5-2024

Development of a Solution Concept Inventory for the High School Chemistry Classroom

Grace Tetschner
gtetschner@unomaha.edu

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Grace Tetschner

University of Nebraska at Omaha

Honors Thesis

Faculty Mentor: Sachin Nedungadi

Spring 2024

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Abstract

Many high school chemistry students struggle to learn the chemistry of solutions because they hold alternate conceptions—beliefs that differ from scientifically accepted ideas—related to the topics covered in a traditional solution unit. For this reason, high school chemistry teachers would benefit from the development of a Solution Concept Inventory (SCI)—a multiple-choice assessment that could be used in the high school classroom to identify student alternate conceptions on the concept of solutions. In this study, common solution-related alternate conceptions were identified, items for an SCI were developed, an analysis was performed to determine the quality of the items, and validity evidence based on test content was obtained. 14 items were developed for the SCI.

Introduction

Alternate Conceptions in the Science Classroom

Every student who walks into a science classroom brings their own conceptions about physical phenomena—conceptions that they developed from their personal experience with the natural world. At least, this would be the view of Jean Piaget, the father of the constructivist theory of learning. Piaget believed that new knowledge is constructed and built on previous knowledge and that human beings form meaning based on experience (Piaget, 1964). The problem for educators, however, is that many students form conceptions that differ from scientifically accepted ideas. These conceptions are known as alternate conceptions. Consequently, it is the science educator's job not only to teach accurate science content but to also bring about conceptual change and reconstruct student understanding.

When new knowledge is presented to a student, two processes can occur: assimilation or accommodation. Assimilation describes the process of fitting new knowledge into existing beliefs, and accommodation refers to the process of changing existing beliefs to understand new information (Posner et al., 1982). When a student holds an alternate conception, educators want the student to go through the accommodation process. Researchers have identified the following four conditions that usually need to be met before an accommodation will occur: 1) the holder of the alternate conception must become dissatisfied with their current conception, 2) a new conception must become understandable to the holder, 3) the holder must be able to see that the new conception is plausible, and 4) the new conception should seem extendable (Posner et al., 1982). In other words, before a student lets go of an alternate conception, they must first realize that their alternate conception clashes with the new knowledge presented to them. They must understand the new conception they will have to form. They must realize that the new conception is reasonable, and they must see the value of changing their old conception—they must see how the new conception will allow them to better understand future knowledge they acquire.

These conditions indicate that students need to be, at least partially, metacognitively aware of their own alternate conceptions before accommodation will occur. Thus, science teachers (who want to call out alternate conceptions and lead their students through conceptual change) would benefit from having an assessment tool that identifies alternate conceptions held by students. One such assessment tool is called a concept inventory.

Concept Inventories

Concept inventories are multiple-choice assessments that are constructed so that the wrong answer choices (the distractors) are derived from commonly held alternate conceptions. If a student selects a distractor for an item on a concept inventory, that student may hold the alternate conception the distractor was derived from. Concept inventories help educators better understand student thinking and make interventions, and they can be used to measure learning gains (Sands et al., 2018). The first concept inventory, the Force Concept Inventory (FCI), was developed in 1992 (Hestenes et al., 1992). Since then, many concept inventories have been developed for a wide variety of science topics. In the field of chemistry, concept inventories have been developed for topics in general chemistry, biochemistry, organic chemistry, and physical chemistry (Abell & Bretz, 2019; Atkinson et al., 2020; Brandriet & Bretz, 2014; S. L. Bretz & Linenberger, 2012, 2012; S. Bretz & Mayo, 2018; Brown et al., 2015; Dick-Perez et al., 2016; Leontyev & Hyslop, 2015; McClary & Bretz, 2012; Mulford & Robinson, 2002; Nedungadi et al., 2021; Tetschner & Nedungadi, 2023; Villafañe et al., 2011; Wren & Barbera, 2013). One of these concept inventories, the Chemistry Concepts Inventory (CCI), was developed to cover all the topics taught in a traditional first-semester general chemistry undergraduate course (Mulford

& Robinson, 2002). This concept inventory contains a few items related to solution chemistry, but the focus of this concept inventory is not on solutions. Thus, there is no existing single-topic concept inventory focused on solutions. Single-topic inventories help assess depth of understanding, whereas concept inventories like the CCI assess breadth of understanding.

Importance of a Solution Concept Inventory

It is important that high school students gain a solid understanding of solutions for many reasons. For one, most chemical reactions occur in solutions. Students also engage with solutions everyday inside and outside the classroom—even if they are not aware of it. Additionally, the concept of solutions (specifically as it relates to acid and base solutions) has been identified as a fundamental general chemistry concept that is important to organic chemistry (Duis, 2011). Therefore, solution chemistry topics apply to other chemistry topics, and students who gain a solid understanding of solutions in high school may be better prepared for undergraduate chemistry courses like organic chemistry.

