Notable High School Chemistry Concepts Not Mastered Prior to Entering General Chemistry

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Abstract

With the advent of the end-of-course (EOC) State of Texas Assessment of Academic Readiness (STAAR) exams in chemistry, it is necessary to hone in on specific topics that need targeted attention. In this study 286 postsecondary students enrolled at a large north Texas public university were evaluated as to their retention of typical first semester general chemistry concepts using the nationally recognized American Chemical Society (ACS) California Chemistry Diagnostic Exam 1997 (CA Dx). The five most common misconceptions held by these general chemistry students were identified as: bond polarity, use of significant figures in laboratory procedures, Lewis dot structures, nomenclature, and algebraic relationships in gas laws. In addition, possible sources of these errors and suggestions for correction are discussed.

Keywords: high school chemistry standards, college readiness, general chemistry, misconceptions, mastery

Introduction

What is learned in high school chemistry is important to students' future success. General chemistry, a known gateway course to several STEM degrees including biology, biochemistry, engineering, and chemistry ultimately impacts future STEM careers. The Texas Education Agency (TEA) sets the standards for public education from first grade to high school in Texas. High school teachers are supposed to base their curricula on the Texas Essential Knowledge and Skills (TEKS). The TEKS were initially adopted in July 1997 and have been revised many times since. The TEKS are tested on the Texas Assessment of Knowledge and Skills (TAKS), a test that students must pass in order to graduate from high school (Texas Education Agency and Pearson, 2009). The State of Texas Assessments of Academic Readiness (STAAR) program, which consists of 12 end-of-course exams (EOCs), will replace the TAKS test as a graduation requirement for students in the ninth grade during the 2011-2012 school year according to the House Bill 3 Transition Plan (Texas Education Agency, 2010a). Since the Chemistry STAAR has yet to be instituted, this study can only assess students' knowledge of those who were required to sit for the generic high-stakes TAKS Science exam. This study also serves to document persistent problem areas that need concentrated attention for current secondary students who choose to matriculate to postsecondary opportunities.

The Texas Higher Education Coordinating Board (THECB) works to ensure the quality of postsecondary education for Texas students. Texas is among the first states to develop a set of readiness standards. These standards have been published as the Texas College and Career Readiness Standards (TCCRS) that were adopted in January 2008 (Texas Education Agency, 2010b). The TCCRS for chemistry include specific competencies for the following concepts: matter and its properties, atomic structure, periodic table, chemical bonding, chemical reactions, chemical nomenclature, the mole and stoichiometry, thermochemistry, properties and behavior of gases, liquids, and solids, basic structure and function of biological molecules, and nuclear chemistry (THECB and TEA, 2008). These standards have played an influential role in the current revised TEKS of 2010.

What is college readiness?

College Readiness Assessment in High School

Mastery of the TEKS is currently measured by performance on the TAKS. The TAKS test was mandated by the Texas Legislature in 1999 and was first administered in the spring of 2002-2003 school year to students in grade 11 (Texas Education Agency and Pearson, 2009). The exit-level TAKS given in grade 11 became a high school graduation requirement for the students that were in grade 8 as of January 1, 2001 (Texas Education Agency, Pearson Educational Measurement, Harcourt Educational Measurement, and BETA Inc., 2004). This test is now being phased out and replaced with the STAAR EOC exams, one of which will be in chemistry. The graduating class of the 2014-2015 school year will be the first cohort of students to be required to take and pass STAAR exams as part of their graduation requirements pending any legislative changes according to the House Bill 3 Transition Plan (Texas Education Agency, 2010a). As of now, Texas Education Code TAC §74.62, which discusses graduation requirements, states that students must meet state assessment requirements as well as complete and pass several courses including a minimum of three credits of mathematics (including one year of Algebra I and one year of Geometry), and two credits of science (including one year of Biology and one year of Integrated Physics and Chemistry (IPC) or one year of a separate Chemistry course) (Texas Administrative Code, 2010).

