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Development of a Chemistry Concept Inventory for Use in Chemistry, Materials and other Engineering Courses

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Introduction

Concept Inventory (CI) is the label given to an exam that explores students' mental models, their qualitative images, of how science and engineering work. It is believed, and data support, that students can often solve mathematical problems in a course but have poor or incorrect mental models about the fundamental concepts behind the mathematics. For example, a student may be able to recall, or deduce, and then apply the proper equation to solve the problem:

Standard Course Question   When 1.00 kJ of heat are absorbed by a 370 gram weight if steel, its temperature rises from 20.00 to 25.45ºC. What is the heat capacity of steel in joules per degree-gram?

However, that same student may not answer the following qualitative, conceptual, question correctly.

CCI-chem I #4 In a classroom there are metal chairs and plastics chairs. Students say that the metal chairs feel colder than the plastic ones. Why?

A) Metal naturally has less heat than plastic.
B) Metal naturally has more cold than plastic.
C) Metal quickly conducts heat away from your hand.
D) Metal attracts and holds cold.
E) Plastic is an insulator and attracts and holds heat.

We teachers would like students to be able to understand and correctly answer both questions. However, our traditional college curricula emphasize the former, quantitative, type exercises and simply assume that student success on these implies strong conceptual mental models that would have them answer the latter, qualitative, question correctly.

Data [1] from the well researched physics CI, the Forced Concept Inventory by Hessten,[2] show that this assumption is not good. Most students who succeed in our science and engineering courses still have seriously immature or outright incorrect mental models about the subjects they have studied. Their concept understanding is much weaker than it should be.

This paper describes the ongoing work on the development and testing of a Chemistry Concept Inventory (CCI) meant to help faculty determine the extent of misconceptions about chemistry that students might carry into their engineering courses. The CCI is also meant to serve as an evaluation instrument for chemistry or engineering faculty who devise new ways of teaching designed to repair students misconceptions and strengthen their correct mental models of chemistry. The work reported here was primarily done by co-author Brooke Jenkins as part of her Masters research in Chemical Education.

History and Scope

The CCI work was conceived and is funded by the managers of the Foundation Coalition [3,4]. Donavon Evans of Arizona State University has put together teams of faculty from around the country to write concept inventories for most fundamental engineering subjects. Among the subjects being addressed are thermodynamics, signals and systems, electromagnetics, dynamics, circuits, strength of materials, statistics and material science[4]. The first objective of all this work is to provide the engineering education community with reliable exams that can be used to determine the extent to which students do hold misconceptions about fundamentals in these engineering and science subjects. The second objective is to have faculty experiment with teaching approaches designed to correct such problems, with the various CIs serving as one assessment method for evaluating and refining teaching methods.

The Chemistry CI was conceived primarily from the work of co-author Steven Krauss on his CI for materials science[5]. This CI contains several questions that relate back to chemistry concepts taught as precursors to engineering courses and it was found that students did carry misconceptions out of their chemistry courses that could impact understanding of engineering concepts. Thus it was deemed wise to have chemistry CIs also available for such overlapping concepts.

The co-authors brainstormed, discussed and refined what they felt were the primary overlapping topics between general chemistry and succeeding engineering courses. The following were identified for the Chemistry CIs.

Table 1. Topics Covered

Test	Topic	Sub-Topics
Chemistry I	Thermochemistry	Heat Concept Thermal Conductivity Thermal Equilibrium
	Bonding	Bond Polarity Octet Rule
	Intermolecular Forces	Intermolecular Forces
Chemistry II	Equilibrium	Equilibrium Rate Equilibrium-Dynamic vs. Static Equilibrium- Le Chatelier's Principle Equilibrium Constant
	Acids and Bases	Acid/Base Neutralization

	Acid Strength PH
Electrochemistry	Oxidation/Reduction Voltaic Cells Electrolytic Cells

The topics are keyed to the two semesters of a normal general chemistry course for ease of testing. Thus two CCIs have been created and are being tested, one for Chem I the other for Chem II. The goal is to have each, as final products, a 20-question multiple-choice exam that can be administered in 15-20 minutes and give reliable information on misconceptions in these fundamental subtopics.

The plan being followed for the development and testing of the two CCIs is outlined below.

Table 2. Steps of Development of reliable CCIs

1. Pick topic topics and subtopics to be to be covered.
2. Search the literature for research on misconceptions in those topic areas.
3. Write at least three questions in each sub-topic.
5. Administer these questions to students. (Version A)
6. Eliminate weak questions based on the discrimination index, difficulty index, and the coefficient alpha.
7. Administer the remaining questions to students. (Version B)
8. Interview students on selected questions.
9. Modify questions based on results from test and student interviews.
10. Administer the modified questions. (Version C)
11. Repeat steps 8 through 10 until acceptable reliable results are attained.

