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Undergraduate Pre–Service Teachers' Understandings and Misconceptions of Phase Equilibrium

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In recent decades many studies have been conducted to reveal the students' understandings of scientific concepts and phenomena *(1)*. The results have indicated that students hold ideas different from those intended by the instruction in a wide range of areas as physics, chemistry, biology and mathematics. The constructivist model of learning proposes that students construct their own understanding as a result of formal instruction, everyday experiences, and interactions with their surroundings, which includes their parents, peers and acquaintances. Planned instructional experiences may count as a main source of meaningful learning but may not always result in correct and scientific conceptualizations *(2)* because as indicated by Ausubel *(3)* the cognitive structure of the preexisting knowledge of learners affects how new knowledge is interpreted. Driver and Easley *(4)* labeled these interpretations as alternative frameworks. Students' conceptualizations were labeled also as misconceptions *(4)*, children's science *(5)* and naive beliefs *(6)*.

Students' misconceptions interfere with subsequent learning. When the students are left to connect new information into their cognitive structure these misconceptions hinder integration of the scientific knowledge. This causes weak understanding or misunderstanding of the concept. In this paper the term "misunderstanding" is used to indicate the identified scientifically incorrect ideas of the students which occur when new information cannot be connected appropriately to the students' cognitive structure that already holds inappropriate knowledge *(7)*.

Science educators, influenced by the idea that knowledge on some basic concepts is essential for subsequent learning, focused on the most important topics in their areas. Particulate nature of matter *(8–10)*, atom and molecule *(11, 12)* have been investigated as essential and fundamental concepts in learning chemistry. Difficulties and misunderstandings in these central concepts may hinder learning other topics such as state changes, dissolving and solutions, chemical equilibrium, bonding, and gas properties.

The phase equilibrium topic, including state changes, solutions, vapor pressure and Raoult's law, colligative properties and phase diagrams, has been a fundamental part of junior, senior, high school and university courses for many years. The unit was chosen because it involves abstract and theoretical concepts that were the focus of many studies that reported misconceptions related to phase equilibrium concepts *(13–18)*.

In a study conducted in New Zealand, Osborne and Cosgrove *(2)* investigated pupils' conceptions of the state changes of water. The results of the study produced evidence that children between 12 and 17 years of age do not possess a scientific understanding about boiling, evaporation, and condensation phenomena. Their study revealed students' belief in the idea that when a substance evaporates it ceases to exist. Bar and Travis *(13)* investigated the conceptual development of the students at the age range 6–14 concerning the boiling, evaporation and condensation concepts. Students described the matter inside the bubbles coming out of boiling water as water, water vapor, and air. Students' answers such as water disappeared, water changed to hydrogen and oxygen, and water penetrated solid objects were interpretations of the process of evaporation.

Sometimes misconceptions occurred as a result of students' tendency to apply macroscopic properties to the molecular level. For example, students state that molecules enlarge with changes of the state *(14)* and that molecules become hot when the substance is heated *(12)*. The idea for 11–14-year-old students that dissolving is the same as melting *(15)* and the idea of first- and third-year secondary school students that solute and solvent particles form separate clumps *(16)* may also account for misunderstandings about the nature of matter. The fact that students cannot view what happens at the molecular level makes the mentioned concepts abstract and difficult to be learned *(19)*.

In Turkey, students are first introduced to the concept of "matter" when they are in grade 4. The students learn definitions of concepts such as matter, solution, mixture, physical and chemical changes, and give examples from everyday life. In grades 7 and 8 students find out more about the classification of elements and compounds, atomic structure, formation of compounds and ions, separation methods of mixtures, and chemical reactions. They also perform some short experiments. In grades 9 and 10 state changes, properties of solids and liquids, solutions and colligative properties, gases and gas laws, rates of reactions, and chemical equilibrium are the main topics. Grade 11 chemistry includes bonding and organic chemistry topics.

At the undergraduate level, students in chemistry education programs encounter all of these concepts again in a general chemistry course taken in the first year of the program. In such programs, physical chemistry is a one-year course taken in the third year. The topics of the course include state changes (melting, freezing, sublimation, etc.), solutions, vapor pressure and Raoult's law, colligative properties (freezing point depression, boiling point elevation, vapor pressure depression, and osmosis), and phase diagrams under the heading of phase equilibrium.

