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A HOLISTIC APPROACH TO ENTROPY IN SCIENCE EDUCATION

Review Study

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Abstract

Entropy is a concept with an extreme controversy which many scientists have been trying to explain. Some of the approaches employed in its definition contradict each other, which made it extremely difficult for high school and college students to understand. Boltzmann was the first person who brought a statistical explanation to entropy and linking it with the disorder concept (S = klnw). The point which received the highest amount of criticism is the similarity between the visual regulation in everyday life and regulation of particles, which is the metaphor that causes the highest number of misconceptions. The primary goal of this study is to go down the roots of the controversy surrounding the entropy concept and propose solutions. In the framework of all these difficulties, the concept was investigated with an integrated and simple approach. In this pretext, the macroscopic and microscopic features of entropy, the difficulties and misconceptions encountered, and the methods used in its education have been thoroughly examined. The final step was developing a "Tripod Approach" to facilitate the explanation of this complicated concept and fill the gaps in this area. In addition to it, alternative energy and probability-based and integrated entropy description, which reflects the essence of both macroscopic and microscopic approaches, was presented, and this description is expected to be a solution for the controversy resulting from the disorder concept.

Keywords: Energy, entropy, unavailability, probability, tripod approach

1. Introduction

Thermodynamics is an essential topic in physics, chemistry, biochemistry, pharmacy, and engineering (Patron, 1997; Sözbilir, 2001). Thermodynamics is an interdisciplinary science with utmost importance and is regarded as the key to natural sciences and affects almost every scientific field ranging from biology to chemistry (Meltzer, 2004; Patron, 1997; Sözbilir 2011). Thermodynamic concepts are of utmost importance to solve nature and enables us to understand nature and nature-based problems such as global warning (Haglund, Andersson and Elmgren, 2015). However, due to the abstract nature of many thermodynamic concepts, especially entropy, they are not easy to comprehend.

The scientific world has been very reluctant to give a net description of many thermodynamic concepts, including entropy (Lambert, 2011). Therefore, the wide use of this concept among different disciplines brings so much contradiction and turmoil with it. Von Neumann explained this situation as (Tribus, M., McIrving, E. C, 1971; Quoted by; Popoviç, 2018): "*since nobody knows what entropy means, the one who used this word always wins.*" Unfortunately, this situation caused severe problems in the teaching and learning processes of this concept. That is why it is crucial to devise a net approach by the investigation of the historical development of this concept.

In this study, firstly, the answers to the following question are to be found:

- What are the macroscopic and microscopic meanings of entropy?
- What sorts of difficulties emerge in the education of entropy?
- What are the alternative approaches and or metaphors in the education of entropy?

As the study proceeded, we attempted to establish an education approach to overcome the problems related to the entropy concept. For this purpose, a "Tripod Approach" based on integrated viewpoints of the Clausius and Gibbs upon entropy was developed.

Since the current entropy descriptions are predominantly based upon the microscopic approach, the macroscopic approach developed by Clausius has been almost forgotten (Popoviç, 2018). As a result of this, it was found that the thermodynamic concepts such as enthalpy, Gibbs free energy, the second law of thermodynamic could not be related to entropy (Haglund, Andersson, and Elmgren 2016). That is why an alternative entropy description was made to overcome the problems resulted from using macroscopic/microscopic approaches (Baierlein, 1994; Kozliak, 2004). Lambert, 2006 mainly developed this description; Haglund et al., 2010; Leff, 2012; Popoviç, 2018, resulting in the eventual development of the tripod approach.

However, the purpose of the study is neither an in-depth analysis of the entropy concept nor enter an argument about this puzzling scheme but establishes an alternative approach to overcome those preceding difficulties.

