Introducing the second law of thermodynamics using Legitimation Code Theory among first year chemistry students

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Abstract

This study investigated the introduction of the second law of thermodynamics using the Legitimation Code Theory (LCT) (semantic waves) among first year chemistry students. The aim of the study was to investigate the extent LTC (semantic waves) reduce the entropy concept's complexity and abstractness when introducing the second law of thermodynamics. A purposive sampling technique was used to sample participants from the accessible population. A sample of two hundred (n = 200) first-year chemistry students was chosen at a public university in South Africa. The study adopted a mixed-method research design. Data were collected using an Introductory Second Law of Thermodynamics Questionnaire (ISLTQ) and semi-structured interviews. Creating semantic waves during the lectures left many students in the trough of the sinusoidal wave of abstractness and complexity. Ranking the concepts related to entropy showed that many students knew the hierarchical order of the concepts. However, the interviews revealed that students tended to link entropy to the spread of particles instead of energy. The findings of this study are diagnostic and they assist module designers in determining the level of abstraction and complexity students face when introducing the second law of thermodynamics.

Key words: Abstraction; complexity; Legitimation Code Theory; second law of thermodynamics; semantic waves.

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1. Introduction

Students require a diverse skill set to fully grasp the second law of thermodynamics in introductory physical chemistry. These skills include the ability to express concepts mathematically, to understanding systems, and to grasp the language of thermodynamics. The second law of thermodynamics, expressed with regard to entropy, relies heavily on differential equations and demands a basic understanding of complex statistical concepts. Introducing the second law is based on the Clausius inequality and the Boltzmann-Plank equation. Chemistry is an abstract subject which require students to operate at three levels of thought. At the heart of this abstraction is the complexity of the language of thermodynamics. The Legitimation Code Theory (LCT) semantic waves frames educational practices as being supported by social codes, providing a framework that can guide instructional approaches. The theory also affords a way of isolating out abstraction and complexity when teaching chemistry.

Statistics on Science, Technology, Engineering and Mathematics (STEM) students' throughput and retention rates in South African higher education reveals a system that is failing many of its first year students. This is a longstanding problem in South Africa, dating back decades (Scott, 2009; CHE, 2013). The 2007 Council on Higher Education (CHE) report stated that the attrition rate is highest at the end of the first year of study. For freshman, the overall pass rate in STEM courses at contact universities is reported to be roughly 29% (CHE, 2007). In 2016, the CHE reported that poor performance was still persistent across South African universities, with degree completion rates falling below 42% at most contact universities. It was also reported that students' conceptual difficulties originate in high school and are not likely to be resolved in the foreseeable future. The onus rests on higher education institutions to find ways of addressing the needs of these students (CHE, 2016). This might require rethinking the current curriculum structure and approaches to lecturing.

Literature on education research connected to the second law of thermodynamics (Kaper and Goedhart, 2005; Sözbilir, 2004; Tsaparlis, 2007; Bain and Towns, 2016) shows three major problems affecting students in introductory thermodynamics: a lack of student motivation, lecture-centred instruction methods and the abstract nature of the topic. This study opted to use the LCT (semantic waves) to address the complexity and abstract nature of the second law of thermodynamics. Although thermodynamics is a pre-requisite for advanced courses in chemistry, studies focusing on the complexity and abstraction in the topic are rare as compared to chemical kinetics (Bain and Towns, 2016). Several instruction methods based on conceptual change approaches in science have been tried, such as concept maps, cooperative learning and simulations, but these are all mainly at a high school level (Abell and Bretz, 2019). There has been limited research on the use of LCT (semantic waves) to guide instruction at university level.

Maton's (2014) LCT is premised on the ideas of social realism where codes are used to organise principles for understanding practices. The LCT proposes three dimensions that are useful to analyse educational practices, viz. specialization, semantics and autonomy. Clarence (2016) suggests that analysing educational practices using semantics enables the hierarchical characterisation of the practice, highlights what is being legitimated, and allows the effects to be considered in detail. Semantics views the teaching of chemistry in terms of semantic structures whose organising principles can be explored in terms of semantic gravity (context-dependence) and semantic density (degree of complexity).