The concept of solutions is important, but this does not mean that the concept is easy to learn. Many chemistry students struggle to understand solution chemistry, and many students hold alternate conceptions about solutions. For a study conducted in 1996, researchers interviewed grade 11 chemistry students to better understand student conceptions on solubility (an important aspect of solution chemistry). The researchers identified three main issues for students trying to learn about solubility: (1) students tried to use "everyday knowledge" to interpret and conceptualize solution phenomena, (2) students tried to extend their knowledge of macroscopic properties of substances to the microscopic level, and (3) the students misunderstood technical vocabulary related to solutions (Ebenezer & Erickson, 1996). Another study examined student understanding of saturated, unsaturated, and supersaturated solutions and found that many students confuse saturated and supersaturated solutions. The students involved in this study mislabeled an image of a saturated solution because they believed that the "excess" solute at the bottom of the container indicated that the solution was supersaturated (Pınarbaşı & Canpolat, 2003). This is a common alternate conception that has been identified by many different studies (Krause & Tasooji, 2007; Mulford & Robinson, 2002). One study, specifically, administered a Materials Concept Inventory (MCI) that contained some questions related to solution chemistry and identified the following student alternate conceptions: unsaturated solutions contain undissolved solute, the concentration of a saturated solution will increase with the addition of more solute, and supersaturated solutions contain both solid and liquid phases (Krause & Tasooji, 2007).

Since many students hold alternate conceptions related to solutions, chemistry teachers would benefit from the development of a Solution Concept Inventory (SCI). An SCI could allow a teacher to identify the alternate conceptions held by their students related to the concept of solutions and could help the teacher make interventions and instructional alterations to bring about conceptual change, and so, the aim of this study is to design and develop an SCI for high school chemistry teachers.

Item Quality

Item quality can be assessed with Classical Test Theory (CTT). In fact, CTT is often used to analyze the initial quality of items on chemistry concept inventories (Abell & Bretz, 2019; Atkinson et al., 2020; Brandriet & Bretz, 2014; S. L. Bretz & Linenberger, 2012; S. Bretz & Mayo, 2018; Brown et al., 2015; Dick-Perez et al., 2016; Mulford & Robinson, 2002; Nedungadi et al., 2021; Villafañe et al., 2011; Wren & Barbera, 2013). CTT is sample dependent and involves simple mathematical techniques, and so, CTT will be used to analyze the quality of items on the SCI. Specifically, item difficulty and discrimination values will be reported for each of the items.

Validity Evidence

Evidence for validity is routinely gathered during the design and development of concept inventories (Brandriet & Bretz, 2014; S. L. Bretz & Linenberger, 2012; S. Bretz & Mayo, 2018; Brown et al., 2015; Chu et al., 2012; Dick-Perez et al., 2016; Luxford & Bretz, 2014; Nedungadi et al., 2021; Tetschner & Nedungadi, 2023; Wren & Barbera, 2013). Validity evidence must be obtained to ensure that an assessment is assessing its intended construct and that interpretations can be made from test scores. The 2014 *Standards for Educational and Psychological Testing* outlines the following five types of validity evidence that should be viewed as different aspects of the validity argument and not as different types of validity: (1) evidence based on test content, (2) evidence based on response processes, (3) evidence based on internal structure, (4) evidence based on relations to other variables, and (5) evidence for consequences of testing (American Educational Research Association et al., 2014). For this study, evidence for validity based on test content will be established for items on the SCI. This type of validity evidence describes the extent to which an assessment covers the construct being assessed (Bandalos, 2018). In this case, the construct being assessed is students' conceptions of solutions. There are two threats—construct underrepresentation and construct-irrelevance—to test content validity (Messick, 1989). The presence of construct underrepresentation indicates that the assessment is too narrow and does not assess all important aspects of the construct. The presence of construct-irrelevance indicates that the assessment scores are influenced by factors unrelated to the construct. One way evidence for validity based on test content can be obtained is through expert review of the content covered on the assessment (Bandalos, 2018).

Aim of Study

In this study, items for an SCI were developed for the high school chemistry classroom. During the development, item analysis was conducted to determine the quality of the items, and evidence for validity based on test content was gathered through expert feedback. Student alternate conceptions related to solutions were identified and are reported in this study. SCI multiple-choice items are also reported. This study is guided by the following research questions:

1. What are the alternate conceptions that high school chemistry students have about the concept of solutions?
2. What evidence supports the quality of the SCI items?
3. What evidence supports the validity of the data obtained by the SCI items based on test content?

Methods

Development of solution items

SCI items were developed under five broad categories: (1) Properties of Water, (2) Types and Components of Solutions, (3) Solubility and the Solvation Process, (4) Concentrations of Solutions, and (5) Acids and Bases. These categories were selected since they represent the solution topics that are often covered in high school chemistry textbooks (American Chemical Society, 2012; Buthelezi et al., 2008; Davis et al., 2002). Items under the Properties of Water category cover water's unique physical properties (boiling point, surface tension, cohesion, adhesion, density, etc.). The Types and Components of Solutions category covers the three types of solutions (unsaturated, saturated, and supersaturated) and the different components of a solution (solutes and solvents). The Solubility and the Solvation Process category covers solubility curves, particle diagrams, dissolution of ionic compounds, and temperature's effect on solubility. The Concentrations of Solutions category contains items that assess students' understanding of the molarity equation and dilutions. Finally, the Acids and Bases category covers the different definitions of acids and bases.

