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A Study of Turkish Chemistry Undergraduates' Understandings of Entropy

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Interest in children's understanding of science ideas has its origins in the classic studies of Jean Piaget *(1)*. Much of the research into students' understanding of chemical ideas has focused on school-age pupils, with less emphasis on undergraduates *(2–4)*. Many high school and university students experience difficulties with fundamental thermodynamic ideas in chemistry *(5)*. Thermodynamics is seen as consisting almost entirely of equations that are not understandable and that have to be learned by rote in order to do calculations and pass examinations *(6)*. Despite the importance of thermodynamics as the foundation of chemistry, most students emerge from introductory courses with only very limited understanding of the subject *(7)*. Physical chemistry courses, where students tackle more advanced ideas of thermodynamics and kinetics, are perceived by many students to be their most difficult courses *(8)*.

Defining Entropy

Entropy is a fundamental concept in chemical thermodynamics that helps to explain the natural tendency of matter and energy in the universe to become less ordered *(9)*. Entropy is defined or explained in a number of different ways, as illustrated in the following brief summary. Entropy provides a measure of the number of ways in which energy is distributed among energy levels within and between particles (*6,* p 7). This means that the more widely spread the energy quanta among the various energy levels, the more probable the state (the greater the number of microstates) and the higher the entropy. However, entropy is not a driving force. Energy's dispersion in a final state compared to an initial state is the driving force. Entropy is the index of that dispersal within a system and between the system and its surroundings. Entropy change is a quotient that measures the quantity of the unidirectional flow of thermal energy *(10)*. As paraphrased by Lambert *(10)*, entropy change measures energy's dispersion at a stated temperature (*10,* p 187). A detailed discussion about entropy is available at Lambert's regularly updated Web site *(11)*.

On the other hand, entropy is defined in terms of "distinguishability", meaning that entropy is a measure of the number of distinguishable ways the energy can be apportioned (*12,* p 1417). According to quantum theory, the molecules in a pure gas are indistinguishable. For example, it does not make sense to regard one hydrogen molecule in hydrogen gas as being different *in any way* from another hydrogen molecule. One effect of indistinguishibility is that if we mixed two samples of the *same* gas we would find that there is *no change* in entropy (*13,* p 283). Detailed analyses of the effects of distinguishability are available *(12, 13)*.

Previous Research on Entropy Misconceptions

Research on students' understanding of entropy has revealed considerable confusion among students. A study of 98 Scottish high school students from ten different schools indicated that students generally interpret entropy as a measure of disorder *(14)*. There was also some tendency to confuse entropy with kinetic energy.

These results are confirmed by other studies *(15)*. For example, a study of 56 student-teachers in their final year of college ascertained their ideas and areas of conceptual difficulties in thermodynamics and concluded that the students seemed to have a belief that there is a strong relationship between entropy and kinetic energy of the particles. Another misunderstanding explored *(15)* seemed to stem from a misinterpretation of the term "disorder" as "chaos". Ribeiro *(16)* also found that many students' understanding of the word "disorder" is different from that of scientists. Students used disorder in the sense of chaos or randomness. It was also reported that the majority of the students considered that disorder was greater when the energy increased (*16,* p 27). Moreover, it was also found that students perceived entropy and disorder as equal, or that entropy was the cause of disorder in the system *(15)*. In one study, students were asked to compare the entropy values of carbon dioxide and propane at the same temperature *(15)*. The results showed that seven out of ten students thought that carbon dioxide had greater entropy than propane at the same temperature.

Another study involved interviewing 14 Portuguese undergraduates in chemistry in their final year *(16)*. It was reported that although the majority of the students remembered the term microstate, only a few of them were able to explain it in terms of the possible arrangements of the particles. It was also found that a microstate was perceived as a little state and not related to entropy. In the same study it was also revealed that students have misunderstandings such as these: The entropy of the universe does not change; A system always goes to maximum entropy; The change of entropy of a reaction is always positive; and finally, in an isolated system, the change of entropy is greater than or equal to zero. It was suggested that university teachers should determine students' existing knowledge, lecturers should be careful in the language they use, scientific ideas must be shown to be useful to explain real phenomena, and students should be helped to see the contextual differentiation of their knowledge more clearly *(16)*.

