mol

Determine if each statement that follows is correct and place a check mark by those that are correct.

_____ There are 5150 grams of water

_____ The molar mass of $FeCl_2$ is 126.75 g/mol

_____ The pressure determined by PV = nRT is 0.862 atm

_____ The reaction is a redox reaction

_____ $FeCl_2$ is the precipitate of the reaction

_____ The ΔH for the reaction is 81.02 kJ/mol

_____ The reaction is exothermic

_____ The chloride ion releases more energy than the iron ion in the reaction

_____ The molarity of chloride ions is 0.0352 M

_____ The name of $FeCl_2$ is Iron (II) chloride

_____ $FeCl_2$ is a covalent compound

_____ The resulting temperature of the water can be determined

Figure 4: Example Assessment to Determine Prevalence of Links

Developing and using a series of such assessments would allow instructors to better understand the ability of students to transfer topics appropriately and also facilitate an ongoing in class discussion about the limits of models. Like CEs this proposed assessment can be considered as only a small portion (equal to one or two questions) of a larger assessment. And thus, while a student would have a 50% chance of guessing each statement correctly, a student would have considerably lower odds of scoring highly on the proposed assessment through chance guessing. For example, the odds of guessing 9 or more of the 12 statements correctly would be 7.3%. Future work from this project can involve developing a series of such assessments based on students CE responses and collecting evidence on the validity of these assessments.

Conclusions

Multiple educational theories value the active process of linking concepts to promote meaningful over rote learning. By examining student responses to CEs, it is clear that students can use the assessment technique to show a diverse range of linked concepts within General Chemistry. In addition, the responses also show novel misuse of linking concepts, which calls to light students' perceptions of the limits of models introduced in this course. The results of this analysis can inform researchers who seek to further investigate the characteristics and traits of meaningful learning or are developing techniques to emphasize meaningful learning in the class. The results inform chemistry teaching on several levels. First, instructors should be aware and emphasize the importance of linking concepts throughout the course. Second, CEs as a mode of assessment will aid in informing instructors about the links students are making, both correctly and incorrectly, as well as emphasizing to students the value placed on making these links. Third, the incorrect responses from CEs can both initiate class discussions regarding the limits of models and the development of a novel assessment technique to measure the same.

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Appendix

CE codes

Black-correct **Blue-incorrect** **Red-irrelevant**

Values in brackets is number of students

Values in parenthesis are student code numbers

Gas Laws

Total number of students: 67

Reacting 1.45 L of 0.41 M of HBr with excess Calcium

Ca (s) + 2 HBr (aq) → H_2(g) + $CaBr_2$(aq)

This reaction occurs at 1.61 atm and 45 degrees Celsius

Conversion

Total 43 students attempted to use this topic, 42 students used correctly, 1 student used incorrectly.

[42] 45 Celsius is 318.15 Kelvin (1, 4, 7, 8, 9, 10, 13, 16, 17, 18, 20, 21, 40, 50, 52, 86, 87, 88, 89, 90, 92, 93, 94, 95, 100, 101, 102, 106, 108, 110, 111, 113, 114, 115, 127, 132, 135, 136, 138, 140, 141, 142)

[2] 1.45L is 1450 mL (89, 90)

[1] Temperature is 318° K (6)

Compound

Total 10 students attempted to use this topic, 9 students used correctly, 3 students used incorrectly.

[6] $CaBr_2$ is an ionic compound or salt (1, 6,106,127,132,138)

[4] $CaBr_2$ is Calcium bromide, HBr is Hydrogen bromide (8, 50,106,138)

[1] Identifies cation or anion (95)

[2] HBr is an ionic compound or salt (1, 11)

[1] H_2 is called dihydrogen (106)

[2] H_2 is hydrogen or Ca is calcium (50,106)

Stoichiometry

[51] 0.59 moles of HBr (1, 2, 6, 8, 9, 10, 11, 12, 13, 17, 18, 20, 40, 50, 51, 86, 87, 89, 91, 92, 93, 94, 96, 97, 98, 99, 101, 104, 105, 106, 108, 109, 110, 111, 112, 113, 114, 115, 116, 127, 129, 131, 132, 133, 135, 136, 138, 139, 140, 141, 142)