A few topics were identified in high school chemistry textbooks that are not covered by items on the SCI. For example, multiple high school chemistry textbooks include sections on colligative properties, pH, Beer's law, colloids, suspensions, and the Tyndall effect (American Chemical Society, 2012; Buthelezi et al., 2008; Davis et al., 2002). These topics were excluded from the SCI because they were not taught in the high school chemistry class the assessment was administered in. These topics are generally covered in more detail in advanced high school chemistry classes (like AP Chemistry and dual-enrolled chemistry), and this assessment was designed for general chemistry. 16 items were initially developed for the SCI. Table 1 shows the number of items in each category.

Table 1. Number of Items Under Each Solution Chemistry Item Category

Solution Chemistry Category	# of Items
Properties of Water	4
Types and Components of Solutions	3
Solubility and the Solvation Process	4
Concentrations of Solutions	3
Acids and Bases	2

The SCI items were developed first as open-ended items. These open-ended items were administered to high school chemistry students ($N = 82$) at an urban high school in the Midwest region of the U.S.A. 51% of the students were male, and 49% of the students were female. Most of the students were 15-16 years old and were in grade 10.

The assessment was administered during a regular school day at the end of the "solutions" unit. The students were given 25 minutes to complete the assessment. For each item on the assessment, the students were asked to provide an answer and an explanation for their answer. Common alternate conceptions were identified based on the students' responses to the open-ended items. The open-ended items were then converted into multiple-choice items to create SCI-1 (the first multiple-choice version of the inventory). The identified alternate conceptions were used to create the distractors for the SCI-1 items. One item from the open-ended version of the assessment was removed after analyzing the student responses, which reduced the total number of items on the SCI to 15.

Evaluating Item Quality

The students' responses to the open-ended assessment were scored dichotomously; all correct responses were given a score of 1, and all incorrect responses were given a score of 0. To be a "correct" response, a response had to contain the right answer and contain correct reasoning for the answer. All other responses were deemed as "incorrect." Thus, a student could select the right answer for an item and still have their response scored as "incorrect" if they provided false or incomplete reasoning with their answer choice. Item difficulty and discrimination indices were determined for all items on the SCI.

Item difficulty refers to the percentage of test takers who answer an item correctly (Bandalos, 2018). Easier items have item difficulty values closer to 1, and more difficult items have values closer to 0. For most assessments, it is acceptable for the items to have difficulty values between 0.3 and 0.8 (Kaplan & Saccuzzo, 1997).

Item discrimination indices describe how well an item differentiates between high-performing and low-performing respondents. To calculate discrimination indices, two groups are identified: a high-scoring group (called the upper group) and a low-scoring group (called the lower group). The discrimination index for an item is calculated by taking the percentage of the respondents in the upper group who answer the item correctly minus the percentage of the respondents in the lower group who answer the item correctly (Bandalos, 2018). Discrimination indices above 0.3 are generally considered to be acceptable (Doran, 1980). Since the assessment was administered to a relatively small sample of students, the upper group was created from the top-scoring 50% of students, and the lower group was created from the lowest-scoring 50% of students (Kelley, 1939).

Obtaining validity data

To gather evidence for content validity, the SCI-1 items were sent out to 6 chemistry faculty members at a mid-sized university in the Midwest region of the U.S.A in the form of a Qualtrics survey. Five responded with feedback. The faculty members were asked to evaluate each item on the assessment by answering the following questions:

1. Is the question appropriately covering the concept of solutions chemistry?
2. Please rank the relevance of the question towards solutions chemistry.
3. Is the wording of the question appropriate?
4. Do you agree with the proposed answer?
5. Please provide any other comments you may have regarding the question.

Based on the chemistry faculty member's feedback, the multiple-choice SCI items were modified, and one item was removed. The updated version of the assessment became SCI-2, and it contains 14 items.

Results and Discussion

Solution-related alternate conceptions

Student responses to the open-ended assessment were analyzed, and alternate conceptions were identified from the most common incorrect responses provided by the students. Table 2 lists alternate conceptions that were identified for each item category on the SCI.

Table 2. Solution-related Alternate Conceptions Held by Students

Item Category	Identified Alternate Conception
Properties of Water	Water molecules consist of two oxygen atoms and one hydrogen atom (HO_2).
	A hydrogen bond is an intramolecular force between a hydrogen atom and another atom.
	Water has relatively low surface tension because it is easy to break.
	The more IMFs between molecules, the less dense the substance is.
	The density of a substance is solely determined from the kinetic energy of the substance's particles (i.e., the slower the particles, the lower the density).
Types & Components of Solutions	Supersaturated solutions will have extra solute piled at the bottom of the container.
	The substance being physically added to another substance to make a solution is automatically the solute.
	In a solution, the solute must be a solid, and the solvent must be a liquid.
	A clear, homogenous solution is automatically an unsaturated solution.
	The words "solvent" and "solution" are interchangeable.
	The solvent is the substance that dissolves, and the solute is the substance that does the dissolving.
	Solutes and precipitates are the same thing.
	If more solute is added than a solvent can dissolve at a certain temperature, then a supersaturated solution is always made.
Solubility & the Solvation Process	When a substance dissolves, it undergoes a phase change and turns into a liquid, and so, its solubility is dependent on its melting point or boiling point.
	When an ionic compound dissolves in water, water molecules will break apart into H^+ ions and O^- ions. These ions will then attach to the oppositely charged ions in the ionic compound.
	When an ionic compound dissolves in water, only one water molecule will interact with each ion.