A classroom-based study *(9)* conducted in a secondary environmental science class that explored the idea of entropy in the study of basic ecology revealed many incorrect ideas developed by secondary students. In addition, the study suggests that students could develop scientifically acceptable ideas if they are taught concisely. Students learned entropy as a physical law of nature rather than an idea that matter becomes more mixed-up. It was suggested that it would be useful to develop tasks at the beginning of the course leading students to discuss and confront alternative ways of thinking about entropy.

The literature synopsis above indicates that there is a shortage of systematic research on students' understanding of entropy at undergraduate level. Of the studies done so far most focused on either secondary-level students, or on only one aspect of entropy. This current study is an attempt to probe undergraduates' understanding of entropy.

Study Purpose and Logistics

This study explored what Turkish chemistry undergraduates understand of entropy and identified and classified what they misunderstand. Therefore, the following research question was addressed in the study.

- What do Turkish chemistry undergraduates understand about entropy and what are their misunderstandings?

For this purpose, diagnostic questionnaires and semi-structured interviews—before and after a course in physical chemistry—were used. Although some results of this study confirm previous findings, it goes further to investigate undergraduates' understandings and misunderstandings extensively in a more systematic way, and also seeks to establish where the identified misunderstandings may originate.

Student Demographics

This empirical study describes part of a longitudinal research project *(17)* and it follows the structure of similar studies (i.e., *18*). The data for this study was collected from two different Chemistry Education Departments in two universities in Turkey, one in western Turkey and the other in eastern Turkey. Both universities are placed in the top 20 of the Turkish Universities League. The students (third-year undergraduates, average age range of 19–23) involved in the study were enrolled in Physical Chemistry I and II courses (4 hours per week for a 14-week semester) at the fifth and sixth semesters, respectively. In addition, in one of the departments, there were four hours of laboratory work per week parallel to the teaching, while in the other department the laboratory course was given the following year. There were 47 majors in one department and 44 in the other.

A diagnostic questionnaire consisting of open-ended questions on key chemical ideas in thermodynamics, including four questions on entropy, was developed and given twice as a pre-test and post-test with a seven-month interval to a total of 91 students. In this study it was accepted that a good diagnostic question is one that generates information accessing respondents' thinking about the ideas being explored (*19,* p 75). Students were divided in two groups: 45 of them answered two of the questions (Seawater and Mixing of Gases) while 46 of them answered the other two (Spontaneous Change and Carbon Dioxide and Propane).

With respect to university education in Turkey, all the students have to be successful in a centralized, nationwide university entrance exam in order to gain access to the university. Students in this study had encountered some of the concepts of thermodynamics at a very basic level both prior to university and in general chemistry courses in the first year of their study in the participating departments. All the students in the participating departments are being trained as chemistry teachers through a four-year program.

Teaching Entropy in Physical Chemistry in the Participating Departments

The content and the design of the courses were determined by the instructors and they were similar in both departments. The physical chemistry course is divided into two main sections in the participating departments. Thermodynamics is covered in the fifth semester, while kinetics was the subject in the sixth semester. Thermodynamics sections in which entropy was covered includes the following subsections:

- The properties of gases (perfect and real gases)
- The first law of thermodynamics (work, heat, energy, thermochemistry, state functions, and work of adiabatic expansions)
- The second law of thermodynamics (the direction of spontaneous change, entropy, third law, effectiveness of thermal processes, and Helmholtz and Gibbs energies)

Entropy, the subject of this study, is covered under the second law of thermodynamics toward the end of the fifth semester in a five-week period (four class hours per week, a total of twenty class hours). The subheadings covered in both departments were the dispersal of energy, entropy, the entropy of irreversible change, entropy changes accompanying specific processes, and the third law of thermodynamics. With respect to the characteristics of teaching, the courses could be described as exposition-dominated lecturing. That means that the instructor actively presents the contents and students mostly listen and take notes; short discussions and question and answer sessions sometimes take place. In addition, homework is assigned to the students. During instruction, no differentiation was made between statistical thermodynamics and classical thermodynamics—instead these topics were intermingled.