According to the LCT any knowledge in chemistry has a specific vocabulary which precipitates into short phrases of complex ideas. Teaching an abstract, complex topic effectively may require the

use of knowledge at lower cognitive levels. Maton (2014) defined semantic gravity (SG) as the degree to which meaning relates to its context. The SG is related to the degree of abstraction and can be stronger (+) or weaker (-) along a continuum of strengths. Semantic Density (SD) relates to the degree of complexity, where meaning is condensed in phrases, concepts and equations. The SD and SG are mutually exclusive. Figure 1 below shows how the SD and SG can be applied when teaching the second law of thermodynamics.

SG-

Abstract concepts Common words used with common meanings on entropy	**abstract** **equation** $\Delta S = \dfrac{q_{\mathrm{rev}}}{T}$ (constant T)

SD-

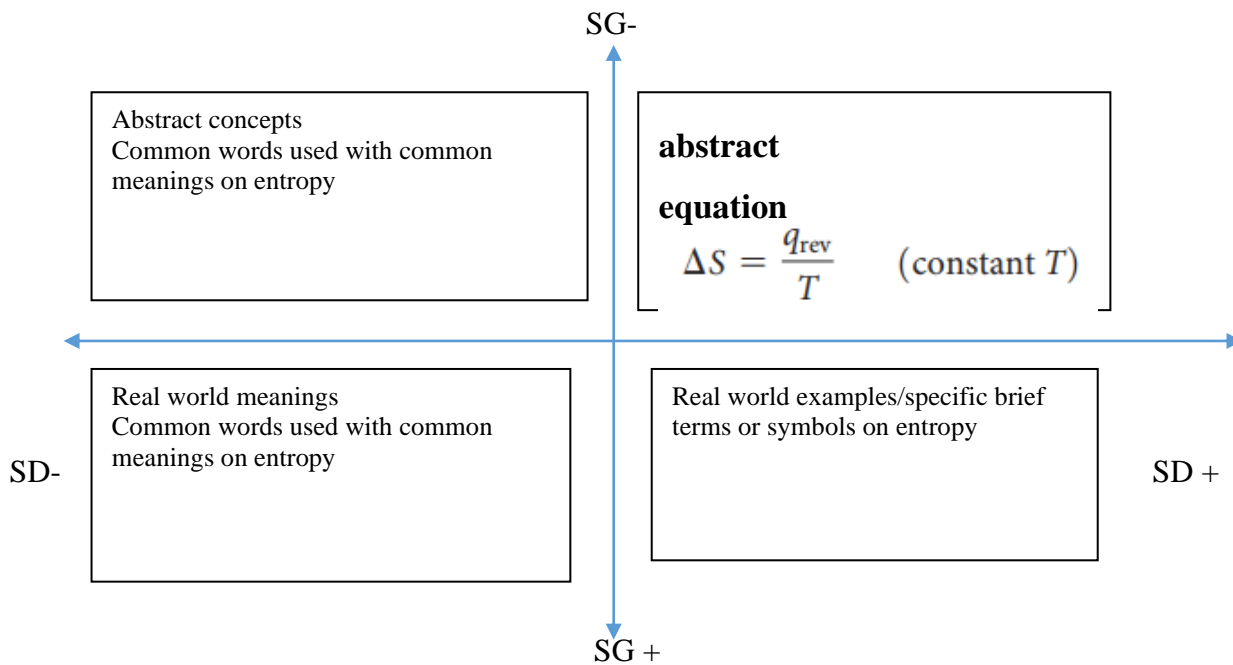| Real world meanings Common words used with common meanings on entropy	Real world examples/specific brief terms or symbols on entropy

SD +

SG +

Figure 1: Semantic gravity and semantic density

The simple equation for change in entropy is an example of weak SG (-) and high SD (+). An abstract equation is the change in entropy of an isothermal process. The ΔS is the heat transferred by a reversible process **q** $_{\mathrm{rev}}$, divided by the absolute temperature measured in Kelvins. In any reaction there are many paths/routes the system can take from one state to another, but only one path is associated with a reversible process. Integrating SG, SD and time during a lesson leads to the key concept of semantic waves. Creating semantic waves involves packing and repacking the concept being taught.