The Exit Level TAKS test includes four sections: English Language Arts, Social Studies, Mathematics, and Science. The TAKS measures statewide curricula in Reading at grades 3-9; in Writing at grades 4 and 7; in English Language Arts at grades 10 and 11; Social Studies at grades 8, 10, and 11; in Mathematics at grades 3-11; and in Science at grades 5, 10, and 11. A student must have satisfactory performance on all sections of the TAKS tests administered in grade 11 to be eligible for a high school diploma in the state of Texas. If a student does not pass the test during this administration, the student has other opportunities to retake and pass the test in order to successfully complete high school (Texas Education Agency and Pearson, 2009).

It is assumed that students at the University of North Texas (UNT) who enroll in General Chemistry for Science Majors (gen chem I) have met the prerequisite requirements for course enrollment. According to the 2010-2011 UNT course catalog, students are required to take and pass College Algebra (or equivalent) before they are allowed to register for this course. The prerequisite for College Algebra is two years of high school algebra, one year of geometry, or the consent of the mathematics department indicating that the equivalent of the College Algebra level has been acquired (University of North Texas, 2010).

Assessment of College Readiness in College Level Chemistry

Noncognitive Predictor: Motivation

According to Zusho, Pintrich, and Coppola (2003) the issue of the students' view of themselves as chemistry students and their impression of the subject of chemistry impact their level of achievement in college chemistry courses. This study found that as students received feedback from their examinations, their confidence levels fell with the exception of the students characterized as high achievers. The authors' conclusions emphasized the importance of maintaining self-efficacy levels and observed that successful students began using self-regulatory and organizational strategies as the course progressed. This study pointed out that in addition to students who typically achieve higher scores in postsecondary chemistry, motivated middle achievers did well in this course (Zusho et al., 2003).

According to a recent student evaluation in gen chem I, prior knowledge is the most important factor that can be used to predict success in this course (Manrique, 2010). This is consistent with the Unified Learning Model (ULM) of Shell, Brooks, Trainin, Wilson, Kauffman, and Herr (2010), and suggests how important it is for high school teachers to successfully teach chemistry material to students. A student's logic skills were also shown to be very important to succeed in the chemistry classroom. A scientist needs logic skills to solve complex problems. The ULM focuses on the basic components of learning that are common amongst all learning theories. It is a simple model that can be used to explain all observed learning phenomena (Manrique, 2010). The main components of this model are: prior knowledge, working memory, and motivation. The working memory is the location where new knowledge is temporarily stored and processed. Knowledge is defined as everything we know stored in long-term memory or our prior knowledge. This prior knowledge includes everything from facts, skills, behaviors and thinking processes. Motivation is the catalyst to learning. If a student is not motivated to learn a new concept, the new knowledge will not even be temporarily stored into the working memory. Motivation directs the working memory to learn a new task (Shell et al., 2010).

Cognitive Predictor: Prior Knowledge

The California Chemistry Diagnostic Test 1997 (CA Dx) was originally designed to be used as screening tool for students interested in enrolling in college level general chemistry in California and has evolved into a useful diagnostic tool (Russell, 1994). It was validated in 1995 as a predictor for academic success (Karp, 1995). This study focused on the use of the CA Dx as a tool for assessment of college readiness for students enrolled in gen chem I. The CA Dx requires that 44 questions be answered in 45 minutes; any question left blank is counted as a wrong answer. The CA Dx has been given as a diagnostic pre-test by the second author since fall 2001 generating a mean (standard deviation) of 18.41 (6.29) with a range of 5 to 42 for a student population of n = 1,638, which is below the national mean of 20.45 (7.56). A copy of the CA Dx exam may be ordered from http://chemexams.chem.iastate.edu/order/index.cfm (American Chemical Society Division of Chemical Education, 2009).

Some schools use the CA Dx as an optional test that allows students to enroll directly into general chemistry when a preparatory course is available. Students at Winthrop University in South Carolina, University of Nevada, Las Vegas and Santa Monica College in California can enroll directly into general chemistry and avoid taking introductory chemistry by passing the CA Dx (Santa Monica College, 2007; University of Nevada, Las Vegas; Winthrop University). UNT does not have this option so all students who enroll in a science major sequence must take General Chemistry for Science Majors. Another option is to score a 3, 4, or 5 on the College Board Advanced Placement Chemistry (AP exam) that usually places students into the second semester of general chemistry (University of California, Riverside, 2010). Not all universities offer an introductory chemistry course nor will all universities accept AP credit. At UNT students who have completed the published prerequisites are allowed to enroll in gen chem I and are expected to acquire any deficient background knowledge on their own.

