International Conference NEW PERSPECTIVES in SCIENCE EDUCATION

Teaching Entropy at Bachelor Level in a Conceptual Change Perspective

Vincent Natalis, Loïc Quinton, Bernard Leyh

MolSyS and DIDACTIfen Research Units, University of Liège, Belgium

Abstract

In the framework of conceptual change theories in the learning sciences, identification of pre- or misconceptions and their replacement by scientifically validated conceptions is a central aspect of any teaching. Recent neuroscientific explorations brought new dimensions to the problem by showing the importance of inhibitory processes. Physical chemistry at the undergraduate level is known for being a difficult topic, due to its abstract character and the need to combine physical insight with a mathematical toolkit. Entropy and the second law of thermodynamics is a central topic in the physical chemistry curriculum, upon which most STEM students step during their first year at university. Specific difficulties linked with these concepts include the existence of two possible approaches, a macroscopic and a molecular one, whose interconnections are seldom made explicit. In this study, we present and discuss results of misconception identification for first-year bachelor students in chemistry, pharmacy and geology in a French-speaking Belgian university, using a pre- and post-test about entropy and the second law, before and after a one-semester course using the most common macroscopic teaching method. The questions of this test have been developed based on a detailed analysis of the approaches of standard physical chemistry textbooks. In addition, the investigation of remaining misconceptions of more advanced students (2nd and 3rd bachelor year, 1st and 2nd master year, not presented here) completed the study. Some of the identified misconceptions are comparable to those already published in the literature, and new ones are detected. Some misconceptions are rather of ontological nature whereas other ones result from inappropriate interpretation of analogies. As far as 1st year bachelor students are concerned, the results indicate that most erroneous conceptions remained after the one-semester course and that some were even aggravated. The obtained results will be a guide to develop new teaching approaches, involving a better link between experimental situations and the conceptual framework and including discovery learning as well as numerical simulations.

Keywords: *Conceptual change, misconceptions, entropy, second law of thermodynamics*

1. Introduction

The existence of student misconceptions is recognized as one of the key elements to be considered in any didactic approach [1]. Concepts and approaches in physical chemistry frequently exhibit a high degree of abstraction, which is partly related to the associated mathematical formalism. This is the source of many of the didactic hurdles typical of abstract subjects [2]. Among the major themes of physical chemistry, our research focuses on one of the fundamental aspects of thermodynamics: entropy and the second law. This topic presents, among others, two didactic characteristics worth of interest: (i) physically speaking, entropy emerges from events at the atomic and molecular level, what we call the microscopic scale, but, historically, it has first been addressed at the macroscopic scale, which leads to two distinct teaching approaches; this is a source of cognitive conflicts that tend to remain even after an introductory course; (ii) it is a cross-cutting subject, addressed in physics, chemistry, biology, engineering and information science, with each branch having its specificities and complementarities [3].

Johnstone's triangle [4] is a key to analysing the problem posed by the appropriation of the concept of entropy. The interconnection of three points of view - macroscopic, microscopic and representational - generates cognitive obstacles specific to chemistry. The present work also fits into the theoretical framework of conceptual change, for which several currents or sensibilities exist, represented among others by Vosniadou [5] or diSessa [6]. These theories conceptualize how students evolve from alternative, naïve, false or incomplete conceptions to scientifically founded ones.

The work presented here is the first step in the development of new methods for teaching entropy and the second law, at the undergraduate level, supported by research in didactics. The first step is to identify the misconceptions of a population of students in their 1st year of chemistry, geology and pharmacy in a French-speaking Belgian university (University of Liège) at the end of a basic general chemistry course (autumn semester) and to analyze the impact on these misconceptions of a more indepth one-semester course (spring semester) using the conventional macroscopic approach. The pre- and post-tests invite students to develop reasonings that question the metaphor of disorder [7].