Semantic waves are created when a lesson is designed in such a way that unpacking meanings of the second law reduces the SG and SD while the repacking increases the SG and SD. Figure 2 below shows how the teaching of a concept progresses, where the unpacking of the concept involves the breaking down of abstraction and complexity and repacking using concrete and simple examples. The unpacking and repacking create semantic waves. This requires a lecturer to introduce new terms, followed by simpler and familiar ways of describing the same phenomena (Curzon, Waite, Maton, and Donohue, 2020).
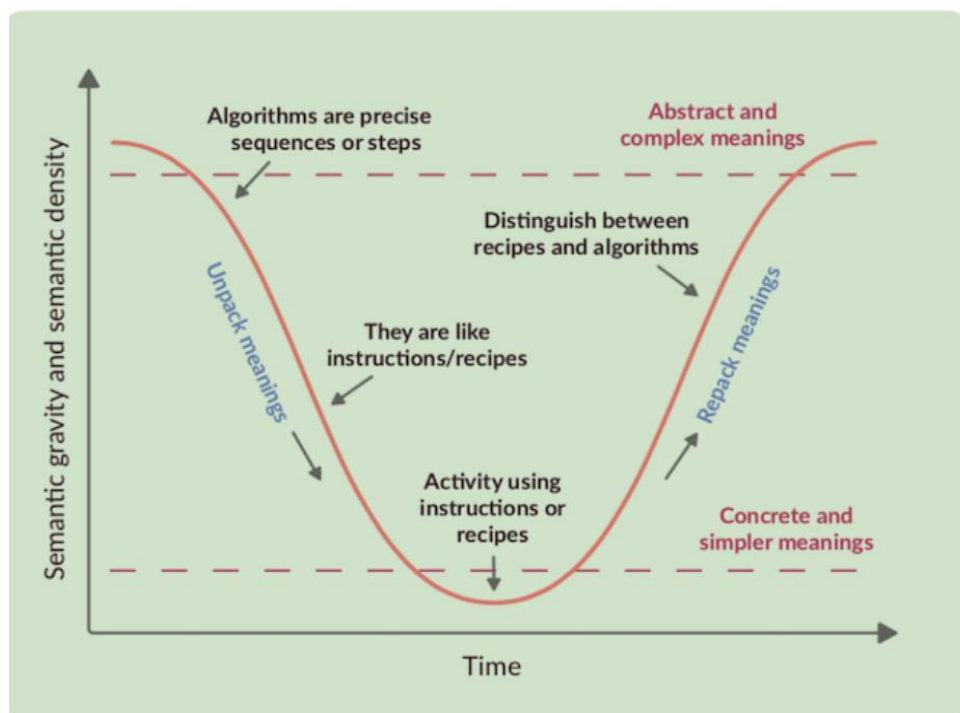
Figure 2: *Unpacking and repacking of a semantic wave*

The South African high school physical science Curriculum and Assessment Policy Statement (CAPS) has three topics (Activation energy, Enthalpy change and Bond energy changes) that are related to thermodynamics under energy and chemical change. Endothermic and exothermic reactions are explained in terms of bond breaking, requiring energy and bond formation which releases energy respectively. Practical investigations on exothermic reactions include mixing anhydrous copper (II) sulphate with water and lithium with water. The topic is covered in the third term of grade 11. First year chemistry students are expected to study the three laws of thermodynamics in both physics and chemistry.

Numerous instructional approaches have been suggested to deal with the abstractness and complexity of the third law of thermodynamics. Carson and Watson (2002) suggest that enthalpy, Gibbs free energy and entropy are old adversaries to students. The conceptual difficulties students face starts in high school and persists even after postgraduate studies (Bain and Towns, 2016. To reduce complexity and abstraction in introducing the second law of thermodynamics, Kozliak (2004) used the Boltzmann's microscopic approach to interpret entropy's microstates bypassing complex statistics. Findings reported an increase in students' conceptual understanding of entropy through a connection between the increase of entropy and heating. However, interviews revealed that students' difficulties with the microscopic approach persisted.

In a similar study, Dreyfus, Gouvea and Geller (2014) introduced entropy using the Gibbs free energy. The approach also connected the second law to the conservation of energy, leading to the interplay of energy and entropy in determining spontaneity. First year biology students took part in the study and interviews were used to collect data. The majority of the students struggled with technical terms, such as chaos, disorder and randomness, when describing entropy. Introducing

entropy using the Gibbs free energy resulted in confusion between enthalpy and entropy as a form of energy.