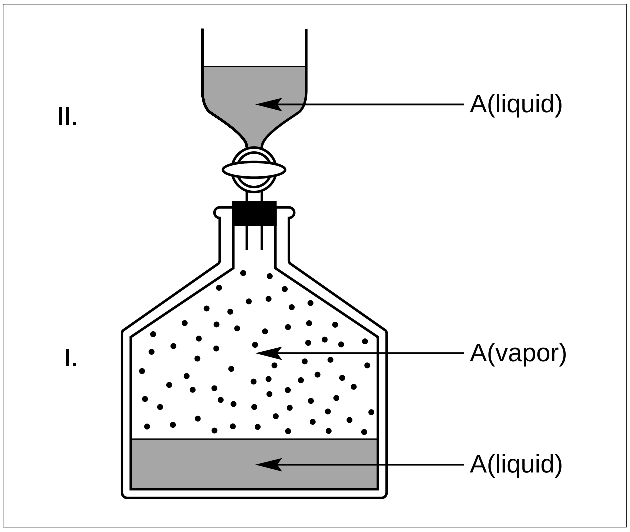

Figure 1. Image from a question testing students' understanding of the concept of equilibrium vapor pressure.

Number	*Concepts Tested by These Questions*
	Equilibrium Vapor Pressure
2.	The effect of the amount of the liquid
3.	The effect of the container volume
4.	Liquids' vapor pressure at the moment of boiling
	Phase Diagrams
5.	Differences in interpreting graphs with positive or negative relationship between pressure and melting point
	State Changes
6a.	Sublimation
6b.	Deposition
	Colligative Properties
1.	Vapor pressure depression: The effect of the dissolved solid substance
7.	Freezing point depression
	Raoult's law
8.	Boiling point of a liquid–liquid solution

Textbox 1. Content of the concept test.

The specific question of this study was: What misunderstandings about phase equilibrium concepts are held by pre-service chemistry *teachers* after instruction?

Methodology

The sample in the present study included 59 pre-service chemistry teachers (undergraduate students preparing to be high school teachers) who were enrolled in a physical chemistry course offered by the faculty of education at a public university in Turkey. The topics of state changes (melting, freezing, sublimation, etc.), solutions, vapor pressure and Raoult's law, colligative properties (freezing point depression and boiling point elevation), and phase diagrams, under the heading phase equilibrium were covered as a part of the regular curriculum in the physical chemistry course. These topics were addressed over a six-week period. The instruction was based on lecturing and discussions in class and was not designed explicitly to facilitate conceptual change. The course was regularly scheduled as four, 45-min periods (sessions) per week. To determine students' understandings and identify their misunderstandings, an eight-question phase equilibrium concept test was administered five days after the topics covered in this study had been taught.

The concept test used in this study was developed by the researchers. One source of material for the test was physical chemistry course examination papers from the last three academic years in Turkey; these were examined and the students' answers were scrutinized with respect to difficulties in explaining phase equilibrium concepts. Some phase equilibrium concepts such as equilibrium vapor pressure, Raoult's law, freezing point depression and vapor pressure depression, sublimation, deposition and phase diagrams were found to be problematic for students. Another consideration in developing the test was findings obtained from the literature *(13–18, 20–25)* related to students' misunderstandings about state changes, solutions, vapor pressure and Raoult's law, colligative properties and phase diagrams. Information from the interviews with instructors was used in developing the conceptual questions testing the selected phase equilibrium concepts. The questions for the pencil-and-paper test were designed as open-ended, with each question accompanied by relevant figures. The blank space for written responses after each question was split into two sections: the first section was designated for answers, the second for explanations about the reasons behind each answer. Figure 1 shows a figure from one of the test questions.

After content validation of the questions by two experienced chemistry educators and two university science lecturers, two pilot studies were conducted to develop and test the questions. At the end of the first pilot study conducted with 80 fourth-year pre-service chemistry teachers, an item analysis was performed and nine questions from the original 12 were retained. The nine-question instrument was administered to 72 third-year pre-service chemistry teachers. Based on the second-round item analysis results, test development was completed and the content finalized, with eight questions remaining. (Textbox 1 lists the concepts investigated by the eight questions on the instrument.) In the pilot studies, the four questions that were deleted did not reveal misunderstandings.