[25] Molecular mass of compound, $CaBr_2$ is 199.886 g/ mol, HBr is 80.912g/mol (2, 6, 8, 10, 11, 18, 50, 52, 86, 88, 90, 89, 93, 98, 100, 102, 105, 107, 111, 112, 127, 136, 138, 140, 142)

[23] 0.30 moles of H_2 gas, 0.30 moles of $CaBr_2$ or Ca (2, 12, 13, 17, 20, 51, 86, 91, 92, 94, 96, 104, 108, 111, 113, 114, 116, 132, 136, 138, 140, 141, 142)

[21] 12 grams of Ca, 48 g of HBr, 0.60 g of H_2 (1, 12, 18, 20, 51, 86, 89, 91, 92, 96, 101, 104, 112, 114, 132, 133, 135, 136, 138, 141, 142)

[1] Percent composition (11)

[18] 0.089 moles (8, 10, 16, 21, 40, 52, 87, 88, 89, 93, 94, 95, 96, 102, 108, 112, 113, 114)

[9] Mass of $CaBr_2$, aqueous product never forms (9, 12, 20, 51, 91, 101, 104, 105, 115)

[7] Solve wrong value of mass (40, 52, 89, 99, 104, 110, 128)

[4] 11 moles from Ideal Gas Law (1, 92, 100, 106)

[3] 0.045 moles of H_2 or $CaBr_2$ (8, 21, 52)

[3] Molecular mass incorrect (92, 110, 128)

[1] 0.029725 moles of $CaBr_2$, H_2 (99)

[1] 1.189 moles of Ca (40)

[1] 0.036 moles of HBr (90)

[1] 0.63 mol of H_2 (105)

[1] Total moles are 0.6 (2)

[1] Mass of $CaBr_2$ wrong (89)

[1] It takes 2 moles of HBr to react with 1 mole of $CaBr_2$ (127)

Solution Chemistry

[14] Assign oxidation numbers or charges (1, 2, 6, 9, 11, 18, 93, 95, 97, 102,109, 111, 127, 131)

[10] HBr is the limiting reagent (6, 17, 18, 21, 52, 101, 103, 106, 116, 138)

[9] $CaBr_2$ is soluble (1, 10, 17, 52, 98, 109, 113, 115, 127)

[9] Assign Ca as oxidized or H as reduced (1, 18, 92, 93, 97, 104, 109, 116, 13)

[7] HBr is an acid or strong acid (2, 50, 88, 108, 111, 115, 141)

[6] Assign H as oxidizing agent or Ca as reducing agent (1, 16, 92, 93, 104, 112)

[5] Single replacement or redox reaction (1, 7, 13, 94, 139)

[5] HBr is soluble (1, 6, 90, 109, 127)

[4] Ca is not limiting or excess (12, 17, 103, 108)

[2] Net Ionic equation $Ca_{(s)} + 2H^+_{(aq)} = H_{2(g)} + Ca^{2+}_{(aq)}$ (1, 109)

[1] Molarity of H_2 is 0.0617 M (136)

[1] Identifies solubility rule that describes $CaBr_2$ is soluble (113)

[1] Ca is insoluble (93)

[1] Identifies Br^- as spectator ion (96)

[1] Identifies reactants and products (138)

[11] Incorrect ionic equation (1,9, 10, 11, 13, 52, 94, 96, 109, 113, 133)

[7] Ca is the precipitate (10, 52, 88, 90, 94, 108, 141)

[4] Wrong charges (18, 102, 109, 111)

[3] Not a redox (9, 20, 115)

[3] Acid base reaction, at this point only Arrhenius theory has been presented (9, 99, 111)

[2] Br is reduced (4, 92)

[2] Molarity of H_2 is 0.205 (51, 113)

[2] H_2 is a precipitate (7, 91)

[2] Products or reaction are or is soluble (95,129)

[2] HBr is solvent Ca is solute (97, 141)

[2] HBr is oxidized or reducing agent (10, 106)