2. Method of the Study

This study aims to critically review and evaluation of the studies related to the entropy concept. In other words, the study is a qualitative critical examination and synthesis study. In this research, qualitative data for a scientific phenomenon were analyzed with an integrated analysis and an inductive approach, and new findings were obtained. According to (Fraenkel, Wallen & Hyun, 2012), qualitative research is a research method to better understand a particular event, where creative studies and new findings are provided. Again, to reveal the relationships between the findings and to reach new results from the findings, the researcher makes comments that will give meaning to the data (Yıldırım&Şimşek, 2008, p. 238). In this study, an alternative teaching approach and a definition for the concept of entropy was developed by analyzing the findings in-depth.

3. Literature Review

3.1. An Integrated Historical Outlook to a Mysterious Concept of Entropy

The history of the entropy concept dates back to the mid-19th century, where the studies to improve the efficiency of the vapor engines were extremely popular. A young scientist Rudolf Clausius gave his utmost attention to thermodynamic studies of Sadi Carnot. Clausius, one of the founders of thermodynamics, was the first scientist who proposed the entropy concept and lighted the fuse of dynamite in his papers published in 1857, 1865, and 1867. Since then, entropy is a mysterious concept with increasing popularity and took the attention of many disciplines.

Popovic (2018) described three different types of entropy, one in information theory, and the other two are in the theory of matter. One of the descriptions of entropy in the theory of matter takes unused energy as the reference (thermodynamic approach), and the other one is based upon the order or regulation of the particles (statistical approach). The entropy description based upon the information theory was first proposed by Shannon (1948), who explained the entropy "as the measure of probabilities to code a message." According to Shannon, there are two equal probabilities in head /tail draw with a coin, while there are six equal probabilities in throwing dices. Therefore, dice throwing has higher entropy than a head/tail draw. Popoviç (2018) states that the use of all tree entropy description one from the information and two from the matter science would be sufficient and all other descriptions would cause confusion

However, Lambert (2006) claimed that entropy is not dependent solely on thermal effects. According to him, probability also plays an important role and should be taken into account. He emphasized that under these conditions, one needs an integrated approach, and none of the descriptions would be sufficient enough alone. In this pretext, we can conveniently say that Shanon's description based on only the probability concept is far from describing the whole picture.

Unfortunately, the controversies and paradoxes surrendering entropy concept caused its perception to be so complicated, and these complications immediately converted into misconceptions, which results in the deviation from our educational targets (Lambert, 2006; Haglund et al., 2015). That is why both the macroscopic (thermodynamic) and microscopic (statistical) approaches should both be used as an essential manner in the description entropy. Below are the brief analyses of these approaches:

3.2. Macroscopic (Thermodynamic) Meaning of Entropy

The macroscopic (thermodynamic) meaning of entropy is based upon the statements of Clausius. He described the entropy function, which means "transformation" in Greek as (Guillen 1995; çev, Tanrıöver s. 211): "*I chose the word entropy willingly to resemble the energy. Because the physical meaning of these two concepts are too close so they should have a very similar nomenclature"* This indicates that although energy and entropy have certain similarities, they are entirely different concepts. Popoviç (2018) says that Clausius first proposed the concept of entropy when he was contemplating on the question "why the combustion engines could not convert the whole energy into work (useful energy)? As seen here, entropy is though as the lost part of the total energy. Clausius assumed the thermodynamic entropy is the unused part (the part which was not converted into work) of the total energy.

The second law of thermodynamics describes entropy as a physical entity, which is a measure of non- convertible energy. It describes the thermodynamic entropy as the ratio of the non-convertible energy to work. The second law of thermodynamics also states that all the irreversible systems try to bring their entropies to maximum and energies to a minimum by keeping the energy at the least convertible form. Although the thermodynamic meaning of entropy is also given by the second law, the following expressions developed by Kelvin-Planck and Clausius are much more prevalent (Dincer and Cengel, 2001).

Kelvin-Plank expression: It is impossible to draw a certain amount of heat from a hot heat reservoir and produce an equivalent amount of work without transferring a sizeable amount of it to the cold reservoir as a useable energy tax (approximately 65-70% depending to the efficiency). You have to work very hard to get any redemption (making the system as reversible as possible) (Sarasua and Abal, 2016; Xue and Guo, 2019).