Because of the lack of quality physical chemistry textbooks written in Turkish, instructors mostly follow textbooks written in English. Most of the students do not know English, and usually rely on notes they take during lectures. This procedure, typical in many countries, is an additional obstacle to the many learning difficulties in physical chemistry. It could be ameliorated by instructors preparing an outline that is handed out at least a few days before each lecture, complete with the basic mathematics that will be employed. An analysis of the problem of "What Makes Physical Chemistry Difficult?" is presented in reference *20.*

The Data

Questionnaire

Administration of the diagnostic questionnaire was carried out by the researcher in a lecture hour (50 minutes). In order to obtain equal number of responses to each question, the order of the questions was varied and four different sets, with the questions in different orders were prepared. This ensured that every question had an equal chance of being answered. No indication was given to the students whether they were expected to provide mathematical derivations, algebraic solutions, or molecular-level explanations. This was intentionally done to see the student's approach to the questions. Students were not permitted to take the diagnostic questionnaire out of classroom or discuss it with their friends or instructors. Diagnostic questions 1–4 (question 1, "Seawater"; question 2, "Mixing of Gases"; question 3, "Spontaneous Change"; and question 4, "Carbon Dioxide and Propane") were designed to test the following ideas, respectively:

- Any process that increases the number of particles in the system increases the number of microstates and therefore increases the entropy of the system.
- Entropy is the measure of the number of ways that energy can be shared among particles. Entropy increases if the number of ways of distributing the available energy among the particles is increased.
- During a spontaneous change the entropy of the universe increases.
- The entropy of a substance depends on its structure and the number of atoms it contains.

The questions (shown in Boxes 1–4 in the Supplemental Material[W]) outline the ideas being tested and the expected answers under the related subheadings of results. Questions 1–3 were devised specifically for this study (question 3 was modified from *21,* p 61). Question 4 was adapted from a previous study *(15)* and modified. Producing high quality diagnostic questions about entropy is difficult. Although the questions used in this study may not be regarded as a perfect set of questions, they were successful in revealing students' understanding of entropy.

Data relating to the questions are presented in Tables 2–5 in the Supplemental Material.[W] In the discussion *f* denotes the frequency with which a particular idea was identified. The word "response" refers to the whole answer given for a single question. It may include both scientifically correct and incorrect ideas as well as misunderstandings. The main categories are highlighted in bold and are the same for all questions. Subcategories vary according to each particular question. Percentages are calculated to help illustrate how often particular misunderstandings or partial understandings were repeated. The totals may exceed 100% in some cases, because some responses included more than one misunderstanding or partial understanding that was coded in different categories. For example, if a particular response to one of the questions included two different misunderstandings and one partial understanding it was coded three times in three categories. In contrast, some of the total percentage figures may be less than 100 because we excluded misunderstandings that occurred with a frequency of less than 5%.

Interviews

Interviews were conducted just after the pre-test and the post-test in order to support the data obtained from the questionnaires. The interviews held after the pre-test (22 interviews) sought to reveal the students' understandings of all the key ideas that were investigated in the entire study, including entropy. The post-interviews (7) sought to explore only the students' understandings of entropy in detail; therefore, there are more pre-interviews than post-interviews. The interviewees were all volunteers and the interviews took place in a staff office on one-to-one basis. Each interview was tape-recorded and then transcribed fully. Students' permission to tape-record the interview was obtained in each case. Interview times varied between 30–45 minutes. Students were not told about the content before the interviews, although they were aware that the topics would be the same as on the questionnaire. The interviews were not carried out as a freestanding study and so were not subjected to rigorous analysis. Selected extracts from these interviews are reported here to illustrate and support the evidence found from the questionnaire data.

Analysis and Results

Data and analyses from this study are provided in the Supplemental Material.[W] The authors invite you to look at the questions, data tables, and interview excerpts provided online to grasp the entirety of the ideas discussed in this paper.

Conclusions and Discussions

This study provides insights into students' understandings of entropy: results from the questionnaires and interviews show that entropy is difficult for undergraduates to comprehend. Students' understandings of the basic aspects of the idea are—in many cases—limited, distorted, or wrong. The difficulties arise from misinterpretation of mathematical equations in thermodynamics and inadequately integrating the new knowledge with students' existing knowledge. Students' misunderstandings identified in this study can be grouped under the following broad headings:

- Defining entropy as "disorder" and considering visual disorder and entropy as synonymous
- Inaccurately connecting entropy with the number of collisions and intermolecular interactions
- Inaccurately connecting entropy of the system and accompanying entropy changes in the surroundings
- Believing that the entropy of the whole system decreases or does not change when a spontaneous change occurs in an isolated system
- Supposing that the entropy of CO_2 is greater than that of C_3H_8, or the same at the same temperature.