The Cronbach α value for the reliability of the instrument is 0.67. Three science educators (two chemistry educators and a science lecturer) reviewed the final test—one semester later the instrument was administered to the study's subjects.[W]

In order to evaluate answers objectively and precisely, a set of correct answers was prepared by the researcher and two science lecturers. The students' answers were categorized and then scored based on the modified scheme used by Haidar and Abraham *(26):*

- (**NR**) No response or no explanation (0 points)
- (**NU**) No understanding: irrelevant explanations or answers such as "I do not know", "I have no idea", or "I do not understand" (1 point)
- (**M**) Misunderstanding: explanations that attempt to describe the target concept but do not match the scientific conception (2 points)
- (**PU**) Partial understanding: incomplete but correct explanation (3 points)
- (**SU**) Sound understanding: explanations that include all components of the science concept (4 points)

Incorrect statements on the test given by 10% or more of the students in the sample (N = 59) were categorized as misunderstandings. To prevent confusion among students' statements, a numerical code was assigned to each student's test. Three chemistry educators assessed the tests and coded the students' responses: agreement between researchers and raters averaged 94%.

Quantitative Results

Table 1 shows the distribution of the students' answers to the conceptual questions. The five categories range from greatest to least quantity of demonstrated understanding (sound understanding to no response), as described above.

The majority of the students (75%) exhibited misunderstandings about the equilibrium vapor pressure of a liquid when a nonvolatile solid is dissolved in the liquid (question 1). Only 15% of the students showed sound understanding by giving a complete, correct answer. Identifying state changes such as sublimation and deposition (question 6) was another question with a high percentage (70%) of students demonstrating misunderstandings. It was surprising to identify that 10% of the students misunderstood the sublimation process and none of the students could show sound understanding of the deposition process. Although all of the questions included in the test required conceptual understanding and asked for conceptual explanations, students frequently preferred to make calculations to predict the effect of the container volume on the equilibrium vapor pressure of a liquid (question 3). The data showed that 56% of the students demonstrated misunderstanding of this concept, often explaining the dependence of the equilibrium vapor pressure on the container volume using Boyle's law ($P_1V_1 = P_2V_2$).

Question 2 revealed further misunderstandings of the ideal gas law and Le Châtelier's principle as students were asked to explain the relation between the amount of a liquid and its equilibrium vapor pressure: 39% of the students exhibited misunderstandings of these. The data showed that 90% of the students failed to demonstrate a sound understanding in applying Raoult's law to predict the boiling point of a liquid–liquid solution (question 8); 37% of the students' answers were categorized as misunderstandings. Interpreting the relations given in a graphical form (question 5) was another item on which 36% of the students failed. On question 4, 34% of the students showed misunderstandings when they tried to predict the vapor pressure of a liquid at the moment of boiling. Similarly, 34% of the students demonstrated misunderstandings on question 7 when trying to predict the effect of

Table 1. Distribution of Students' Responses Indicating Understanding or Misconception, by Concept

	Concept Tested in Each of the Questions	Distribution of the Assessments of Student Responses (N = 59) (%)				
		SU[a]	PU[b]	M[c]	NU[d]	NR[e]
1.	Predicting the vapor pressure depression	15	—	75	10	—
2.	Explaining the relation between the amount of the liquid and its equilibrium vapor pressure	36	8	39	15	2
3.	Explaining the relation between the container volume and the equilibrium vapor pressure of a liquid	29	8	56	5	2
4.	Predicting the vapor pressure of a liquid at the moment of boiling	44	7	34	10	5
5.	Interpreting a pressure–melting point graph	39	15	36	10	—
6a.	Identifying sublimation	71	—	10	7	12
6b.	Identifying deposition	—	—	70	8	22
7.	Predicting the effect of pressure and impurity on the freezing point of a pure substance	25	17	34	19	5
8.	Predicting the boiling point of a liquid–liquid solution	10	26	37	15	12

[a]Sound understanding; [b]Partial understanding; [c]Misunderstanding; [d]No understanding; [e]No response

pressure and impurity on the freezing point of a pure substance. The category NU was ≤ 15% in all questions except 7, which was 19%. For this question, some students were able to predict the effect of one variable (pressure or impurity) on freezing point of a pure substance; however, the question required students to consider the effects of both variables.