	A chemical reaction occurs when a substance dissolves.
Concentration of Solutions	The number of moles of solute changes during a dilution.
	When you add more solute to a saturated solution, the concentration of the solution increases.
	To have a relatively high concentration, there must be more solute present than solvent in a solution.
Acids & Bases	In a reaction, the acid is always the substance with more hydrogen atoms.
	The Bronsted-Lowry definition and the Arrhenius definition are the same.

Many of the students who struggled with the Properties of Water items appeared to have a fragmented understanding of introductory chemistry topics, and so, most of the alternate conceptions identified for this category can be traced back to alternate conceptions the students developed when learning the basics of chemistry at the beginning of the school year. For example, many students struggled with item 1 (shown below as Figure 1).

1. Which of the following substances would you expect to have a higher boiling point? Explain your answer.

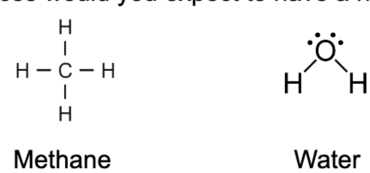

Figure 1. Item 1 on the open-ended version of the SCI.

Many students incorrectly selected “methane” as the substance with the higher boiling point when answering item 1. Water has a higher boiling point than methane because there are stronger intermolecular forces between water molecules. Hydrogen bonds (a strong type of intermolecular force) can form between water molecules and cannot form between methane molecules. Interestingly, almost every student understood the solution concept being assessed with this item (they understood that the substance with more hydrogen bonds will have the higher boiling point). The students who selected “methane” chose methane because they believed methane “has more hydrogen bonds.” These students had an alternate conception about intermolecular forces—a topic that is generally taught during a bonding unit at the beginning of the school year. Either these students did not know what a hydrogen bond is, or these students did not understand that the term, “hydrogen bond,” is generally used to describe an intermolecular force and not a covalent bond involving a hydrogen atom. Either way, the students held an alternate conception about a fundamental chemistry topic, and this conception led them to develop an alternate conception about a more advanced solution chemistry topic.

Many of the other alternate conceptions identified for the Properties of Water category appeared to be similarly derived from alternate conceptions of fundamental chemistry topics. Some students believed water’s formula to be HO_2 instead of H_2O, and many students struggled to answer questions about the density of water because they did not fully understand intermolecular forces, kinetic energy, states of matter, or the variables of the density equation.

The students who struggled with the Types and Components of Solutions items held alternate conceptions over the differences between solutes, solvents, and solutions and over the differences between unsaturated, saturated, and supersaturated solutions. The students’ responses to item 6 reveal many of these alternate conceptions. Item 6 is displayed as Figure 2 below.

6. To create a solution, you dissolve 53.2 grams of potassium hydroxide in 300 mL of ethanol. What is the solute and what is the solvent? Explain your answer.

Figure 2. Item 6 on the open-ended version of the SCI.

Many students correctly answered item 6 and said that the solute is potassium hydroxide and that the solvent is ethanol, but a large portion of the students provided incorrect reasonings for their answers. Many revealed that they thought all solutes are solids and that all solvents are liquids. Some explained their answer by saying that the solute is always the substance that is being physically added to another substance. Additionally, some students implied that the terms "solvent" and "solution" mean the same thing by using the words interchangeably in their explanations.

Many students also struggled to differentiate between the different types of solutions when answering items in the Types and Components of Solutions category. These students thought that supersaturated solutions contain excess, undissolved solute, and so, they falsely labeled saturated solutions as supersaturated solutions. They did not understand that all the "excess" solute in a supersaturated solution is dissolved. The word, "excess," seems to be the cause of confusion. Others indicated that any clear, homogenous solution is an unsaturated solution and did not understand that all types of solutions can appear that way in certain conditions.

The identified alternate conceptions for the Solubility and the Solvation Process category all focus on the solvation process at the microscopic level. Students revealed that they believed the following: a) water breaks apart into ions to dissolve ionic compounds, b) only one water molecule will surround each dissolved ion in solution, c) a solid solute melts into a liquid when it dissolves in a solvent, and so, solubility increases once the temperature of the solution starts to approach the solute's melting point, d) a gas condenses into a liquid when it dissolves in a solvent, and so, solubility increases as the temperature starts to approach the gas's boiling point, and e) a chemical reaction occurs when a solute dissolves in a solvent. These alternate conceptions indicate that students struggle to visualize what is happening at the particle level when a substance dissolves.

When answering the Concentration of Solutions items, the students struggled to explain how and if the variables of the molarity equation will change during different processes. For example, many students stated that the number of moles of solute will change during a dilution.

Others incorrectly argued that the concentration of a saturated solution will increase if more solute is added. Either these students did not understand that the molarity equation describes only the *dissolved* number of moles of solute (not necessarily all the solute added to a solution), or they falsely believed that a saturated solution could dissolve more solute.

Most students answered the Acids and Bases items incorrectly. However, very few alternate conceptions were identified for this category of items because many unique wrong answers were provided; there were very few commonalities between the students' incorrect responses. In general, the students confused the Arrhenius and Bronsted-Lowry definitions of acids and bases, and multiple students implied that the acid in a reaction is always the substance that contains the most hydrogen atoms.

Item 16 (shown as Figure 3) was an item in the Acids and Bases category.