Clausius expression: No system draws heat from the cold reservoir and transfers it to the hot reservoir without outside help. Heat always goes from a hot reservoir to a cold reservoir. If you want to do the otherwise, you need outside contribution (Sarasua and Abal, 2016; Xue and Guo, 2019).

Since Clausius's expression is based upon a spontaneous natural process (cooling), it is much easier to comprehend. On the other hand, Kelvin–Planck expression is based upon non-spontaneous natural process (heating); it is relatively difficult to perceive for the learners (Xue and Guo, 2019). Andrews (1971; Quoted: Kesidou and Duit, 1993) describe this situation "all the energies finally go to the same situation which certain parts are useless" is a simple expression of the first and second laws of thermodynamics.

Johari (2010) has described the entropy according to chemical thermodynamic as *"It is qualitatively the measure of the extension of the energy of the molecules."* This description reflects the Clausius macroscopic theory adapted to multi-atom systems (Popoviç, 2018).

The mathematical expression of entropy was given by Clausius as dS≥ dQ/T. This expression shows that the total entropy is zero for the reversible and more significant than zero for the irreversible processes. This assumes that the entropy is a state function questionable since it is not independent of the routes of the process (Akman, 2013).

Another macroscopic thermodynamic concept that is related to entropy is the Gibbs Free energy, which represents the available energy at constant pressure and temperature ∆G=-SdT + VdP). Here entropy is the unusable or unavailable energy for the conversion to the usable energy (work). $\delta w = \delta w_{useb.} + \delta w_{exp}$ Here the expansion work is regarded as the unusable work. Therefore the first law can be written as $dU = \delta w_{usable} - PdV = TdS + \delta w_{usable} - PdV$.

Gibbs energy is given after solving the derivatives as $dG = dU + d(PV) - d(TS) + \delta w_{usable} = TdS - PdV + PdV + VdP - TdS - SdT + \delta w_{usable} = -SdT + VdP + \delta w_{usable}$. As can be seen, determining the maximum operating condition (i.e., constant T and P) is much easier when using Gibbs internal energy. That is why the most widely used thermodynamic derivative. The unavailable energy here is expressed in the entropy term (Gillet, 2006; Quoted: Popoviç, 2018). The Gibbs free energy is, therefore, the maximum available energy under constant pressure and temperature, which are the conditions (more or less) that exist in our daily lives (Gibbs, 1873; Quoted: Popoviç, 2018).

The second law of thermodynamic facilitates the determination of the maximum work produced in a particular process, and it is a highly valuable asset in engineering. It is possible to calculate energy efficiency values using this feature. The second law of thermodynamics provides an in-depth insight into the mechanistic function of nature (Kesidou and Duit, 1993). It helps us to understand the energy problems of the community (Dincer and Cengel, 2001).

Dincer and Cengel (2001) argued that the science of thermodynamics can be described in a much broader perspective as the science of energy, exergy, and entropy (except for the zeroth and third laws of thermodynamic).In this context, entropy can be described as thermodynamic exergy, an expression of the loss of usable energy in an irreversible system (Hepbaşlı, 2012) or the part of the total energy convertible to other types of energies (Rant, 1964).

3.3. Microscopic (Statistical) Meaning of Entropy

It was not possible to explain the tendency of entropy to increase in spontaneous or irreversible processes using Clausius Thermodynamic theory. The foundation stones of the thermodynamics were laid by scientists such as Boltzmann, Maxwell, and Gibbs (Haglund, Jeppsson, and Strömdahl, 2010). Especially Boltzmann found a statistical explanation relating entropy (S) and microstates (W) as $S=k_B lnW$ corresponding to an isolated system. Here k_B corresponds to Boltzmann constant with a value of $1.38x10^{-23}$J/K (Haglund et al., 2010).

Microstates(W) are the states where the position and momentum of the particles (atoms or molecules) are known. Microstates can easily related macrostates and macro events. In other words, the higher is the number of microstates, and the higher is the probability (www.entropysite.com). That is why the following description of entropy was generally adapted: *"A state of the system is the measure of the realization of that state. The lower probability states have lower, and high probability states have higher entropy"*. This probability-based approach is a much more comprehensive explanation of the second law of thermodynamics (Dincer and Cengel, 2001).