2. Method

A questionnaire was submitted to N= 181 students in the following sections, following common courses: Chemistry, N=27; Geology, N=12; Pharmacy, N=142. Five closed-ended questions aimed at probing expected misconceptions, in light of the literature and the analysis of recognized textbooks. Five semi-open-ended questions (multiple choice and request for justification) seek to elicit cognitive conflict by confronting students with paradoxes related to alternative misconceptions. The questionnaires were validated by 20 experts. The pre-test was organized face-to-face, while the post-test was offered online and without obligation, resulting in a significantly lower answer rate (N = 49). The comparison of the two tests was limited to the common respondent population. A system of identifiers makes it possible to monitor the individual progress of the participants.

3. Results and Discussion

We shall focus here on one question of each above-mentioned category to illustrate two aspects of identified preconceptions: ontology and analogy.

3.1 Closed question analysis: example of entropy definition

Figure 1 presents the results of the first question, which attempts to identify the concepts that students consider as ontologically related to entropy.

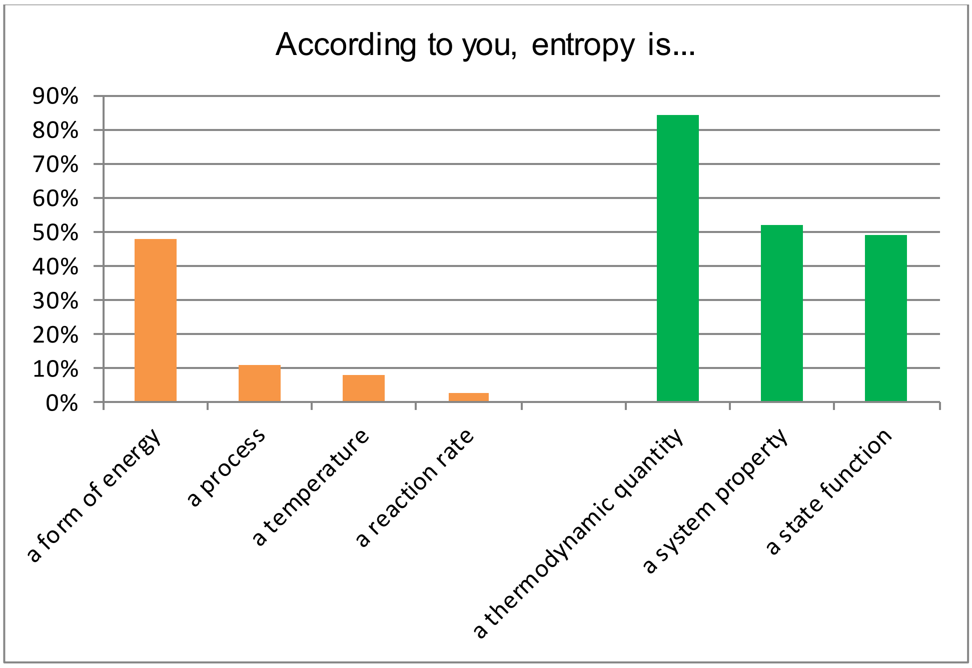

Figure 1: Percentage of choices for the different statements related to the definition of entropy. Pretest data (N=181). Multiple answers are possible. Green: correct choices. Orange; incorrect choices.

The assimilation of the concepts of energy and entropy is a misconception that is significantly present (48%), even though the two concepts are distinct: energy is the capacity of a system to perform work, whereas entropy represents the degree of energy dispersion over the accessible states. Energy is conserved, unlike entropy, which increases during a spontaneous process. While more than 80% of the students recognize entropy as a thermodynamic quantity, only half of them perceive it as a property of a system (52%) or as a state function (49%). This may be related to the fact that the macroscopic approach focuses on the entropy change, in line with Clausius' equation, therefore obscuring the fact that entropy is a property of a system. The notion of state function remains very formal and is only touched upon in a basic course.