Qualitative Results

Through analysis of the students' test responses, 18 distinct misunderstandings were identified. Table 2 indicates these misunderstandings and the number of students demonstrating each misunderstanding ($N = 59$).

Vapor Pressure Depression

Question 1 tested whether students could interpret the changes in the equilibrium vapor pressure of a liquid when a nonvolatile solid is dissolved in the liquid. The first four misunderstandings in Table 2 reflect the ideas of 75% of the students. Although the colligative property as vapor pressure depression is related to the number of particles of the solute, students holding the second and fourth misunderstandings

Table 2. Distribution of Students' Misunderstandings Derived from Assessments of Students' Test Responses

	Description of Students' Misunderstandings as Identified by the Concept Test	Student Adherents ($N = 59$)
1.	Addition of a substance in a solvent always results in an increased boiling point.	9
2.	NaCl molecules dissolved in water weaken the attraction forces between water molecules and more water molecules evaporate, resulting in a vapor pressure increase.	11
3.	The boiling point of a mixture is a value between the boiling points of its components.	11
4.	NaCl dissolved in water increases the intermolecular interactions that make vaporization of water molecules difficult. As a result vapor pressure decreases.	13
5.	In a closed container, an increase in the amount of the liquid content will decrease the volume of the vapor above the liquid. According to the ideal gas law ($PV = nRT$) a decrease in vapor volume will result in an increase in equilibrium vapor pressure.	10
6.	Considering the balance A(liquid) ↔ A(vapor), when the amount of liquid increases the system will react in favor of vapor and pressure will increase.	7
7.	Given A(liquid) ↔ A(vapor), as the amount of liquid is increased the volume occupied by vapor decreases and the pressure increases. To re-equilibrate, the system reacts in a way that will decrease the vapor pressure.	6
8.	Equilibrium vapor pressure depends on the volume of the container in which the liquid is present.	33
9.	A P–T graph for CO_2 implies positive relationship between pressure and melting temperature, that is, an increase in pressure leads to an increase in temperature. So, CO_2 can melt easily.	21
10.	Because a CS_2 molecule is bigger than an H_2O molecule, the CS_2 molecule boils at a lower temperature. A lower boiling point requires a higher vapor pressure during the boiling process.	9
11.	A substance with a small molecule mass (water) has a low boiling point and passes easily to vapor phase. As a result water has a higher vapor pressure during boiling than CS_2.	11
12.	Vaporization is a state change from a solid to a gas (solid → gas).	6
13.	Condensation is a state change from a gas to a solid (gas → solid).	19
14.	Sublimation is a state change from a gas to a solid (gas → solid).	16
15.	The freezing point is constant for each substance; its value does not depend on pressure changes.	14
16.	The presence of an impurity makes freezing difficult and increases the freezing point.	6
17.	An addition of CS_2 increases the boiling point of benzene. Solutions always have a higher boiling point than their pure liquid components.	12
18.	Benzene and CS_2 are not miscible; therefore they boil separately at their individual boiling points.	6

tried to explain this phenomenon on the basis of intermolecular interactions. Some of the students held the idea that the solute molecules weaken the attractive forces among water molecules by entering between them, causing an increase in vapor pressure. Another group of students thought that solute particles interact with water molecules and this interaction makes the evaporation of water molecules difficult. These answers show that many students failed to correctly interpret the frequently used formula of vapor pressure depression, $\Delta P = P^{o}_{\text{solvent}}\, x_{\text{solute}}$, where ΔP is the difference between equilibrium vapor pressure of the pure solvent and equilibrium vapor pressure of the solvent after addition of the solute, P^{o}_{solvent} is the equilibrium vapor pressure of the pure solvent, and x_{solute} is the mole fraction of the solute in the solvent. This formula clearly shows that the vapor pressure depression is related to the mole fraction or number of particles of the solute.