One of the statistical approaches which enable us to understand the entropy concept at the molecular level is the Gibbs equation. Gibs used the following equation to calculate the entropy of a system depending upon the statistical distribution of microstates:$S = k\sum_i p_i ln p_i$. Here p_i is the probability of the microstates of the system. Boltzmann and Gibbs equation also improved our knowledge of entropy at the molecular level. Entropy, according to the Boltzmann, is dependent upon the number of microstates accessible in the system, while the Gibbs equation states that entropy represents the measure of the probability of the microstates. Although both these approaches enable us to do the statistical evaluation of entropy, the quantitative results differ a lot. Haglund et al. (2010) attributed this situation to the fact of Gibbs equation is much more generalized than Boltzmann equation and can be applied in a much more comprehensive range. Although different mathematical models give so-called different results, it is generally accepted that the Gibbs equation gives many correct and generalized results.

Another concept that is widely employed in the statistical evaluation of entropy is "the degree of freedom." According to it, entropy is the measure of the free-acting capacity of the particles. Statistical mechanics is interested in the behavior of the particles (atoms and molecules). To describe the behavior of a particle, we must have a definite knowledge of its momentum and location. Popoviç (2018) stated that to define a particle, one needs three-dimensional momentum and the exact time of it. Therefore, for the definition of 6×10^{23} monoatomic particles, we need 18×10^{23} degrees of freedom. In order to define the instantaneous microstates, we take an instantaneous picture of an ideal gas system in equilibrium where the molecules move arbitrarily. However, since the particles are perpetually in action in spite that they are in equilibrium, microstates change by the time. Therefore one only needs two parameters to define a macrostate; to do the same for a microstate, and you need each degree of freedom in addition to it.

While the controversy surrounding entropy was continuing since Clausius, Boltzmann (1898) aggravated the situation when he tried to link the entropy concept with order/disorder concepts. Akman (2013) explained the order as the distribution of the total energy among particles and the fact that after converting some of the energy as useful work, the system lacks the capacity of returning the previous position.

The quantitative equation of entropy $dS_{rev}=dQ/T$ derived from the second law of thermodynamics does not give us a clue about the absolute value of it. However, the calculation of the number of probable routes for the order of the particles is possible by the third law of thermodynamics. According to this law, the entropy of a perfect crystal at 0 Kelvin is zero. However, if the temperature is deviated from (0 K), there are big changes in the order of the crystal structure, and the remaining entropy is described as residual entropy.

3.4. The Problems Encountered In Teaching Thermodynamic Concepts and Misconceptions

Meltzer (2004) reported in his study seeking the opinions of the students about the thermodynamic concepts that, even though heat, work, and internal energy are entirely different concepts, most of the students could not make this distinction. The students mostly have a hard time understanding the internal energy, and their insistence on this misconception was attributed to their previous knowledge. Similarly, Cotignola et al. (2002) and Erickson and Tiberghien (1985) claimed that students possess instinctive ideas upon heat and temperature.

Pinto Casulleras (1991) reported that the students have a grave misunderstanding of the concepts of conservation of energy and decreasing energy and concluded that the confusion of the similarities and differences prevailing among heat, temperature, and energy stem from the failure of the in-depth investigation of these energy concepts before. There are similar studies in the literature reporting that the students have serious problems to distinguish heat and temperature concepts(Brook, Briggs, Bell, and Driver, 1984; Tiberghien; Quoted by Kesidou and Duit, 1993, Unpublished Ph.D. thesis, 2020).

Christensen and Rump (2008), on the other hand, report that the problems of university students to understand the thermodynamic concepts originated from the fact that they all come from different disciplines. This result was supported by Becker et al. (2013) in their study carried out with a small group containing the students from the chemistry and physics departments. He observed that, while the physicists approach the thermodynamics in a macroscopic manner without taking its microscopic nature into account, chemistry students predominantly chose an approach taking the molecular interactions into account. In a study where the university students studying in different departments were asked to give an order of some thermodynamic concepts according to their relations with entropy, and it was found that their answer differed according to the departments they came from(Haglund, Andersson and Elmgren, 2015; Haglund, Andersson and Elmgren 2016).