16. What are the products of the following neutralization reaction: $Ca(OH)_2 + H_2SO_4 \rightarrow$ __________. Explain your answer.

Figure 3. Item 16 on the open-ended version of the SCI.

This item received various responses from the students. Very few students provided the same wrong answer, and only a few students provided an explanation with their answer. Thus, alternate conceptions could not be derived from the student responses to the item, and distractors could not be created. Consequently, item 16 was removed from the SCI—which lowered the total number of items on the assessment to 15.

Evidence for item quality

Item difficulty and discrimination indices for each of the items on the open-ended version of the SCI are displayed below in Figure 4. Six items on the open-ended version of the SCI have acceptable difficulty and discrimination values. Six items have difficulty and discrimination values that are relatively close to the accepted values, and four items (item 1, 9, 10, 15) have unacceptable difficulty and discrimination values that are not very close to the accepted values.

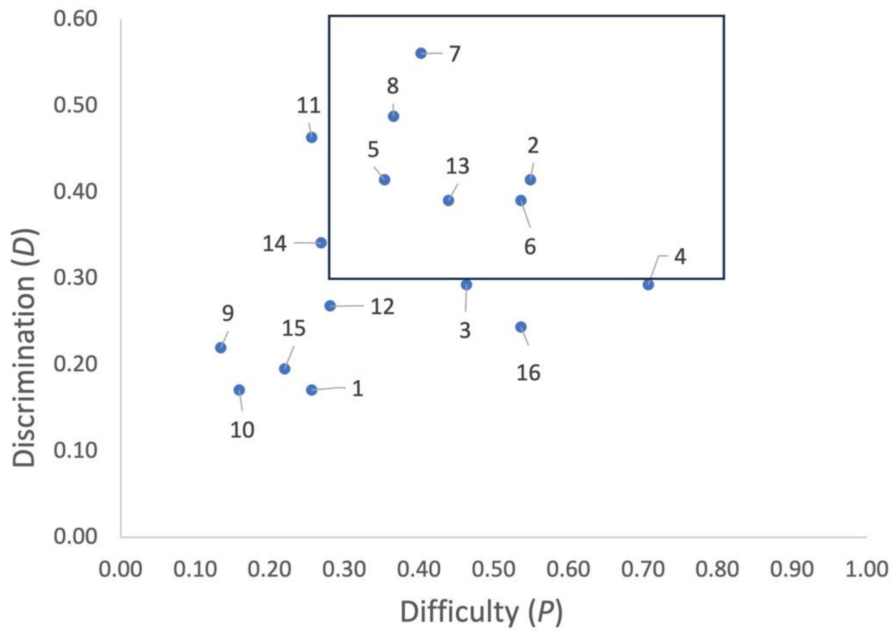

Figure 4. Item difficulty and discrimination values. Items inside the box have acceptable difficulty values ($0.3 < P < 0.8$) and acceptable discrimination indices ($D > 0.3$).

Many of the items are too difficult and have difficulty values below 0.3. This may be because the items are open-ended items (and not multiple-choice) and because the difficulty values were determined based on how many students provided both a correct answer and a correct explanation. Most of the easier items come from the Properties of Water category or the Types and Components of Solutions category—which makes sense since these topics are fundamental to the more advanced topics covered in the other item categories.

At this stage of the study, it was decided that more information was needed to determine if items (other than item 16) needed to be removed or significantly modified since the difficulty and discrimination values were derived from responses to an open-ended assessment and since the assessment was administered to a small sample size. Though, items 1, 9, 10, and 15 were still flagged for potential removal. Faculty feedback was needed to determine the fate of these four items.

Evidence for validity based on test content

The chemistry faculty members (*N* = 5) evaluated the SCI-1 items based on how well the items covered the concept of solutions and how relevant the items were to the concept of solutions. They also determined the appropriateness of the wording of the items, and they stated if they agreed with each item's proposed answer. The faculty members' feedback is reported in Table 3. The values in the table represent the number of faculty members who answered the four survey questions with a certain response (yes, no, important, neutral, or not important).

Table 3. Faculty Feedback on the SCI Items

Item	Appropriate Coverage of Solutions?		Relevance of Item toward Solutions?			Appropriate Wording?		Appropriate Answer?	
	Yes	No	Important	Neutral	Not Important	Yes	No	Yes	No
1	4	1	2	3	0	4	1	5	0
2	3	2	2	1	2	4*	0*	5	0
3	3	2	1	3	1	5	0	5	0
4	3	2	1	3	1	5	0	5	0
5	4	1	3	1	1	4	1	3	2
6	5	0	4	1	0	4	1	4	1
7	4	1	3	2	0	2	3	4	1
8	4*	0*	2*	2*	0*	3*	1*	3*	0*
9	4	1	4	0	1	5	0	5	0
10	4	1	4	0	1	5	1	5	0
11	5	0	5	0	0	5	0	5	0
12	5	0	5	0	0	5	0	5	0
13	5	0	5	0	0	5	0	5	0
14	5	0	5	0	0	5	0	5	0
15	3	2	2	1	2	4	1	4	1

**Indicate questions that not all 5 faculty members answered on the survey*

Most chemistry faculty members gave positive feedback for all items on the SCI; the majority agreed that all 15 items appropriately covered the concept of solutions, had important or neutral relevance to the concept of solutions, were worded appropriately, and had correct answers. This indicates that evidence for validity based on test content was obtained.