In addition, careful examination of the percentages of the misunderstandings identified reveals that instruction did not prevent misunderstandings; instead misunderstandings increased in some cases (see especially tables 2, 4, and 5 in the Supplemental Material[W]). This finding supports the notion that misunderstandings are resistant to change in traditional teaching environments and special precautions have to be taken in order to prevent them *(22).*

Entropy depends on the temperature, volume (in the case of gases), the state of a substance or system, and type and amount of substance. Students' written responses and interview results suggest that factors affecting entropy were poorly understood or in some cases, not understood at all. Students argued that entropy is equal to the disorder of the system or simply stated that "entropy is disorder" in some cases. The findings also indicate that a major difficulty among the undergraduates who took part in this study was the students' understanding of the word "disorder". Almost all of the respondents defined entropy from the visual disorder point of view indicating chaos, randomness, or instability in some cases. Further probing on the use of the word "disorder" revealed that it was used to refer to movement, collision of particles, or "mixed-upness", similar to previous studies' *(15–16)* findings. Furthermore, the findings of this study suggest that "visual disorder" and "entropy" were considered as synonymous. This may be because of the fact that the meaning of the word "disorder", as used in the context of chemical thermodynamics, is inconsistent with its everyday meaning and misleading. Textbook writers and teachers commonly use "disorder" without defining it and the meaning varies among users. Whatever is meant by "disorder" should be clearly stated, defined, and consistently used throughout by the users. Perhaps another alternative to avoid the problems related to language would be encouraging students to explain in their own words and avoiding mere "parroting" of rote-memorized teacher language. In this way students and instructors may arrive at shared meaning *(23)*.

Moreover, recent research suggests that using "disorder" in teaching entropy should be avoided as it does not help students understand the concept *(10, 24–25)*. Instead, it was suggested that entropy should be defined as the index of energy dispersal within a system and between the system and its surroundings (*10,* p 187). It was argued that entropy could be considered from two viewpoints, classical thermodynamics and mechanical thermodynamics *(25)*. From a classical thermodynamic viewpoint, entropy can be seen as a measure of the energy dispersal changing from localized to spread out. From a molecular thermodynamics point of view, it can be considered as the change in the system from having fewer accessible microstates to having many more accessible microstates. However, it was also argued that teaching entropy as "disorder" is misleading as a descriptor for entropy. Entropy is neither disorder nor a measure of disorder or chaos. Entropy is not a driving force. Energy's diffusion, dissipation, or dispersion in a final state compared to an initial state is the driving force in chemistry. Entropy is the index of that dispersal within a system and between the system and its surroundings *(10)*.

The majority of the content of the responses was composed of basic facts or statements about the subject and only a small number of the students attempted to discuss the ideas at the molecular level. Although students tended to use mathematical equations and preferred algebraic solutions, and in the responses for pre-tests and post-test responses displayed some interpretations and conceptual understandings, no systematic trend has been observed in the responses between pre- and post-tests. Students' habit of using algorithms to solve problems may be due to the unintended impression that science is a sort of mathematics, "math in disguise", unintentionally caused by science teachers. Algorithms may be fostered by the instructors by placing more value on algorithmic learning than on conceptual learning and also by the exam system in which more algorithmic problems are preferred for the sake of easy grading.

The majority of the students could not use thermodynamic principles to explain the change in entropy of a system. The students' thinking was found to be poor and limited at a microscopic level. Mostly they considered their answers at a macrophysical level and consequently were unable to provide interpretations at a molecular level. In many cases, everyday meanings of the words dominated students' understandings, indicating that they are more likely to use an everyday notion of a scientific concept than the accepted scientific one.