Haglund, Anderssona and Elmgren (2016) argued that introducing the degree of entropy with the degree of disorder is vague. Students develop alternative conceptions since the term 'disorder' itself has various interpretation possibilities and depends on the context. Furthermore, it is easy to induce alternative conceptions through excessive generalization in students who are new to entropy. The authors recommended a holistic approach to the abstraction and complexity of language and concepts when introducing entropy. Furthermore, students were asked to rank nine concepts with how closely they are related to entropy. The ranking involved arranging the terms according to how important they were in explaining and describing entropy. A negative correlation was observed between the degree on the terms and the explanations. Most students relied on equations to rank the terms and failed to explain how important they are to entropy. Airey and Linder (2015) described this observation as a tension between pedagogical methods and the conceptual understanding of entropy.

Christensen, Meltzer, and Ogilvie (2009) investigated first year physics students' understanding of entropy and the second law of thermodynamics at two large universities in the United States of America (USA). Open-ended questionnaires were used to collect data from an accessible sample of 1184 students. More than half of respondents struggled with the overall increase of entropy in a system. Alternative conceptions based on the particulate nature of matter were reported especially when describing the spreading of energy among the microstates. The study did not look at how students ranked the concepts related to entropy.

Starikov (2010) investigated the many faces of entropy and introduced the second law using Bayesian statistical mechanics. The approach was designed to derive the Boltzmann-Planck formula for entropy mathematically based on experimental facts. Furthermore, it revisited the fundamental idea of thermodynamic equilibrium by explaining the interconnection between Boltzmann-Gibbs and statistics. The students struggled to identify entropy with disorder and with complications between the system and its surroundings.

Bhattacharyya and Dawlaty (2019) prefer to introduce entropy concepts by relating them to the thermodynamic definition of entropy, $dS = dQ/T$ (Clausius's equation), with the statistical definition, $S = k_B \ln\Omega$ (Boltzmann's equation). Combining the thermodynamic entropy and statistical definitions is known as the one phase space perspective. The approach links the number of configurations (Ω) with real and momentum spaces. The results revealed that relating dQ to $d\Omega$ reduced students' common alternative conceptions on adiabatic compression. Fire and dice were used as starting points to introduce heat and microstates. However, some concepts of entropy were found to be more demanding, such as microstates and energy distribution across energy levels.

Introducing entropy to chemical engineering students, Yu (2020) investigated how quantum volume concepts could be integrated into the teaching of thermodynamics. The approach used Sackur-Tetrode equations and binomial distribution entropy diagrams. Entropy diagrams were used to aid the visualization of quantum volume and system volume. In a related study, Melander, Gustavsson and Weiszflog (2013) investigated engineering students' conceptions of entropy. They completed a questionnaire about their ideas on entropy based on work-done, disorder, heat, temperature and energy. The majority of the students linked entropy with disorder and least with work. Furthermore, students were given short texts about entropy to study and summarise their ideas. The texts described entropy using macroscopic and microscopic approaches. Most of the students had difficulties

explaining the microscopic approach of entropy and struggled with the technical terms used when introducing entropy.

The literature reviewed has shown that introducing entropy is still a challenge, especially with the technical language used. The second law is based on experimental observations and the atomistic understanding of the processes remain elusive among high school and university students. Many approaches have been tried that include the statistics and thermodynamics, heat, temperature and work done. Despite the various approaches, introducing the second law has remained a challenge.

The aim of our overall research endeavour has been to contribute to the understanding of how creating semantic waves when introducing the second law, expressed in terms of entropy, to reduce the concept's complexity and abstractness. Furthermore, the present study sought to probe deeper into the way students rank the concepts used when introducing the second law of thermodynamics. Against this background, the following research question guided this study:

1.   How does creating semantic waves when introducing the second law of thermodynamics, expressed in terms of entropy, reduce complexity and abstractness of the concept of entropy?

2.   How do students rank the concepts related to the introduction of thermodynamics?

2. Methods

This study employed a mixed-methods sequential explanatory research design and included sources of quantitative and qualitative data, i.e., questionnaires and interviews. The sequential explanatory design consists of the dominant quantitative approach (Quan) followed by the qualitative approach (qual) (Creswell, 2015). The logical basis of this approach is two staged, that the quantitative approach provides a general understanding of the research problem. Qualitative approach compliments the quantitative approach by refining and explaining statistical results in-depth (Tashakkori & Teddlie, 2008).