Problem

Despite the national and state standards required to graduate from high school, there will always be concepts that are not retained by students between the time they are evaluated on the TEKS and when they enter general chemistry at the postsecondary level. Students enrolled at UNT have been shown to lack knowledge of foundational general chemistry concepts such as significant figures (especially those needed to employ rules for adding/subtracting), chemical structure (such as bond polarity and Lewis structures), basic chemical nomenclature, and algebraic relationships (such as those used in gas law calculations). Students are also making careless errors such as not paying attention to accepted definitions or not using their time allotted wisely.

The purpose of this investigation is to identify the most common concepts not retained by postsecondary students (i.e., misconceptions of students enrolled in entry-level gen chem). After identification, the approach evolves to identifying the most commonly chosen wrong answers of the most commonly missed questions on the CA Dx and attempting to give supporting explanations for these persistent misconceptions that directly relate to their prior chemistry content knowledge.

Method

The Students

The students involved in this study have been admitted to one of the top four largest universities in Texas. Students enrolled in gen chem I are mostly science majors as the title of the course implies, but some are engineering majors and a few others (e.g., education and psychology majors) are enrolled. Data from the CA Dx were used to assess the prior chemistry content knowledge of the 286 students who gave IRB consent. Responses of these students were chosen based on their enrollment in the course during one of three consecutive semesters. All of these courses were sections of gen chem I during the long-term semesters (i.e., no summer sessions were included).

The Test

The means (standard deviations) for the students who participated in this study are listed in Table 1. These means are slightly below what was reported above for the entire sample. In general, fall-semester students (n = 1111) available for study outperform the spring students (n = 527) by 1.70 points of the 44 total points on the CA Dx instrument. The general conscience for this discrepancy is that the spring students usually do not have the required mathematics (i.e., successful completion of college algebra) or have a negative perception to studying chemistry, which has delayed them from beginning the required courses for their respective science and engineering degrees. In this particular sample (n = 286), there was no significant difference in the CA Dx means. The item analysis results of these tests were combined to determine the top five missed questions on the CA Dx exam and the most common incorrect answers for these questions in order to examine misconceptions held by entering gen chem I students.

Table 1. Student Averages on the ACS California Diagnostic Exam

	N	CA Dx Mean (SD)
Semester 1	101	18.23 (6.00)
Semester 2	43	18.40 (6.60)
Semester 3	135	18.39 (6.35)
Combined	286	18.33 (6.26)

This test is given to students enrolled at the beginning of the semester as a pretest to assess prior content knowledge. The students are told that the results of this test would not impact their course grade. The instructions on the test indicate that only one answer choice is correct and the final score is based on the number of correct responses. Access to a periodic table of the elements and table of abbreviations/symbols are available as part of the CA Dx exam; the use of a non-programmable calculator is permitted.

Data Analysis

The responses provided by each student were entered into a Microsoft Excel spreadsheet to determine the number of responses for each answer choice on each question. The number of responses was compiled as indicated by the number of the most commonly chosen wrong answers and the number of correct responses. The z score value was calculated for the most commonly chosen wrong answer responses and the correct responses. The occurrences of the most commonly chosen wrong answer choice and the correct answer choice were tested to determine if statistically significant difference existed at the 95% level of significance. The z critical value for this sample size for a two tailed hypothesis test with an alpha of 0.05 was +/- 1.96.

The common wrong answers with positive z scores above +1.96 were considered choices that were chosen more frequently than they would have if all answers were chosen randomly. An interpretation of this situation is that many students thought that these were the correct answers in addition to the random guesses. The correctly chosen answers with negative z scores below -1.96 were considered choices that were chosen statistically less often than they should have been, based on a 25% chance at being chosen at random (i.e., each of the 44 questions has 4 possible choices). An interpretation of these results is that there was another answer choice that was a successful distractor indicative of a misconception.