Another misunderstanding is hidden in the answer that the addition of any substance into a solvent always increases the boiling point of the solution. The students overgeneralized the boiling point elevation fact and forgot that there are different kinds of solutions with respect to their components' states, such as solid–liquid, liquid–liquid, and gas–liquid solutions, whose properties differ from each other. Furthermore, as in misunderstanding 3, students neglected the properties of solutions with two miscible liquid components, in which solutions always have lower vapor pressure compared with the pure solvent vapor pressure. Additionally, misunderstanding 3 indicates that many students use "mixture" and "solution" as interchangeable concepts.

Equilibrium Vapor Pressure

Question 2 in the instrument tested students' understanding of the relationship between the amount of liquid and its equilibrium vapor pressure. The correct answer would be that the equilibrium vapor pressure value does not depend on the amount of the liquid. Remarkably, students explained the change in the vapor pressure using the ideal gas law. The misuse of the $PV = nRT$ formula confirmed the study results of Lin et al. *(27)* that students are successful in memorizing formulas yet often use them in inappropriate situations.

The other two misunderstandings on the same question relate to the misuse of Le Châtelier's principle. The students considered the liquid as the reactant and its own vapor as the product of a chemical reaction between the liquid and the vapor. As in misunderstandings 6 and 7, the increase in the amount of the liquid was interpreted as a factor affecting the equilibrium between the liquid and the vapor, and consequently the equilibrium vapor pressure value. These misunderstandings confirm the results of the study conducted by Gussarsky and Gorodetsky *(28)* that students typically do not distinguish between physical and chemical equilibrium, and misuse Le Châtelier's principle *(29)*.

Question 3 was intended to test students' understandings of the relation between equilibrium vapor pressure and container volume. Misunderstanding 8 is an attempt to explain that the equilibrium vapor pressure of a liquid has different values for different volumes of the container using Boyle's law ($P_1V_1 = P_2V_2$). This reveals the students' weak understanding of gas laws and, again, the tendency to apply algorithms to solve conceptual problems.

Question 4 required comparison of the vapor pressure values of two different liquids (H_2O and CS_2) at the moment of boiling. All of the students holding misunderstandings 10 and 11 explained that they needed to know boiling point values of these two liquids. The students with this intuition explained that knowing the boiling point values is important in comparing the relative values of the vapor pressures of the liquids. Because the boiling point values were missing the students first tried to estimate them by considering the relationships between boiling point value and molecular properties such as size or mass. Secondly, the students established a relationship between the estimated boiling points and the vapor pressure values and decided on the substance with high or low vapor pressure at the moment of boiling. These misunderstandings show that students who hold them have no idea about the nature of the boiling process.

Phase Diagrams

Question 5 was assigned to test students' abilities to interpret the graph that gives information about changes in melting point of a substance under different pressures. For this question two P–T (pressure–melting point) graphs, one for water and one for carbon dioxide, were presented and students were asked to select which of the substances would melt easily under high pressure and explain why. Because of the negative slope between pressure and temperature, water, not carbon dioxide, has the lower melting point.

Students misinterpreted the graph as if P were an independent variable and temperature a dependent variable. This misinterpretation led to misunderstanding 9: increased pressure means increased temperature for CO_2 and therefore quicker phase change.

State Changes

Question 6 was designed to test misunderstandings related to state changes from solid to gas and from gas to solid. Although 71% of the students were successful in identifying sublimation, a subsection of students defined the change as vaporization. The students' ideas about the process of passing from gas to solid varied widely. Some students called the process condensation while others called it sublimation (by indicating that this is a reversible process and the same name can be used in labeling the two directions of the process). Additional definitions for the process of deposition—different from those given in misunderstandings 13 and 14—were freezing, solidification, crystallization, and hoarfrost or rime. Fully 22% of the students did not define this process. Only one student explained the reason of the missing answer, writing simply "I have no idea". The answer "I have no idea" was thought provoking. After a short investigation of course textbooks used as main and additional sources, none of them were found to include a definition of deposition. This lack required students to construct their own definitions that could be plausible and fruitful explanations of the process.

Freezing Point Depression

The ability of students to evaluate the effects of pressure and impurity on freezing point was measured through question 7. The correct answer is that the freezing point value of a pure substance changes depending on the pressure changes and the amount of the impurity. Misunderstanding 15 (exhibited by nearly 24% of the students) is a transformation of the knowledge that physical properties such as freezing point (or melting point), boiling point, and density are discriminating properties for a pure substance. Misunderstanding 16 indicates many students' confusion concerning freezing point depression and boiling point elevation concepts. The most frequent explanation was that the freezing point increases because of weakened molecular interactions that make freezing difficult.