2.1 Setting and Participants

The study was conducted in the first semester of 2019 at a public university in South Africa. All two hundred students were enrolled in the Faculty of Education, Department of Mathematics, Science and Technology Education (MSTE) module of natural science and technology. The module is divided into three consisting of Chemistry (50%), Geography (20%) and Physics (30%), and had three instructors. The module was given in the first semester and completed in three months. Students entered the course directly from high school and the entry requirements included a pass in both Physical Sciences and Mathematics. Students were assessed through a questionnaire and pair interviews. Ethical clearance was obtained from the university to collect demographic information through questionnaires and interviews.

2.2 Data Collection Instruments

The collection of quantitative data was followed by the collection of qualitative data to provide insight about students' understanding of introductory concepts related to entropy. The Introductory Second Law of Thermodynamics Questionnaire (ISLTQ) had five open ended questions. The questions were guided by the educational experience of the author and literature, especially Blackie (2014), who suggested that semantic density (complexity of meanings) and semantic gravity (dependency on context) are crucial in designing questionnaires. Second and third laws of thermodynamics concepts covered in the questionnaire were based on defining entropy, explaining the relationship between entropy and the number of microstates, predicting the sign of the entropy

change for chemical and physical processes, and entropy changes for phase transitions and chemical reactions.

Three chemistry lecturers and three high school educators checked the validity of the instrument's content. The reliability of ISLTQ was calculated using the Cronbach alpha coefficient of 0.74. The five questions instrument difficulty indices ranged from 0.38 to 0.68. A semi-structured interview (Gay and Mills, 2016) data collection instrument was used to gain insight into how students understood introductory entropy concepts. The researchers moderated the semi-structured interviews where two students were allowed to enact a dialogue which closely resembled an authentic collaborative learning setting. Students were allowed to share their ideas about entropy and express their agreed ideas.

Informed consent was gathered from all twenty participants who volunteered to take part in the study. To guarantee anonymity students were identified using the first twenty letters of the alphabet. Ten interviews were conducted each lasting about 30 minutes, and the students were selected in pairs based on the similarity in their questionnaire responses. The first question involved the qualitative and quantitative aspects of entropy, and students were allowed to discuss, express, list and rank six key terms related to entropy using Figure 3 below:
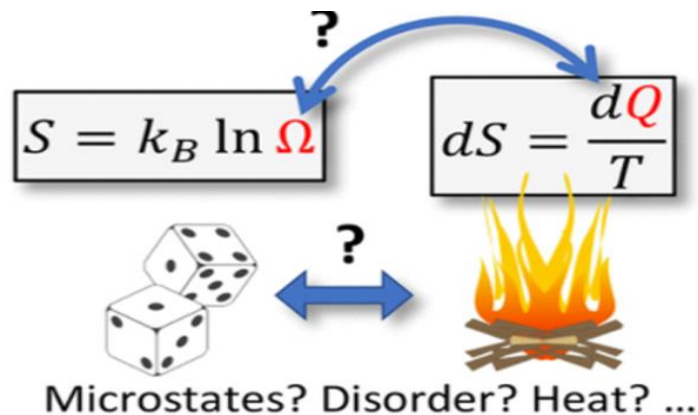

Figure 3: Interview question

The first question was based on the common words that are related to entropy as reported by Larson (2011) and Haglund, Anderssona and Elmgren (2016). The students were also allowed to rank the words on cards in descending order in terms of how closely they are related to entropy. The second question was designed to illicit students' semantic density and gravity. Students were allowed to explain their reasons related to the ranking of the terms.

2.3 Semantic Waves

The lesson plans were designed according to the LCT semantics with the sole purpose of increasing semantic density and lowering the semantic gravity. Variations between the SD and SG during the introduction to entropy can be viewed as a sound wave that has rarefactions and compressions. Rarefactions, which represent the trough in a wave profile, depict the time where chemical terms and equations are explained using familiar vocabulary. Similarly, equal time was allocated in repacking, moving slowly towards conceptual complexity. According to Maton (2014), this approach creates semantic waves through the unpacking and repacking of ideas, as shown in Figure 2. The approach described by Mouton and Archer (2019) requires the lecturer to create semantic waves during the progression of the lecture as shown in Table 1 below.

The unpacking and packing of the SG and SD during the progression of the lecture produces sinusoidal waves. Lesson plans take into consideration the equations and terms used when introducing entropy that are to be unpacked and repacked. Activities including interactive simulation of PhET states of matter and experiments were used during the unpacking stages as the lecture progressed. Lessons plans evaluated using Table 1 below to ensure uniformity in the delivery of lectures.