The 44 questions were ranked from most correct to least correct for the five questions that produced a negative z score below -1.96 for the number of correct responses along with a positive z score above +1.96 for the most commonly chosen wrong answer (see Table 2). The five questions in which the correct answers produced negative z values < -1.96 were the top five most missed questions, and the most commonly chosen wrong answer showed positive z scores > +1.96. The calculated z values of these five questions indicated that students chose the most common wrong answers more than randomly predicted and the correct answers less than randomly predicted. These results are most likely due to misconceptions or wrong concepts that students held at the time of the test.

Table 2. Most Common Misconceptions on the CA Dx Exam (n = 286)

Most Missed Question Number (least to greatest): Topic	z Wrong	z Correct	Most Common Wrong Response	Correct Response
19: Bond Polarity	5.12	-2.94	109	50
34: Significant Figures	16.18	-2.94	190	50
24: Lewis Dot Structures	15.64	-3.89	186	43
2: Nomenclature	16.73	-4.57	194	38
44: Algebraic relationships in gas laws	6.62	-5.67	120	30

Results

The fifth most commonly missed question ranked in the top 5 most missed questions for each administration of the test. This question has a z value of 5.12 for the most popular wrong answer and a z value for the correct answer of -2.94. In other words, 109/286 or 39.1% of the students tested chose the same wrong answer. This question asked the student to choose the bond with the highest polarity from a list of bonds. The most commonly chosen wrong answer was a pure covalent nonpolar bond, the exact opposite of what the question was asking. Fifty-three students may not have seen the more electronegative element on the periodic table. Sixty-nine students chose the least polar bond of the polar bonds given. Five students left this question blank and only 50 chose the correct answer. It appears that these students do not know the definition of a polar bond or how elements differ in electronegativity. This concept corresponds to TEKS Chemistry 5C, which states that students are expected to "use the periodic table to identify and explain periodic trends, including atomic and ionic radii, electronegativity, and ionization energy" (Texas Administrative Code, 2009a). Students should be able to "determine if a molecule is polar", according to TCCRS (THECB and TEA, 2008).

The fourth most commonly missed question had the second largest z value for the commonly chosen wrong answer out of all of the questions at 16.18. In other words 190/286 or 68.1% of the students tested chose the same wrong answer. The z score for the students that chose the correct answer was -2.94. The results of this most commonly chosen wrong answer is indicative that the concept tested is either a common misconception or concept that failed to be retained. This question asked about a laboratory technique using a balance, and reported the measurement of the weighed container with and without the mass using different numbers of significant figures. One hundred ninety students chose the answer that indicated an understanding of the procedure, but disregarded the add/subtract rule of using significant figures when reporting answers. Thirty-nine students chose the distractor that failed to take into account the combined mass of the container and object, and only gave the container's mass. Three students chose the other distractor and four left this question blank.

The results of this question show that students are not aware of significant figure rules at the time of the test. According to Benchmarks for Science Literacy: Project 2061, "Students by the end of the 8th grade should know that calculations (as on calculators) can give more digits than make sense or are useful …" and "decide what degree of precision is adequate and round off the result of calculator operations to enough significant figures to reasonably reflect those of the inputs" (American Association for the Advancement of Science, 1993). This also corresponds with TEKS Chemistry 2F, which states that students are expected to "collect data and make measurements with accuracy and precision", and 2G "express and manipulate chemical quantities using scientific conventions and mathematical procedures, including dimensional analysis, scientific notation, and significant figures" (Texas Administrative Code, 2009a). Significant figures are listed in the TCCRS under the Geometry standards and under the Foundation Skills: Scientific Applications of Mathematics section of the Science standards (THECB and TEA, 2008) and will supposedly be stressed on the upcoming Chemistry STAAR exam.