[1] Molarity is 0.061 (95)

[1] $CaBr_2$ is the precipitate (98)

[1] Double displacement reaction (127)

[1] Net ionic wrong equation (52)

[1] Reaction is not balanced (130)

[1] Ca is being reduced or oxidizing agent (106)

[1] $CaBr_2$ is the reducing agent (6)

[1] H_2 is the reducing agent (102)

[4] No precipitate (no solids) (9, 95, 116, 130)

[3] Equation is balanced (7, 129,136)

[2] Molecular equation as written (86, 139)

[1] Calcium would not be soluble with SO_4^{2-} (50)

[1] Not an acid base reaction (7)

[1] Reaction happens in water (50)

[1] Reaction will occur (13)

Gas Law

[10] 4.8 L of H_2 gas formed (9, 17, 20, 91, 104, 116, 132, 136, 140, 142)

[3] H_2 is a gas (141, 50, 52)

[1] Density of H_2 is 0.12 g/L (136)

[1] Mole fraction of H_2 is 1.00 (17)

[1] Partial pressure of H_2 equals total pressure (17)

[22] Use 1.45 L in the ideal gas law (1, 8, 10, 16, 21, 40, 52, 87, 88, 92, 93, 94, 95, 97, 100, 102, 106, 108, 112, 113, 114, 115)

[14] Density incorrect (9, 10, 11, 18, 51, 52, 86, 88, 93, 106, 112, 116, 141, 142)

[6] State simple gas law relationships (17, 93, 95, 103, 112, 114)

[4] 9.6 L of gas (18, 50, 86, 111)

[1] 4.832 L of $CaBr_2$ formed (140)

[1] Volume of HBr is 0.59 L (90)

[1] Volume of Ca is 1.45L (103)

[1] Temperature is 47.45 Kelvin (97)

[1] Partial pressure of H_2 is 0.48 (94)

[1] Identifies Br as gas (86)

[1] Rate of H_2 is slow since it has a low mass (17)

[1] Rate of H_2 is fast (142)

Miscellaneous

[1] Ca is a nonmetal (6)

[1] No bases (116)

[1] H_2 is diatomic (131)

[1] Ca is in column II (127)

Thermodynamics

Total number of students: 31

In the reaction, below 23.0 g of $FeCl_2$ undergoes the reaction in 5.15 L of water initially at 25.0 Celsius (assume 1.0 g/mL).

$$FeCl_2(s) \rightarrow Fe^{2+}(aq) + 2\ Cl^{-}(aq)$$

$H_f(FeCl_2) = -341.8$ kJ/mol $H_f(Fe^{2+}) = -87.9$ kJ/mol $H_f(Cl^{-}) = -167.46$ kJ/mol

Conversions

[7] 25.5 Celsius to 298.15 Kelvin (4, 7, 8, 17, 18, 127, 128)

[3] Conversion to 5150 g or 5.15 kg of water (1, 16, 20)

[2] 5.15L is 5150 mL (3, 8)

[2] Mass of water converted incorrectly (6, 15)

Atomic Structure

[1] Fe has 26 protons, 26 electrons, Cl has 17 protons, 26 electrons (8)

Compound

[2] Fe(II) is the cation, Cl^- is the anion (1, 18)

[2] Electrolytes are present (20,124)

[1] $FeCl_2$ is an ionic compound (4)

[1] $FeCl_2$ is Iron (II) chloride or ferrous chloride (3)

[1] Charge of Fe^{2+} is 2^+ (1)

[1] Charge of Cl^- is 3^- (1)

[1] Aqueous solution has charged ions that flow free in the solution (16)

Stoichiometry

[13] 0.181 moles of $FeCl_2$ (1, 4, 13, 14, 17, 18, 19, 20, 21, 22, 123, 124, 128)

[12] 126.75 g/ mol molar mass of $FeCl_2$ (1, 2, 3, 4, 5, 6, 8, 12, 15, 17, 18, 124)

[7] 0.181 moles of Fe^{2+}, 0.363 moles of Cl^- (1, 17, 19, 20, 21, 22, 124)