To date the chemists at ASU, particularly Brooke Jenkins, have taken the process through step 10. Particulars are given in the next sction.

Data on the CCIs

An extensive literature search was carried out to identify misconceptions that have already been studied associated with the our CCI topics and subtopics. There is a large body of literature available on chemistry misconceptions. However, no previous CI directly useful for our purposes is directly available since most studies focused on one topic or subtopic only. There are two prominent broad Chemistry CIs available in the literature[6,7], but these do not cover our topics well enough and one is not easily available for general use. However, because of this extensive literature available, distracters could be designed to test for known misconceptions and insights on others were established.

For each subtopic, at least three questions were written giving a total of 30 questions for the Chemistry I inventory and 31 questions for the Chemistry II inventory. The questions were intended to be conceptual, not mathematical or algorithmic. These questions were initially given to the students in Chemistry I and II as part of their weekly quizzes. The questions were then compiled into Version A of the CCI. Because the questions were given after the students had covered the information in lecture, only post-test data were available. Table 3 summarizes these results.

Table 3. Results from CCIs Versions A

Chemistry I	Chemistry II
N = 326 Students	N = 158 Students
Alpha = 0.7883	Alpha = 0.7855
Post-Test Mean = 14.73/30 = 49.1%	Post-Test Mean = 18.53/31 = 59.8%

The Cronbach coefficient alpha, discrimination index and difficulty index were used to evaluate these first versions of the CCIs. The coefficient alpha is a measure of the internal reliability of the test, the ability of the test to evaluate an individual consistently. Alpha ranges from 0 to 1 with 0.7 or higher indicating the test is reasonably reliable. It was pleasing to see that the Chemistry I and Chemistry II inventories both scored above 0.7. An alpha is calculated for the whole test. In contrast, discrimination and difficulty indices are calculated for each individual question. The discrimination index is a measure of how well the question discriminates between the students. To calculate a discrimination index, first the students are ranked by performance on the exam. A top portion of the class is compared to the bottom portion. If every student in the top portion answered the question correctly and every student in the bottom portion answered the question wrong, then the question perfectly discriminates between good students and poor students. The discrimination index would be 1. The discrimination index ranges from –1 to 1. Along with the discrimination index it is important to consider the difficulty index. The difficulty index is the percent of students that answered the question correctly. Since a question can receive a low discrimination index because the majority of the class answers the question right or the majority of the class answers it wrong, it is important to combine these two indices when evaluating a question.

Another way of evaluating questions is to see what effect eliminating a question will have on the coefficient alpha. One of the goals of the CCI is for it to be administered it in a short period of time. In order to do so, the test had to be shortened. Questions were eliminated so that the Chemistry I and Chemistry II inventories were 20 questions long. The three questions were written on each sub-topic so that one question could be eliminated leaving two questions on that sub-topic. But eliminating questions also has a converse affect on the alpha, thus lowering the reliability of the CCI. Therefore after a question was eliminated, the alpha was calculated to see what affect that elimination had. Eliminated questions were those that would have the least negative affect on the alpha.

These data as well as expert judgment were combined to eliminate weak questions to leave two 20-question tests. Also, a number of questions were modified to make them clearer. The Chemistry I and II Version B were then piloted during the summer of 2003. The Chemistry I Version B of CCI was given to university students at the beginning of the semester for a pre-test and again at the end for a post-test. The Chemistry II Version B was given at a community college at the beginning of the semester as a pre-test. Then the questions were spread out over several weekly quizzes. Results from the weekly quizzes were combined to use as the post-test. Results from Version B of the CCI are summarized in Table 4.

Table 4. Results from CCI Version B

Chemistry I	Chemistry II
N = 42 University Students	N = 42 Community College Students
Alpha = 0.7135	Alpha = 0.4188
Pre-Test Mean = 5.48/20 = 27.4%	Pre-Test Mean = 7.17/20 = 35.9%
Post-Test Mean = 10.60/20 = 53.0%	Post-Test Mean = 10.93/20 = 54.7%

During the summer of 2003, 11 students were interviewed in depth on seven questions on molecular shape from the CCI Chemistry I Version B. Student interviews give helpful insight into how students solve problems and to identify misleading wording in the questions and are a consistently used tool in misconception research. For these interviews using Version B, students were chosen from those students currently taking the first semester of general chemistry. They were interviewed just after covering the relevant information in lecture. These interviews led to some to some needed clarifications in question wording. Because the interviews also uncovered misconceptions held by these students, they also helped to validate the test.

These interviews and the results from Version B testing lead to changes which became C versions of the CCIs. During Fall 2003, the Chemistry I and II CCIs were administered to a large number of students. Available information from this version is in Table 5.