All five chemistry faculty members agreed that 5 of the 15 items appropriately covered the concept of solutions, and at least 4 out of the 5 experts agreed that 11 out of the 15 items appropriately covered the concept. Those who reported that four of the items (items 2, 3, 4, and 15) did not appropriately cover the concept of solutions explained that they believe the following topics are only "marginally related" to solution chemistry: water properties, acids, and bases. The four items they identified as not appropriately covering the concept of solutions came from the Properties of Water category and the Acids and Bases category on the SCI. However, since these topics were taught in the high school the open-ended assessment was administered in and since these topics are commonly covered before and after more advanced solution chemistry topics (such as solubility and concentration) in high school chemistry textbooks (American Chemical Society, 2012; Buthelezi et al., 2008; Davis et al., 2002), these items were not removed from the SCI at this stage of the study.

Four out of the five faculty members agreed that the wording of 13 of the items was appropriate, and four out of the five faculty members agreed with the proposed answer of 13 of the items. The other, "non-appropriate" items were modified based on the experts' feedback. For example, multiple faculty members argued that item 5 (shown as Figure 5 below) did not have an appropriate answer.

5. You create a saturated solution at a high temperature by heating a salt and water mixture in the flame of a bunsen burner. You lower the temperature of the solution by placing it in an ice bath. During this process, you observe no precipitation. What type of solution have you created?

    a. **Unsaturated**; since there was no change in the solution after the temperature change. The solution appears homogeneous.
    b. **Saturated**; since no precipitation occurred after the temperature change. The solution is “full” with solute.
    c. **Supersaturated;** since more solute is dissolved in the solution than normally possible at the lower temperature.
    d. **Unknown**; it is not possible to determine the type of solution without adding more solute and observing what happens.

Figure 5. Item 5 on SCI-1.

These professors explained that the item assumes the solubility of all salts will increase with increasing temperature and that this is not true. To fix this, the item was modified slightly to be about a specific salt, KNO_3, whose solubility does increase with increasing temperature. Figure 6 shows the modified item (which became item 4 after an item was removed).

4. You create a saturated solution of KNO_3 at a high temperature by heating a salt and water mixture in the flame of a bunsen burner. You lower the temperature of the solution by placing it in an ice bath. During this process, you observe no precipitation. What type of solution have you created?

    a. **Unsaturated**; since there was no change in the solution after the temperature change. The solution appears homogeneous.
    b. **Saturated**; since no precipitation occurred after the temperature change. The solution is “full” with solute.
    c. **Supersaturated;** since more solute is dissolved in the solution than normally possible at the lower temperature.
    d. **Unknown**; it is not possible to determine the type of solution without adding more solute and observing what happens.

Figure 6. Item 4 on SCI-2.

Three out of the four items flagged for potential removal from the item quality analysis (items 1, 9, and 10) received positive feedback from the faculty members. Four out of the five experts agreed that these items appropriately covered the concept of solutions, were worded appropriately, and had appropriate answers. Thus, these items were kept in the SCI—despite their low difficulty and discrimination values. Item 15, however, received more mixed feedback. As mentioned before, some professors believe that the topic of acids and bases is unrelated to the concept of solutions. Though, for reasons already stated, it was decided that these items would not be removed based on their topic, and so, item 15 was modified slightly (based on feedback provided by the professor who stated the item did not have an appropriate answer/wording), but it was kept in the SCI.

One item, item 4, was removed based on the professor's feedback. The professors pointed out that the item was connected to item 3. A student's answer to item 3 could potentially influence their answer to item 4. For this reason and since item 3 and item 4 both covered the same property of water (density), item 4 was removed from the SCI. This lowered the total number of items on the SCI to 14. All 14 SCI-2 items can be viewed in the supplementary information.

Conclusion

Overview of Results

Students hold a variety of alternate conceptions over solution-related topics. Many of these alternate conceptions can be traced back to introductory high school chemistry topics. For example, multiple students believed that a chemical change occurs when a substance dissolves. Some students drew water molecules as HO_2, and many students confused hydrogen bonds (an intermolecular force) with covalent bonds involving hydrogen atoms (an intramolecular force). The students were found to hold a popular alternate conception—that supersaturated solutions contain excess, undissolved solute—that has been reported in many different studies (Krause & Tasooji, 2007; Mulford & Robinson, 2002; Pınarbaşı & Canpolat, 2003). The students also displayed confusion over the differences between solutes, solvents, and solutions and between the Bronsted-Lowry definition of an acid and the Arrhenius definition of an acid. Overall, the students struggled to visualize solution processes at the particle level.

The item analysis determined that only six items on the open-ended version of the SCI have acceptable difficulty and discrimination indices. However, since these values were determined from the administration of an open-ended assessment and not from a multiple-choice assessment, it is believed that the quality of some of the items will improve with modification.

Sixteen open-ended items were developed for the SCI. One item, item 16, was removed based on the students' responses to the open-ended assessment. The identified alternate conceptions were used to develop distractors for the remaining 15 items and to create SCI-1. Faculty feedback was collected for the SCI-1 items, and evidence for content validity was obtained. Based on the faculty feedback, one item, item 4, was removed from the inventory, and many of the other items were modified. The modified 14 items are presented as SCI-2 in the supplementary information.