Figure 2 compares the pre-test and post-test results for the items we have just discussed. The other statements have similar answer rates for the pre- and post-test. We recall that the respondent population is significantly lower for the posttest (N = 49 out of N = 181 on the pre-test). It can be assumed that the posttest results come from the most motivated students.

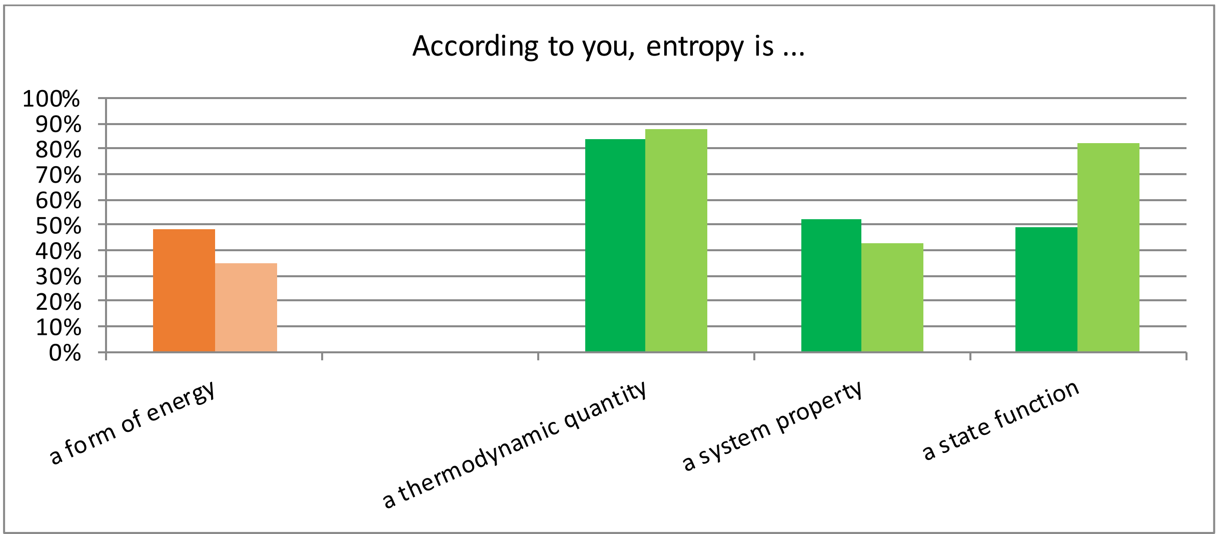

Figure 2. Percentage of choices of statements related to the definition of entropy. Data obtained before and after the spring semester course. N=49 common participants to both tests. Dark colours: pre-test; light colours: post-test.

Figure 2 highlights the following aspects.
- The misconception "entropy is energy" is receding but remains present for more than one third of the students.
- The correct statement "entropy is a state function" progresses significantly. This seems to be consistent with the macroscopic approach, which emphasizes "entropy as a function of state" for use in classical thermodynamic procedures to calculate entropy variations. However, the concept of state function seems only partially understood, since only 43% of the students recognize the link with the item "property of a system".

3.2 Open Question: Example of overcooling

The following open-ended question is adapted from Sözbilir and Bennett [7] and simplified to remove some ambiguities.

Water, when it is very pure, can be kept in a supercooled state down to -10°C at atmospheric pressure, which means it's still liquid when it should be solid. When an ice crystal is added to this sample of water, crystallization starts immediately. This phase change is exothermic.

To study this process in detail, a known quantity of water is placed in a supercooled state, in a Styrofoam box (thermal insulation): there is therefore no possible heat exchange with the environment. Then, a small ice crystal is added through a hole in the cap, which is immediately closed, triggering spontaneous crystallization. The mass of the added crystal is small enough for its contribution to entropy to be neglected. How does the entropy of the system change after the ice crystal is added?

- ◯ It increases.
- ◯ It decreases.
- ◯ It remains constant.
- ◯ None of the above three answers is correct.