Table 1: Semantic gravity and semantic density employed to evaluate lesson plans

Concrete experiments, simulations and examples	SG++	Familiar vocabulary on introducing entropy	SD-
Information about general abstract concepts of entropy		Connecting with prior high topic on chemical change and systems	
Prior knowledge linked with the context on entropy		Scientific language on entropy, e.g., state symbol, microstates	
New terms on the second and third law related to introducing entropy	SG-	New concepts such as disorder, heat, spreading, spontaneous	SD++

2.4 Data Analysis

Responses from the questionnaires were coded and entered into an excel spreadsheet. The four quadrants proposed by Maton (2011) that link the relationship between semantic gravity and semantic density were used to code the responses. The change in entropy equation would fit into SG-/SD+ quadrant. The abstract concept of change in entropy is summarised using symbols for heat and temperature. Expressing entropy in terms of a mathematical expression has a weak SG. In SG+/SD-, the response uses simple everyday language with real-world meanings and common meanings on entropy.

In SG-/SD-, familiar terms are used and the response represents a higher level of abstraction. The questionnaire response should include terms such as 'reversible process', 'spontaneous' and 'microstates'. In SG+/SD+, the response includes concrete real-life examples with the correct way of using the terminology. The categorised responses were analysed using Statistical Package for Social Sciences (SPSS) for generating descriptive statistics. Interview responses were tape-recorded and transcribed, and the Maton (2011) quadrants were used to analyse the responses.

3. Findings

3.1 Complexity and Abstraction of Entropy

Students' responses on defining entropy were analysed first. Figure 4 below provides an overview of the results. Most of the responses (about 45%) on defining entropy was in the SD+/SG+ categories. The least (about 8%) was in the SG-/SD-. Though about 33% of the responses remained in

the SG-/SD+, these were definitions of entropy based on equations. In SD+/SG+, the responses provided real examples, such as the change of the state of matter. Entropy was defined as the dispersal of energy when particles spread out and gained freedom of motion. Some of the responses would start from the equation, explain the terms in the change in entropy equation, and then give related examples based on the phase transitions.

The weakening of semantic gravity and increasing semantic density revealed a reduction in complexity and abstraction. SG-/SD- had few responses where students displayed abstraction and the terminology used when describing entropy according to the second law of thermodynamics. Entropy was described as a spontaneous process which increases in an isolated thermodynamic system. In systems that are not isolated, a mathematical equation was provided (Universe = System + Surroundings).
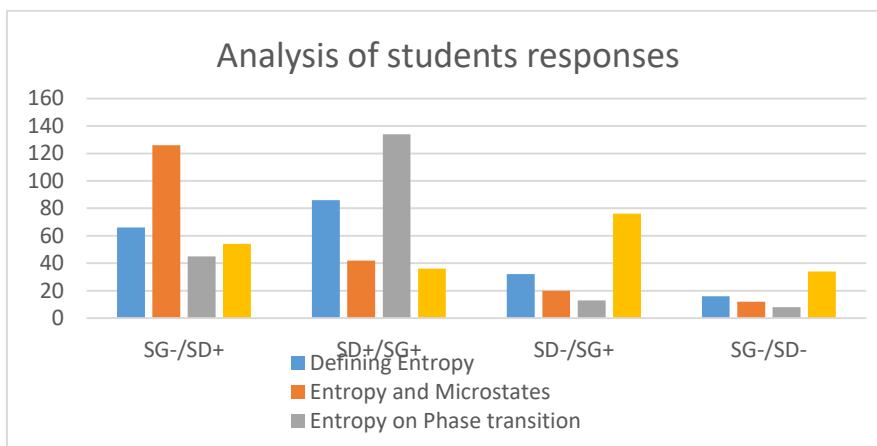

Figure 4: Analysis of questionnaire responses

Entropy and microstates had more than 60% in the SG-/SD+, where students relied on an equation. Real examples linked to microstates were the phase changes of water. Evaporating water, where liquid boiling water changes phase to a gas, was an example that was mentioned most about increase in entropy. Only 6% of the students described entropy as spreading of energy in terms of the distribution or dispersal of energy across energy levels. Similar results were reported by Melander, Gustavsson and Weiszflog (2013), where students struggled with the microscopic and macroscopic qualities of entropy.