[3] $FeCl_2$ is 44.1% Fe by mass (or 55.9% Cl, or 10.1 g and 12.9 g) (4, 11, 21)

[2] Moles wrong (10, 126)

[2] $1.08 * 10^{23}$ atoms of $FeCl_2$ or molecules of $FeCl_2$ (1, 19)

[1] 0.181 L of $FeCl_2$ (11)

[1] 62.2076 moles of $FeCl_2$ (13)

[2] Molar mass of Fe or Cl (15, 18)

[1] One mole makes two moles (20)

[1] Reaction is balanced (7)

Solution Chemistry

[9] Dissolution or dissociation or decomposition reaction (2, 5, 6, 10, 12, 18, 124, 125, 129)

[8] $FeCl_2$ is soluble (3, 5, 14, 16, 20, 21, 127, 128)

[2] Molarity of $FeCl_2$ is 0.0352 M (18, 125)

[1] $FeCl_2$ dissolves (126)

[3] Molarity Wrong (14, 16, 126)

[2] $FeCl_2$ is a precipitate or solid that forms (7, 18)

[1] $FeCl_2$ is insoluble (1)

[2] Solution is an aqueous solution (16, 20)

[1] Solution is yellow (3)

Gas Laws

[4] Pressure from PV = nRT (4, 17, 18, 19)

[1] Simple gas law to find new volume (19)

[1] Density of water and temperature makes STP, so P = 1 atm (20)

Thermodynamics

[10] Exothermic reaction (1, 2, 6, 7, 14, 17, 125, 126, 127, 128)

[9] ΔH = -81.0 kJ/mol (4, 5, 14, 15, 17, 19, 124, 125, 128)

[2] 14.7 kJ energy released by reaction (12, 125)

[7] Amount of energy released wrong (or energy needed) (1, 6, 9, 10, 11, 14, 129)

[1] Change in temperature wrong, ΔT =-167.46 kJ/mol (7)

[4] ΔH = 81.02 kJ/mol (11, 12, 126, 129)

[4] Endothermic (10, 12, 123, 129)

[3] Amount of energy calculated from Q = mCT, where T is 25 °C (6, 7, 12)

[3] Solve for the energy of each component in the reaction (20, 22,128)

[1] 255 kJ/mol is given off in the product side (17)

[2] ΔH = -86.44 (2, 6)

[2] ΔH = 86.44 (9, 10)

[1] Reverse reaction is exothermic (11)

[1] Energy of products is 422.87 kJ/mol (126)

[1] Equation is an energy equation (16)

[1] $FeCl_2$ releases the most energy, Fe^{2+} releases the least (5)

[4] Specific heat of water is 4.186 J/g°C (5, 6, 7,127)

[1] At room temperature (3)

[1] Heats of formation are all exothermic (18)

[1] Specific heat is constant (16)

Miscellaneous

[1] Density of $FeCl_2$ is 3.16 g/mL (3)

[1] Density = 0.00447 g/mL (3)

[1] Cl^- has a density of 3.2g/L (11)

[1] Hydrogen bonds between water weaken (20)

Molecular Shapes

Total number of students: 31

COH_2 where C is the central atom

Electronegativity values: C = 2.5, H = 2.1 and O = 3.5

Atomic Structure

[1] Hydrogen has 1 electron, 1 proton (8)

[1] Oxygen has 16 electrons, 16 protons (8)

Compound

[1] Ionic compound (16)

Stoichiometry

[7] Molar mass of COH_2 is 30 g/mol (3, 6, 17, 41, 5, 58, 60)
[1] Molar mass is incorrect (50)

Periodic Trends / Electron Configuration

[2] Electron configuration, H is $1s^1$, O is $1s^2 2s^2 2p^4$ (4,43)
[1] Oxygen has smallest ionization energy (52)
[1] Oxygen has largest electron affinity (52)
[3] Incorrect electron configuration (4, 43, 52)
[1] Oxygen has smallest atomic radius (52)