Figure 3 Open-ended question about supercooling

This question addresses the misconception "the variation in entropy is determined by the visually observable change in spatial disorder". Although the order increases during the transition from a liquid to a solid at constant temperature, the entropy must nevertheless increase here: it is indeed a spontaneous evolution in an isolated system. The process is indeed accompanied by a temperature increase. 58% of the students seem to follow the misconception and consider that entropy will decrease. In addition, the post-test shows that the distribution does not change after the spring semester course, showing the resistance of this alternative design to change.

In Figure 5, we can observe the distribution of the student justification categories. More than 20% of the students who provide the correct answer do not justify it correctly or not completely. For example, some students state that the addition of a crystal increases the entropy of the system, in contradiction with the provided information (fig. 3).

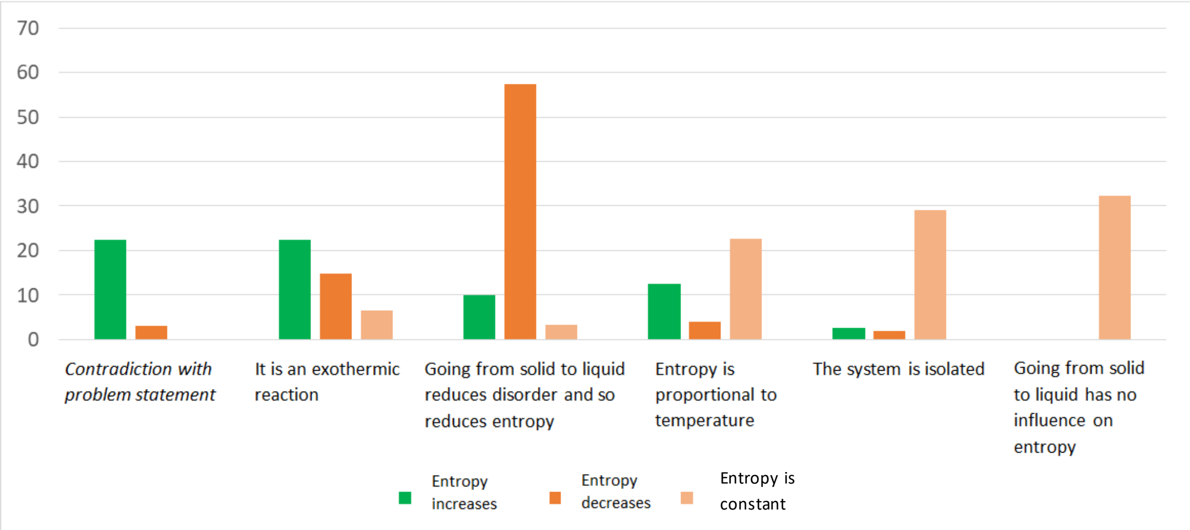

Figure 3 Percentages of occurrences of typical justifications for the question on undercooling. Pretest: N = 181. Some answers provide several different justifications.

4. Conclusion

Entropy and the second law of thermodynamics, because of the involved degree of physical and mathematical abstraction, the difficulty to make a link between the macroscopic and the microscopic scale, and the cognitive conflicts they generate, represent a didactic challenge. In this paper, we show that first-year students present many misconceptions of the concept of entropy and its use through the second law, and that a traditional thermodynamics course does not necessarily correct or even aggravate them. Some misconceptions are ontological in nature, such as the assimilation of energy and entropy, others seem to be related to a superficial understanding, and thus misuse, of a metaphor ("entropy = disorder") already introduced at the birth of Boltzmann's statistical thermodynamics.

These results, supplemented by ongoing analyses of other first-year student populations, will constitute a basis for the development of didactic approaches aimed at enabling students to make appropriate connections between various experimental situations and the conceptual framework, either through investigative learning or the development of numerical simulations.

5. References

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