Furthermore, Bhattacharyya and Dawlaty (2019) reported that some aspects of entropy were found to be more challenging, such as microstates and energy distribution across energy levels. Students confused the spreading out particles with spreading out of energy across energy levels. The interpretation of spreading out of particles in relation to entropy has been reported previously by Sözbilir and Bennett (2007), implying a confusion between entropy, kinetic energy and microstates. According to the LCT semantic waves on microstates remained in SG-/SD+ because energy levels and microstates are related to energy and not the spread of particles.

Predicting entropy for physical changes (about 38%) was in SD-/SD+. Complexity and abstraction were reduced as correct predictions were made. Phase transitions were linked to the states of matter, with freezing being associated with an ordered structure that reduces entropy. In the SD-/SG-, very few students saw freezing as a phase transition that reduces the number of microstates and therefore a decrease in entropy. The semantic wave could have left many students in the trough

during the unpacking stage. Repacking, that leads to abstraction to the crest took 4% of the students. Statements such as 'fewer microstates lead to small dispersal low entropy' and 'more microstates lead to spread of energy high entropy' showed that students in SD-/SG- had the correct terminology on predicting phase transitions. The prediction of entropy of a chemical reaction was based on a question of two gas molecules oxygen and hydrogen combining to form water in liquid form. Most students predicted that entropy would decrease since liquid has a more defined shape than the two gases. The states of matter were linked to predicting change in entropy. In the SD-/SG-, responses pointed to the decrease of microstates and giving a negative sign for **ΔS.**

3.2 Ranking the Concepts Related to Entropy

Qualitative data were collected to answer the research question. The students were asked to rank concepts related entropy. Students were paired according to the similarity of their responses in the questionnaires. The pairs were shown the Figure 3 and allowed to explain the micro and macro properties of entropy, and identify and rank the key terms associated with entropy. Almost all the student pairs agreed that it is easy to understand entropy using the equation and to then unpack the symbols. Most students ranked the terms based on the equation of change in entropy, heat and temperature. All the key words were listed as follows: spontaneous, microstates, reversible process, heat, energy dispersal, temperature, non-spontaneous, thermodynamic system.

As in the questionnaire responses, entropy was linked to the phase transitions. In unpacking the equation (**ΔS**=q/**T**), few students related it to the systems, spontaneous and reversible processes. In line with Bhattacharyya and Dawlaty (2019), who started with the Figure 3 to introduce entropy, the result of the present study showed how students failed to reach the SD-/SG- in explaining the key terms. This is exemplified by the fourth pair G and H:

G: *The equation will guide the most important terms about change in entropy which is heat and temperature in an isolated system.*

H*:   Looking at the equation the important terms are temperature and heat I agree. The equation is the starting point and it does not overload my mind.*

The view on entropy, which is restricted to mathematical formalism, is recognised from previous research as reported by Blackie (2014). The excerpt above shows how students would treat an equation as the starting point of unpacking change in entropy. The next pair also shows students' reliance on the phase transitions and the formula for change in entropy as reported in previous research by Loverude (2015):

E: *Entropy is the spreading out or dispersal of energy of the particles. The phase transition of the states of matter provide a better understanding of entropy*.

F: *Also a better understanding of heat and temperature can help to explain entropy. From the equation heat has to enter or leave the system*. *A gas has more entropy since the particles are spread out and have more freedom to move in any direction.*

E: *I agree ranking in terms of entropy will be gases >liquids> solids*. *The change in entropy equation has all the terms related to entropy. It's easy why are we even ranking the states of matter.*

The pair has the SD+/SG-, but they lack the proper terminology of how entropy can be described to reach SD-/SG-. Student E explains the dispersal of energy well and quickly reverts back to the equation.

The seventh pair, M and N, proved how students can reach SD-/SG- without referring to the equations:

M: *Entropy can occur in thermodynamically isolated system or the open system that occurs in many reactions. There is always a catch on the spreading out of kinetic energy among the energy levels. The energy levels are the microstates and if they are many the more entropy the system will have.*

N: *As for me I don't rely much on the equation but the spreading out which is a key characteristic of spontaneous reaction. Coming to the equation entropy provides the extent of energy spread out in a system at a specific temperature. Microstates or energy states can be related to the translational, rotational and vibrational motions of the particles or molecules in a system.*

Neither relied on equations, but still had a firm grasp of what entropy was all about. All the key words were listed down as follows: spontaneous, microstates, reversible process, heat, energy dispersal, temperature and non-spontaneous. Most students ranked the terms based on the equation of change in entropy, heat and temperature. The SG-/SD+ used the equation to list the most important terms related to entropy. Three pairs of students in SD-/SG- started with energy dispersal, microstates at the specific temperature and spontaneous. The interviews have shown that most students rely on the change in entropy equation to explain and identify key terms on entropy.