Although all colligative properties such as vapor pressure depression, boiling point elevation, freezing point depression, and osmosis are properties directly related to the number of the impurity particles, the students with misconceptions explained colligative properties on the basis of molecular interactions.

Raoult's Law

Question 8 asked students to explain how the boiling point of (liquid) benzene would change after the addition of some (liquid) CS_2. The boiling point values and vapor pressures of the pure liquids were given. The students should be able to explain that Raoult's law allows one to predict the vapor pressure value of the solution. Consequently the students can decide on the value of the boiling point of the solution by comparing qualitatively the solution's vapor pressure value with the pure liquid's vapor pressure value. Misunderstandings 17 and 18 show that many students failed to use Raoult's law. Furthermore, their explanation that benzene and CS_2 are not miscible indicates a lack of basic knowledge about the physical and chemical properties of organic compounds. Figure 2 shows the distribution of the 18 misunderstandings identified from the pre-service teachers' test responses.

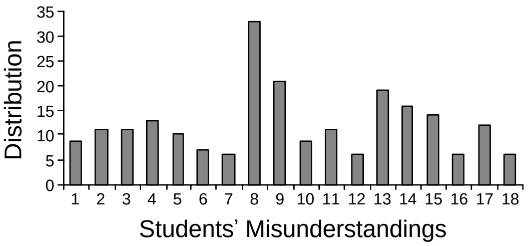

Figure 2. Distribution of students' misunderstandings as identified by examining the results of the concept test. (For the statements of these numbered misunderstandings, see Table 2.)

Discussion and Implications for Chemical Education

This study identified 18 conceptual misunderstandings expressed by pre-service teachers about some important concepts of phase equilibrium topics in physical chemistry, despite six weeks of detailed instruction.

The investigation of students' misconceptions and alternative frameworks has importance because of its contributions to the construction of new teaching approaches taking into account the students' difficulties in learning the scientific concepts. In a number of studies it has been demonstrated that students, prior to instruction, have misconceptions and retain them even after instruction *(30, 31)*. According to the constructivist model of learning, the misconceptions persist because conventional teaching approaches do not intentionally promote conceptual change *(32, 33)*. One way to show that misconceptions held by students are not scientifically sound is to design experiments, if feasible, that disprove students' misconceptions. Different studies *(34, 35)* have reported that textbooks are possible sources of misunderstandings. Instructors should be aware of this and pay close attention to whether the pictures, graphs, and definitions in textbooks (and other teaching and learning resources) under consideration may contribute to students' misconceptions.

Some of the misunderstandings revealed in this study underscore the fact that although most students are successful in solving the algorithmic problems, they often fail in solving the conceptual problems. Similar results have been reported by Nakhleh *(36)* and Nurrenbern *(37)*. To improve the students' conceptual problem-solving abilities, teachers should ask conceptual problems during the instructional process and require students to give qualitative explanations rather than algorithmic solutions alone.

The comprehensive nature of the phase equilibrium topic and the complicated relations between concepts in this topic may be another reason that students have misunderstandings, yet all of these concepts have been taught as main topics at previous grade levels.

The fact that the subjects holding these misconceptions are pre-service teachers makes the findings remarkable. Teachers should themselves possess a sound understanding of science concepts before they help students learn these science concepts. Lin et al. *(27)* stress that pre-service and in-service training programs should emphasize the importance of conceptual problem-solving and provide opportunities for prospective and in-service teachers to become aware of their understandings. Because teachers are faced with the challenge of transforming students' misconceptions, effective conceptual change teaching techniques must be taught and modeled during teacher preparation *(38, 39)*. Changes are also needed in chemical education, including chemistry curricula and textbooks, as well as teacher education programs *(38)*. Identification of pre-service teachers' misunderstandings in chemistry has the potential to improve teaching and learning significantly. We hope the results of this study will help those designing teaching approaches that promote pre-service teachers' conceptual understanding of phase equilibrium concepts.

ʷSupplemental Material

The concept test discussed in the paper is available in this issue of *JCE Online*.

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