Implications for teaching

Many of the students struggled with the SCI items because they held alternate conceptions over fundamental chemistry topics, and so, high school chemistry teachers should focus on reviewing content throughout the school year. Specifically, high school chemistry teachers should consider reviewing the following topics before teaching their students about solutions: 1) chemical and physical changes, 2) heterogenous and homogenous mixtures, 3) particle diagrams of the different states of matter, 4) ions and ionic compounds, 5) intramolecular and intermolecular forces, and 5) direct and inverse relationships. Teachers should also consider implementing learning activities that support long-term retention of knowledge (like inquiry-based learning activities) at the beginning of the school year (Schmid & Bogner, 2015).

Many of the students were not able to visualize the solvation process at the particle level, and some students struggled to interpret particle diagrams of different states of matter. Thus, chemistry teachers should emphasize particle diagrams in class and have students practice drawing particle diagrams to explain chemical processes and natural phenomena. To do this, teachers may want to implement a modeling-focused curriculum. Modeling curriculums have been researched extensively and have been found to support student learning in chemistry classrooms (Cullen, 2015; Dukerich, 2015; Jenkins & Howard, 2019; Posthuma-Adams, 2014).

The 14 SCI-2 items are reported in the supplementary information. High school general chemistry teachers can administer the assessment in their own classrooms and may want to administer the SCI-2 before formally testing over solutions (since content validity evidence was gathered that supports the use of the assessment to identify student alternate conceptions). AP chemistry teachers and dual-enrolled chemistry teachers may also want to administer the assessment in their classrooms. If these teachers administer the SCI-2 before diving into more advanced solution topics (as a pre-test), they may be able to identify the alternate conceptions their students have from general chemistry.

Future work

To gather more information about the quality of the SCI items, the SCI-2 items should be administered to a larger, more diverse sample of students. The assessment would also benefit from the collection of other evidence for validity. To do this, interviews could be conducted with students to better understand how students are approaching each of the items and to determine if any outside factors are influencing responses. The information gathered from these interviews could provide evidence for response process validity. A Differential Item Functioning (DIF) analysis could also be performed to determine if the items are biased against specific groups of respondents and to gather evidence for validity based on internal structure. Reliability data should also be collected and reported.

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Supplementary Information

SCI-2 Items

1. Which of the following pure substances would you expect to have a higher boiling point?

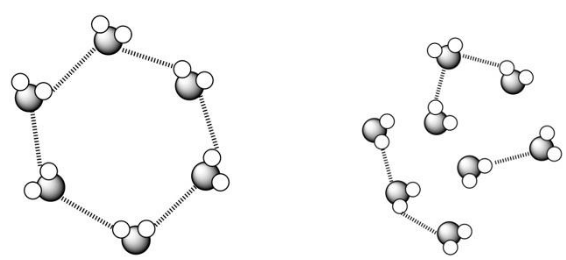
Methane **Water**

   a. **Methane**; the molecule contains more hydrogen bonds.
   b. **Methane**; there are more hydrogen atoms in a methane molecule.
   c. **Water**; hydrogen bonds can form between water molecules.
   d. **Water**; there are less hydrogen atoms in a water molecule.

2. Does water have relatively high or low surface tension in comparison to other liquids?

   a. **High**; since there are strong intermolecular forces holding water molecules together.
   b. **High**; since there are strong covalent bonds between atoms in a water molecule.
   c. **Low**; since the surface tension can easily be broken with the addition of soap.
   d. **Low**; since many light objects will not float on top of water's surface.

3. Which particle diagram represents the less dense sample of water?



1 **2**

   a. **1**; since there are more connections between molecules.
   b. **1**; since there are less molecules in the same amount of space.
   c. **2**; since there are fewer connections between molecules.
   d. **2**; since there is less space between individual molecules.

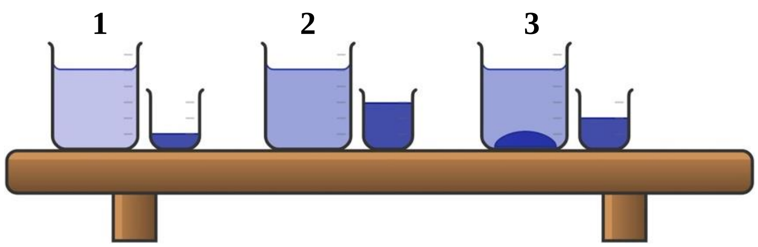
4. You create a saturated solution of KNO_3 at a high temperature by heating a salt and water mixture in the flame of a bunsen burner. You lower the temperature of the solution by placing it in an ice bath. During this process, you observe no precipitation. What type of solution have you created?

   a. **Unsaturated**; since there was no change in the solution after the temperature change. The solution appears homogeneous.
   b. **Saturated**; since no precipitation occurred after the temperature change. The solution is “full” with solute.
   c. **Supersaturated**; since more solute is dissolved in the solution than normally possible at the lower temperature.
   d. **Unknown**; it is not possible to determine the type of solution without adding more solute and observing what happens.