The third most missed question with the third most commonly chosen wrong answer had a z value of 15.64. The correct response had a z value of -3.89. The most commonly chosen wrong answer for this question was in the top 5 most commonly chosen wrong answers for each administration of the test and produced a most common wrong answer rate of 186/286 or 66.7%. This concept is another concept that needs to be looked at more closely in order to improve the quality of chemistry instruction based on these z values. This question tested the understanding of Lewis dot structures. The most commonly chosen wrong answer misinterpreted the dots on the diagram as the atomic number, as opposed to the number of valence electrons.

This question involves knowledge of the structure of an element, specifically the Lewis dots, which represent valence electrons. This knowledge corresponds to TEKS Chemistry 6E, which states that the student is expected to "express the arrangement of electrons in atoms through electron configurations and Lewis valence electron dot structures" (Texas Administrative Code, 2009a). The TCCRS state that students should be able to "draw Lewis dot structures for simple molecules" (THECB and TEA, 2008).

The American Association for the Advancement of Science states, "By the end of the 12th grade, students should know that atoms are made of a positive nucleus surrounded by negative electrons. An atom's electron configuration, particularly the outermost electrons, determines how the atom can interact with other atoms. Atoms form bonds to other atoms by transferring or sharing electrons" (American Association for the Advancement of Science, 1993).
Under the National Science Education Standards by the National Research Council (1996) students in grades 9-12 in physical science are to master the following related concepts:

- Atoms interact with one another by transferring or sharing electrons that are furthest from the nucleus. These outer electrons govern the chemical properties

of the element.
- An element is composed of a single type of atom. When elements are listed in order according to the number of protons (called the atomic number), repeating patterns of physical and chemical properties identify families of elements with similar properties. This 'Periodic Table' is a consequence of the repeating pattern of outermost electrons and their permitted energies. (pp. 178-179)

The second most commonly missed concept regarded formula writing for ionic compounds. The most commonly chosen wrong answer for this question used the symbols for the ions in the compound, but disregarded the impact of the charges of the individual ions to determine the subscripts. This response had a z score of 16.73 with 194/286 or 69.5% of the students choosing this response. The answer choice that involved using the charge of the cation to determine the subscript of the anion without using the charge of the anion was chosen by 29 students. Seventeen students chose the answer in which the charge of the ion was used as the subscript for that ion and eight failed to respond.

The expectation of writing a chemical formula is also expressed in the TEKS. This concept corresponds with TEK 7B, which states that students should "be able to write the chemical formulas of common polyatomic ions, ionic compounds containing main group or transition metals, covalent compounds, acids, and bases" (Texas Administrative Code, 2009a). According to Benchmarks for Science Literacy: Project 2061, students should know that atoms combine with one another in distinct patterns (American Association for the Advancement of Science, 1993). Under the National Science Education Standards by the National Research Council (1996) students in grades 9-12 in physical science are to master the following related concepts:

Bonds between atoms are created when electrons are paired up by being transferred or shared. A substance composed of a single kind of atom is called an element. The atoms may be bonded together into molecules or crystalline solids. A compound is formed when two or more kinds of atoms bind together chemically. (p. 179)

The question that was missed the most overall was also either the most or second most commonly missed questions for each administration of the test. This question had the lowest z score for the correct answer of all of the items included on the test. For this question, 120/286 or 43.0% of the students tested selected the same wrong answer. The z score for the correct answer was -5.67, with the z score for the most commonly chosen distractor being 6.62. The wrong answer for this question was the eighth most commonly chosen wrong answer overall. The question asked for students to consider a formula and answer a conceptual question regarding how a relationship would change in light of maintaining a constant, if two variables were changed (i.e., increasing one by a factor of X and decreasing another by a factor of Y). In order to get this incorrect answer, the students failed to take into account that the direction of change in the numerator increased and the direction of change in the denominator decreased along with the fact that a constant must be maintained. The second most common incorrect answer (i.e., 73 responses) reported the correct overall direction of change but did not take into account that the denominator's variable was decreasing and needed to be compensated for by increasing the numerator by that factor. The answer choice for the third most common wrong answer (i.e., 46 responses) had the correct magnitude of change but opposite direction indicating they may have understood the magnitude of change but not the concept of a constant. This question was left blank by 17 students and answered correctly by only 30 students (just over 12% of the student responses evaluated).