Table 5. Results from CCI Version C

Chemistry I	Chemistry II
N = 845 Students	N = 136 Students
Alpha = .5541	Alpha = .4761
Pre-Test Mean = 4.94/20 = 24.7%	Pre-Test Mean = 6.51/20 = 33.6%

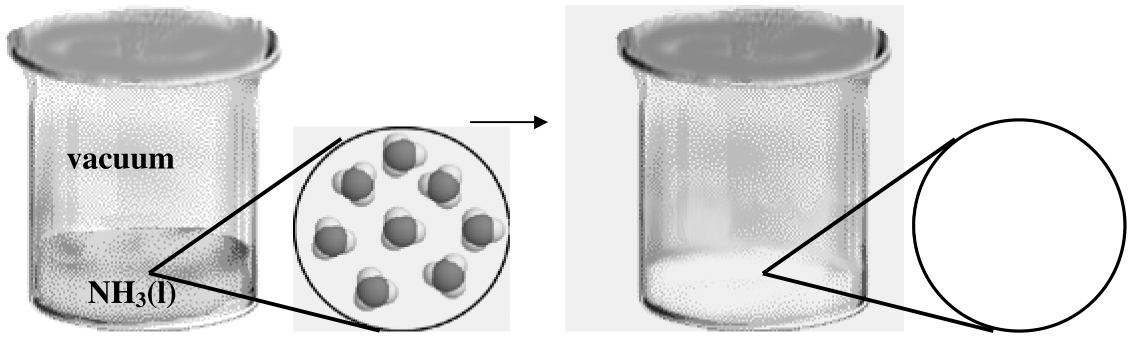
Two things should be noted about these results. First, the alphas for each test are low. This is expected because the information on the CCI has not been covered. Once the post-test has been given, the alpha will be calculated with that data; this will give a more true reliability measure. Second, the results show that each group's Pre-Test Mean is consistent with guessing, which is also expected given that the students are at the beginning of the semester. At the end of the Fall semester, the CCIs was administered again as a post-test. These data have not yet been analyzed, but will be by the time of final submission. The difference between the pre and post-test scores will represent what was gained by being in a that class. Results may be used to explore the effect of teaching style on student learning, at least in a priliminary way.

Value to Teaching and Learning of CIs

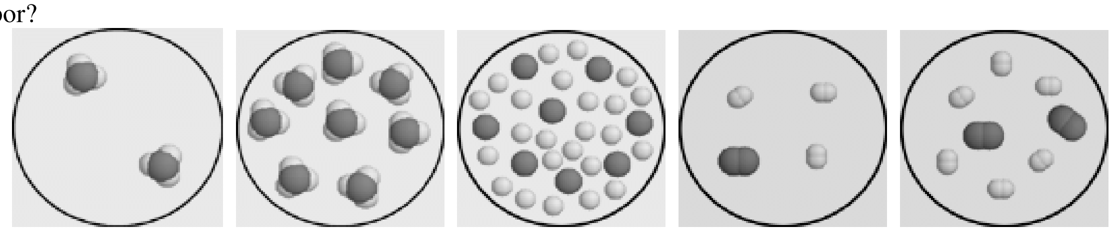
The main purpose behind all the CIs being developed by the Foundation Coalition is to allow faculty to assess students' knowledge on fundamental concepts. The vast literatures on misconception research as well as the data collect in the current study indicate that troubling misconceptions are prevalent after courses are completed. Below we give selected questions from the CCIs to show the problem.

Topic: Intermolecular Forces

CCI-chem I #19. A sample of liquid ammonia (NH_3) is completely evaporated (changed to a gas) in a closed container as shown:



Which of the following diagrams best represents what you would "see" in the same area of the magnified view of the vapor?



A. B. C. D. E.

CCI-chem I #20. Which of the following statements describes overcoming intermolecular forces?

A) Separating nitrogen and hydrogen atoms in ammonia (NH_3).
B) Separating sodium and chloride ions in sodium chloride (NaCl).
C) Separating methanol molecules from each other in liquid methanol (CH_3OH).
D) Separating hydrogen atoms from each other in hydrogen gas (H_2).
E) All of the above.

Answers are A and C, respectively. If students do not automatically see these as proper answers after studying phase changes and intermolecular forces in general chemistry, how will they be able to understand heats of vaporization, complex phase diagrams or fluid action in engines in their later engineering courses? Data show that a large fraction of students tested, more than half, get these questions wrong.