3.3 Discussion

This section will first reflect on the extent to which the purpose of the study has been fulfilled, and will then draw conclusions from the study with reference to the research questions. Lastly, the focus is shifted to the educational implications of the study. The use of LCT semantic waves for reducing abstraction and complexity when introducing the second law of thermodynamics is achieved to a lesser extent. Creating waves left many students in the unpacking trough (SD+/SG+) and few reached the abstract and complexity crest of repacking. Entropy was defined as the spreading of the particles' kinetic energy and molecules.

The finding by Bhattacharyya and Dawlaty (2019) showed that some aspects of entropy were found to be more challenging, such as microstates and energy. Particles gaining kinetic energy and changing phases was viewed as gaining entropy. Predictions of entropy on phase changes and chemical reactions were done well using the states of matter. Problems associated with entropy were on using the correct terminology, especially the dispersal of energy among the microstates as reported by Blackie (2014). The findings are similar to those reported by Dreyfus, Gouvea and Geller (2014) about students facing difficulties in using technical terms when describing entropy. Still, students struggled to understand and visualize microstates during phase transitions and chemical reactions. The findings are line with Sözbilir and Bennett (2007), who reported students' confusion among entropy, kinetic energy and microstates.

Though concrete and familiar examples were used in the unpacking stage, repacking proved difficult on entropy. Only a handful of students managed to reach the trough and crest (SD-/SG-) of the semantic waves mentioning microstates, dispersal of energy, isolated and open systems and signs on change in entropy. Phase transitions and chemical reaction predictions on entropy had many students who reached the SG+/SD- and only a few reached SG-/SD-. Semantic waves made students to give real examples, but the complexity remained for the few students. SG-/SD- required students to mention microstates, the spread of energy and the sign of entropy in their responses.

Analysis of interview responses showed similar results with the questionnaire responses. Most students relied on the equation to rank concepts related to entropy. The view on entropy which is restricted to mathematical formalism was reported by Blackie (2014). According to Loverude (2015), students must not rely on the formula to describe entropy, or they will miss important concepts.

4. Conclusion

The findings of this study show that semantic waves are knowledge builders as proposed by Maton (2014). An accumulation of waves passing through the unpacking trough and repacking crest results in knowledge accumulation in the introduction to entropy. Effective teaching of entropy depends upon effective knowledge-building practices, which successfully bridge the gap between SG (the ability to grasp abstract concepts) and SD (the ability to communicate within specific academic languages). This is dependent upon both the strengthening and weakening of semantic gravity (context dependence). This study agrees with the suggestion by Shalem and Slonimsky (2010), who view semantic waves as knowledge builders through sinusoidal movements between abstract and contextual detail. A good lecture on entropy is the result of both gravitation (unpacking) and levitation (repacking).

The implications for science education are that lecturers need to be conscious about creating semantic waves during lectures. Chemistry is an abstract and complex subject. Unpacking terms associated with entropy requires concrete examples and familiar vocabulary. A single high level abstract concept such as the equation of change in entropy requires the incorporation of several different strands of knowledge. Lesson progression should be characterised by iterative movements from higher semantic density to lower semantic density and subsequently from weaker semantic gravity to stronger semantic gravity. Importantly, as has been shown by the findings of this study, it is important for lecturers to introduce entropy without rushing to use equations. The findings of this study also show that repacking was achieved on entropy and phase changes, but still difficult with respect to microstates.

4.1 Recommendations

In light of this study's findings, it is advised that chemistry educators focus on describing the second law of thermodynamics using real life examples. The findings show that students rely on equations to describe entropy. Students should be encouraged to approach entropy using energy and microstates. Furthermore, studies related to the correlation between the ranking of entropy concepts and how they influence students' SD and SG are necessary for future studies. In addition, for book authors, it is recommended that they prepare their books' contents with as many physical examples of entropy as possible.

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