This question may have thrown students off because it is a question concerning gas laws without any reference to gases, corresponding to TEKS Chemistry 9A, which states that the student is expected to "describe and calculate the relations between volume, pressure, number of moles, and temperature for an ideal gas as described by Boyle's law, Charles' law, Avogadro's law, Dalton's law of partial pressure, and the ideal gas law" (Texas Administrative Code, 2009a). The TCCRS state that students should be able to solve for gas temperature, pressure, or volume using algebraic symbols and formulae (THECB and TEA, 2008). This question was the last question on the exam and mathematically the most challenging, since changes in different directions of multiple variables were involved. However, prior chemistry knowledge was not important to finding the answer to this question—only good algebraic skills! This question had the third most responses that were left blank out of all of the questions further supporting how important algebraic skills are to success in general chemistry and the importance of teaching gas laws from a conceptual standpoint.

Discussion

Possible Sources of Error

One cannot determine the intentions of the students beyond their responses on the answer sheet and so all of the answer sheets that had any responses on them counted toward these results. It is possible that students may not have taken the test seriously having the knowledge that the results of this test would not affect their grade in the course, but most students do take this exam seriously since it is usually the first test they ever taken in college and they desire to get off to a good start.

Explanation of Findings

Students entering gen chem I are expected to be proficient on the topics tested on the CA Dx upon entry into the course. There are a few explanations as for why these students had not mastered these concepts before entering this course. The concepts targeted in these results were bond polarity, significant figures in laboratory procedures, Lewis dot structures, nomenclature and algebraic relationships in gas laws. All of these concepts are indicated as college readiness standards as of fall 2010 (THECB and TEA, 2008). At the time of this study several of these concepts have not been tested on the TAKS test because the TAKS test was designed to ask chemistry questions based on the more basic IPC course. Since current graduation plans still allow for IPC to count as a year of science, this provides a loophole that allows students to be able to graduate high school without a full year of chemistry (Texas Administrative Code, 2010). In light of the recent changes to the state standards, high school teachers are now making changes to their course curricula that reflect the new expectations. It may also be possible that the revisions that have been made to support the new standards need more work in order to be effectively received by students.

Conclusions and Suggestions

Students are not retaining or lack knowledge of general chemistry concepts that are expected of a student entering gen chem I, such as polarity, significant figures, periodicity, naming and algebraic manipulations. Students are making careless errors such as not paying attention to the definition of a constant or failing to apply skills that should have been acquired before entering college, such as manipulation of fractions and decimals (Texas Education Code, 2006) and proportional reasoning (Texas Education Code, 2009b).

The next generation of the TEKS assessment is the STAAR program which, according to the House Bill 3 Transition Plan, is designed to increase the rigor of course assessment so that students will know when they meet a higher level of academic knowledge and skills needed to meet the challenges of the 21st century (Texas Education Agency, 2010a). However since the STAAR results on individual subject tests can be combined to determine a student's eligibility for graduation, this still leaves room for vital chemistry concepts to fall through the cracks. These topics (bonding, significant figures, Lewis dot structures, nomenclature, and gas laws) are basic concepts that a student should not leave high school chemistry without. Our data also indicate that mastery of mathematical understanding is very important to student success even on a conceptual chemistry exam.

Finally, it is important that chemistry instructors of all levels make chemistry relevant to their students. The relevance of chemistry in everyday life helps students identify and grasp some concepts more readily than others. Students should therefore be given the opportunity to practice these concepts and delved more in depth into more complex concepts at different cognitive levels so that they are aware of what is expected of them now and in the future. At the very least, assessments, assignments, and lectures should be designed to complement each other and provide students with the foundational knowledge they need to excel in gen chem I.

Students need to meet educators half way, but educators need to be prepared to guide their students through possible roadblocks that may thwart their success in the courses. The material presented in the high school classroom needs to provide the student with a basis to continue their education whether it is at a postsecondary institution, career, or independent study beyond the course. The guidelines set up for high school teachers to follow need to adequately reflect the purpose of these courses. This will aid in maintaining the students' academic self-image, assuming that they are motivated to succeed in the course.

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