Topic: Equilibrium

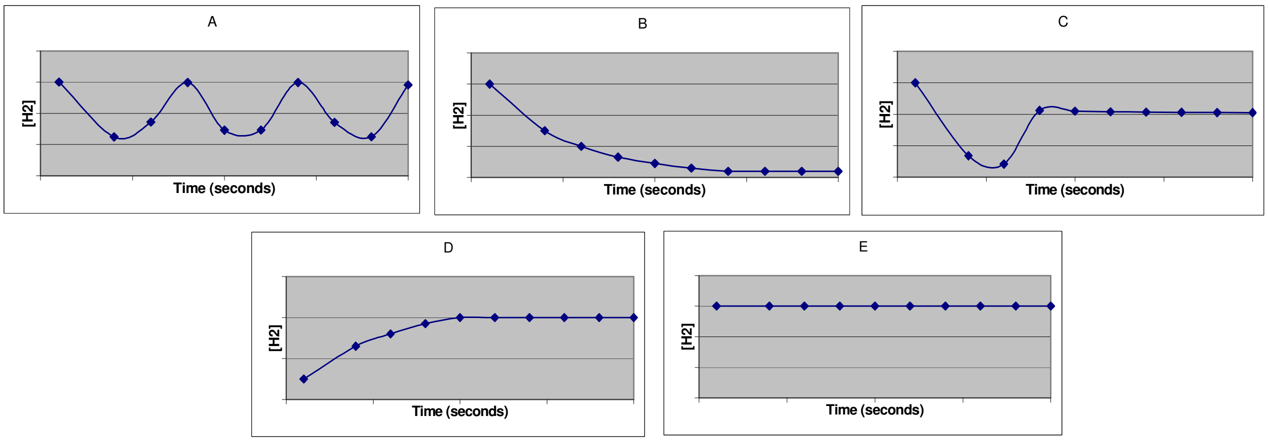
CCI-chem II #3 Once a system reaches equilibrium:

A) The forward and reverse reactions no longer occur.
B) The forward and reverse reactions continue to occur and alter the concentrations of reactants and products.
C) The forward and reverse reactions occur, but do not alter the concentrations of the reactants or products.
D) Only the forward reaction continues to occur.
E) Only the reverse reaction continues to occur.

CCI-chem II #6 Consider the following reaction:

$H_2(g) + I_2(g)$ « 2 $HI(g)$

If H_2 and I_2 are mixed together and allowed to come to equilibrium, what would the graph of



the concentration of H_2 look like over time?

Answers are C and B respectively. Again, any student who does not see the correct answers, or cannot see the errors in the wrong answers, has a very weak or incorrect image of how systems reach and maintain their equilibria. Our data to date indicate that a large fraction of students leaving their freshmen year have this problem.

The final two examples presented below deal with acids and bases. These may appear to be more terminology questions than mental models question, but that is not the case. The mental model of what constitutes a strong versus weak acid and what this says about the strength of the conjugate base is directly tested in these two questions. Students who have a strong, correct mental model of conjugate acid-base behavior will easily identify the correct and incorrect answers. The correct answers are B and B respectively.

<u>CCI-chem II #11</u> How can you distinguish a weak acid from a strong acid?

A) All acids are strong.
B) A weak acid doesn’t dissociate as much in water.
C) A weak acid has fewer protons to donate.
D) A weak acid will be more dilute.
E) A weak acid is smaller than a strong acid.

<u>CCI-chem II #12</u> Which of the following statements about strong acids are true?

A) All strong acids have more bonded hydrogens.
B) Strong acids are completely ionized in water.
C) The conjugate base of a strong acid is itself a strong base.
D) Strong acids are very concentrated.
E) Strong acids produce solutions with a high pH.

The fact that a large portion of students leaving their freshmen courses cannot correctly answer these Chemistry Concept Inventory questions indicates that their views of science, their mental models of how things work are flawed. This inaccurate thinking will get in the way of their properly understanding related topics in succeeding engineering and materials courses. Thus it is incumbent on the teachers of general chemistry and of upper level engineering courses to assess students' mental models and to find teaching approaches that correct and deepen them. If we look at the data from expert researchers in misconceptions, this is not a trivial task. We recommend the work of Michelene Chi of the University of Pittsburgh as a good starting place for veiwing this body of work. Reference #6 below is a recent overview with useful citations.

It is the long-term goal of the authors and others in the Foundation Coalition to experiment with teaching approaches that make qualitative mental models of how things work a more consistent and explicit part of our courses. Thus we will add our efforts to those of the expert researchers in misconceptions to finding ways to better educate our students, to have them learn more deeply about how the world of science and engineering works. This should put them in a better position to use their knowledge to improve the human condition.

References

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[6] "General Chemistry (Conceptual) Exam", Examination Institute of the American Chemical Society, University of Wisconsin, Madison, WI. Access to ACS Exams Institute available at http://www.uwm.edu/Dept/chemexams/MATERIALS/

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