Implications for Teaching

The results of this study suggest that many students in an advanced undergraduate class have difficulties in understanding entropy, as well as having difficulties in acquiring advanced thermodynamics ideas *(17)*. It is likely that many of the learning difficulties identified in this study would be found among physical chemistry students in general, although the subjects in this study were from only two university chemistry departments in Turkey. Therefore, the findings of the present study may provide some clues about the quality of student learning in typical physical chemistry classes. The results indicate that a substantial review and reform of teaching strategies at the tertiary level of education is essential.

Since this study provides evidence that students' explanations of scientific phenomena are based on the macrophysical world and they demonstrate a limited ability to think at the molecular level, instructors should ensure that students have acquired the correct scientific meanings of entropy and related concepts and that they can apply the ideas learned in different situations, whether it is an everyday phenomenon or a theoretical one *(15)*. In addition, instructors should pay attention to everyday, out-of-class ideas associated with the scientific terms they use. They should also be checking whether students have understood concepts in the way instructors intend.

Sometimes the best way to become aware of the shortcomings of one's own knowledge is to compare it with that of others *(26)*. A classroom discussion covering areas of confusion (entropy change in a system and the surroundings, disorder, visual disorder, spontaneity, entropy and intermolecular interactions) could be an effective way of identifying students' learning difficulties and stimulating students to think about basic concepts in a problem before proceeding to a solution. Short-answer questions prepared in different forms such as multiple choice, true–false, and two-tier diagnostic questions could be an alternative in determining students' misunderstandings both prior to teaching and during teaching. Furthermore, in-class writing, previously used *(27)* to identify students' learning difficulties in thermodynamics, could be another alternative. The essence of in-class writings is based on posing students short-answer, open-ended questions during teaching. Reading in-class writing of students may provide clues to the level of students' understandings and misunderstandings they hold during the teaching process. A previous study *(27)* provides evidence that in-class writing is a powerful means for identifying students' problems and misunderstandings so that they can be remedied at the time. Showing good student writing examples to the students during the next lecture can help clarify troublesome concepts. In addition, instructors can give additional coverage of identified topics if necessary. However, doing this in a nonthreatening manner should not be forgotten. Perhaps employing an informal and ungraded format would be a better way to probe student knowledge effectively.

A context-based teaching approach that uses scientific applications and context as a starting point may provide better help for students in developing an understanding of some areas of chemistry as compared to traditional approaches *(28).* A recent study *(29)* provides evidence that a context-based approach in teaching chemical thermodynamics at the undergraduate level improves learning as well as increasing interest in chemistry. Context-based approaches can be a viable alternative to the more traditional approach without sacrificing rigor or quality of learning. In addition, a recent study *(30)* points out that thermodynamic entities should be defined qualitatively and their effects talked about before they are defined quantitatively, reversing the usual procedure in which numerical problem solutions are set first and then understanding follows. Holman and Pilling's *(29)* study applied this notion in teaching chemical thermodynamics and reported success in the quality of student learning.

Kozliak *(31)* argues that using simple examples (based on the Boltzman distribution) the concept of entropy can be introduced consistently on a molecular basis by emphasizing energy distribution among the accessible microstates. Students are strengthened in their understanding of chemistry as a molecular science. Then they can remain focused on the ensuing phenomenological consideration of thermodynamics because a molecular foundation exists for the concrete and well-defined goal of calculating entropy using the experimental measurable values of work, heat, and temperature. As a result, the content and nature of physical chemistry courses may be reconsidered, liberating it from a textbook-driven and mathematical derivation-driven course and providing informative, interesting, and content-rich materials to help students learn physical chemistry concepts. Some of the mathematical burden can be removed by the appropriate use of software to enable students to focus on learning the significance of physical chemistry *(20).*

Finally, studies that reflect the theoretical aspects and students' understandings of entropy are limited *(32).* Students' difficulties with entropy need further exploration, as do other thermodynamic concepts. High school and university students' understandings of the relationships between entropy changes and temperature, entropy and spontaneity, and entropy changes in the case of solid and liquid matter would benefit from further research. It is also important to make available the findings of the studies reviewed above to classroom teachers, instructors, and students so that their findings may be incorporated into practice.

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[W]Supplemental Material

Thee questions used in this study, the data analysis coding scheme, analysis and discussion of the questionnaire and interview data, and misunderstandings as well as their possible sources are all available in this issue of *JCE Online*.

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