Lewis Structures

[21] Correct Lewis structure (1, 2, 4, 7, 36, 37, 38, 39, 40, 43, 13, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60)
[4] Molecule satisfies the octet rule (43, 13, 36, 54)
[4] O is the most electronegative (6, 5, 53, 57)
[3] C obeys the octet rule (1, 40, 55)
[3] C has zero lone pairs (3, 54, 55)
[3] Oxygen has two lone pairs (1, 53,57)
[3] 12 valence electrons (7, 10, 56)
[2] Harder to break double bond than single (4, 60)
[2] Calculate ΔEN (39, 40)

[1] Oxygen has a full valence shell (5)

[1] Hydrogen one single bond (13)

[1] Oxygen has two bonds (13)

[1] CO is a double bond (57)

[1] The atom has 2 single bonds and 1 double bond (1)

[1] States two lone pairs (43)
[1] Calculates formal charges for each atom (51)

[1] Formal charge is 0 (4)
[1] C can have up to four bonds (3)
[1] COH_2 has four bonds (41)
[1] Total electrons are 16 (52)
[1] Single line equals two electrons (55)
[1] Hydrogen only needs two valence electrons (55)
[1] Pairing of single electrons makes a bond (42)
[1] O has an electronegativity that is greater than the H atom (60)
[9] Incorrect Lewis structure (6, 8, 10, 16, 17, 41, 42, 5, 50)
[4] The molecule contains 12 electrons (6, 17, 5, 55)
[2] H is the most electronegative (4, 7)
[1] Carbon has 6 valence electrons, oxygen 8, hydrogen 2 (39)
[1] Oxygen has 9 valence electrons (40)
[1] One lone pair of electrons (16)
[1] Lewis Structure has no lone pairs (36)
[1] Carbon shares all its electrons (42)
[1] Oxygen only shares one pair of electrons (42)
[1] Attempts to share resonance by rotating molecule (50)
[1] Oxygen needs six bonds to complete octet (16)
[1] Carbon likes to be the central atom (13)
[1] C to O is a non-polar covalent bond and C to H is polar covalent bond (40)
[1] Polar bonds between each element (39)
[1] Since O is greater EN it pushes H's closer together (60)
[1] There are no free radicals (10)
[1] No resonance (10)

Geometry/ Shape
[15] Bond angle is 120° (1, 2, 4, 5, 13, 17, 36, 37, 40, 43, 54, 55, 58, 59, 60)
[14] Polar molecule (1, 3, 5, 13,16,6, 10, 38, 43, 41, 51, 54, 55, 56)
[11] Draws trigonal planar (3, 4, 7, 36, 37, 39, 41, 54, 55, 58, 59)
[10] Electron geometry is trigonal planar or trigonal planar electron cloud arrangement (1, 3, 36, 37, 40, 54, 55, 56, 58, 59)
[8] Molecular geometry is trigonal planar (5, 13, 36, 37, 40, 54, 56, 58)
[7] State trigonal planar (2, 7, 17, 50, 53, 57, 60)
[3] Shape is trigonal planar (1, 6, 39)
[3] Three electron groups or three bonding sites (2, 4, 17)
[1] Physical geometry is trigonal planar (43)
[3] Tetrahedral electron geometry (10, 16, 43)
[3] Bond angle is 109° (7, 16, 43)
[3] COH_2 is nonpolar (17, 36, 37)
[2] Tetrahedral shape (10, 38)
[1] Draws tetrahedral (16)
[1] Geometry is T-shaped (2)
[1] Shape is bent (2)

Valence Bond Theory

[7] C to O has a sigma and pi bond present (C to H is a sigma bond) or tallying of sigma or pi (1, 37, 38, 40, 13, 51, 53)

[2] sp^2 hybridization (2, 40)

[1] The single bond is call a sigma bond (4)

[2] The double bond is called a pi bond (4, 53)

[1] Has 2sp orbital (38)

[1] Hydrogen bond is weak in s-orbital (50)

[1] Double bond in p-orbital (50)

[1] CO is sp^2, HC is sp (51)

Miscellaneous

[2] Hydrogen is a diatomic molecule (6, 5)

[1] Colorless gas (3)