5. To create a solution, you dissolve 53.2 grams of potassium hydroxide in 300 mL of ethanol. What is the solute and what is the solvent?

   a. **Solute = ethanol, solvent = potassium hydroxide**; since ethanol is present in the greater proportion.
   b. **Solute = ethanol, solvent = potassium hydroxide**; since ethanol is a liquid and KOH is a solid.
   c. **Solute = potassium hydroxide, solvent = ethanol**; since the KOH is being added to the ethanol.
   d. **Solute = potassium hydroxide, solvent = ethanol**; since ethanol is present in the greater proportion.

6. In the large beakers are 3 solutions. One of the numbered solutions is saturated. Another is unsaturated, and a third one is supersaturated. The small beakers next to the large beakers show how much solute is dissolved in each of the solutions. The identity of the solute and the solvent is the same for all beakers. Which solution is the supersaturated solution?



   a. **2**; since the beaker contains the most dissolved solute.
   b. **2**; since the largest amount of solute was added to the beaker.
   c. **3**; since there is excess, undissolved solute at the bottom of the beaker.
   d. **3**; since precipitation formed when the solute was added to the beaker.

Use the solubility graph to answer Questions 7-9:

7. In a beaker, you mix 120 grams of KNO_3 with 100 grams of H_2O at 40℃. What would you expect to see in the beaker after mixing?

   a. **A supersaturated solution**; since more solute was added than should normally be possible at 40℃.
   b. **A supersaturated solution**; since this value is above the KNO_3 line on the solubility curve at 40℃.
   c. **A saturated solution**; since more solute than can be dissolved was added without a change in temperature.
   d. **A saturated solution**; since some solid will precipitate out of solution and settle at the bottom of the beaker.

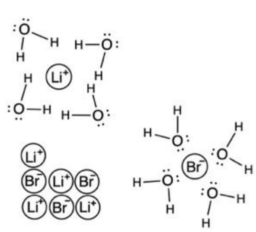
8. How does increasing the temperature affect the solubility of gases like SO_2?

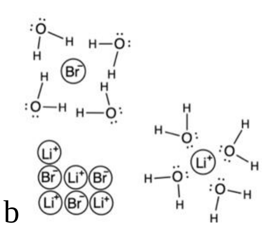
    a. **Increases gas solubility**; gas particles are more easily separated and dispersed throughout the solution at higher temperatures.
    b. **Increases gas solubility**; solvent particles have more kinetic energy and more easily surround and "capture" gas particles at higher temperatures.
    c. **Decreases gas solubility**; dissolved gas particles more easily evaporate when the temperature of the solution reaches the boiling point of the gas.
    d. **Decreases gas solubility**; at higher temperatures, dissolved gas particles have more kinetic energy and solvent-solute intermolecular forces are more easily broken.

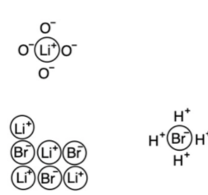
9. How does increasing the temperature affect the solubility of solids like NH_4Cl?

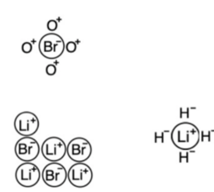
    a. **Increases solid solubility**; at higher temperatures, solvent particles have more kinetic energy and solute-solute interactions are more easily broken.
    b. **Increases solid solubility**; as the temperature of the solution approaches the melting point of the solid, the solid more easily melts into its component ions.
    c. **Decreases solid solubility**; at higher temperatures, the solid particles have more kinetic energy and are less easily "captured" by solvent particles.
    d. **Decreases solid solubility**; at higher temperatures, some of the solvent may evaporate, meaning there may be less solvent available to dissolve a solid.

10. Select the image that best represents the microscopic picture of a LiBr crystal starting to dissolve in water.

a. 

b 

c. 

d. 

11. During a dilution, how does the concentration of the resulting solution compare to the original solution?

    a. **It is lower**; since there is less solute in the resulting solution after a dilution.
    b. **It is lower**; since there is more solvent in the resulting solution after a dilution.
    c. **It is higher**; since there is more solute in the resulting solution after a dilution.
    d. **It is higher**; since there is less solvent in the resulting solution after a dilution.

12. You leave an aqueous solution outside and some of the water in the solution evaporates, how does the concentration of the resulting solution compare to the original solution?

    a. **It is lower**; since there is less solvent in the resulting solution.
    b. **It is lower**; since there is less solute in the resulting solution.
    c. **It is higher**; since there is less solvent in the resulting solution.
    d. **It is higher**; since there is less solute in the resulting solution.

13. You have a saturated solution. You add more solute to the solution. How does the concentration of the resulting solution compare to the original solution?

    a. **It is lower**; since there is more solvent in the resulting solution.
    b. **It is higher**; since there is more solute in the resulting solution.
    c. **It is the same**; since the added solute will not dissolve in solution.
    d. **There is not enough information to answer**; since values were not provided.

14. Out of the compounds involved in the forward reaction below, which one would be considered an "acid" according to the Bronsted-Lowry definition of an acid?

$$CH_3NH_2 + H_2O \rightarrow CH_3NH_3^+ + OH^-$$

    a. **CH_3NH_2**; since it contains more hydrogen atoms.
    b. **H_2O**; since it donates H^+.
    c. **$CH_3NH_3^+$**; since it contains H^+.
    d. **None**; since OH^- is produced and not H^+.