The macroscopic change in entropy can be given as $dS \geq dQ/T$ (Thomas and Schwenz, 1998; Haglund and Jeppsson, 2014; Loverude, 2015). For instance, in a thermodynamic course in the engineering department, the students were given survey forms containing six thermodynamic concepts as heat, temperature, work, disorder, energy, and probability, and they were asked to range them according to increasing relation with entropy. As seen from $dS_{rev}=dQ/T$ heat and temperature have a much higher correlation with entropy than disorder; the students chose that the most and the least related concepts are disorder and work, respectively. (Gustavsson, Weiszflog and Andersson, 2013).

Since thermodynamic concepts and especially entropy is regarded among the most difficult concepts to understand by the students, the metaphors and analogies are frequently employed in their education process. The most common metaphor used in the education of entropy is the disorder concept. The disorder concept was first used by Boltzmann to reflect his point of view upon the microscopic world of entropy. However, this concept was subjected to harsh criticism by the scientist all over the world (Styer, 2000; Lambert, 2002; Sözbilir, 2007). Styer (2000), claimed that the entropy is a vague concept which does not fully express what is intended to mention and sometimes it is not sufficient to relate the order/ disorder of a room analogically to the energy distribution. According to Haglund et al. (2010), one of the disadvantages of using disorder as a metaphor in entropy education is concentrating upon the solely mechanical structure and the spontaneous appearance of the microstate.

Many reports are claiming that what the students understand from entropy is mostly disorder (Selepe and Bradley, 1997; Sözbilir, 2007; Gustavsson et al., 2013; Haglund et al., 2015). For instance, in a detailed study on the knowledge of thermodynamic concepts of engineering students taking the chemical thermodynamic course, the students were given thermodynamic concepts of disorder, degree of freedom, heat, motion, enthalpy, Gibbs free energy, the second law of thermodynamics, spreading and microstates and they were asked to put them in an order according to their relation with entropy and comment on how scientific and applicable they are (Haglund et al., 2016). The data were evaluated according to Spearman's rho scale (Table 1). The data were evaluated according to Spearman's rho scale (Table 1). The low numerical values correspond to a high correlation with entropy.

Table 1: *Averages across the student pairs' rankings of how strongly concepts are related to entropy; how scientific they are; and how useful they are for explaining what entropy is?*

	Strongly Related to Entropy		Scientific		Useful for Explaining Entropy	
Student pairs' rankings of how	disorder	freedom	Gibbs free energy	enthalpy	disorder	freedom
	2.17	2.17	1.67	2.00	1.50	4.50
	enthalpy	Gibbs free energy	disorder	freedom	Gibbs free energy	enthalpy
	6.67	6.33	7.67	7.33	6.17	6.17

When the resulting data are investigated, one immediately realizes a striking result. The students ranked Gibbs free energy, and enthalpy concepts are the most scientific ones among the thermodynamic concept. However, they ranked these concepts as the least related ones to entropy and the least applicable ones. Also, there were similar results reported using the second law of thermodynamics (5.67, 2.33, 5.83). Although it is not scientifically accepted, the choice of the students for the most widely accepted and useful concept was by the far disorder. This is a moral wrecking outcome.

In light of all these data, we can make the following conclusions :

- Both the students and teacher are widely using disorder concept to teach the entropy
- Although the students use the concepts Gibbs free energy and enthalpy, which are very useful in macroscopic explanation entropy, in the solution of the qualitative problems, they were incapable of an in-depth evaluation of their relations with entropy.
- Students have a significant problem in the integration of microscopic and macroscopic explanation of entropy, and they were nearly oblivious about their macroscopic meaning.

Since entropy is directly or indirectly bound to the spontaneous processes and second law of thermodynamics, Haglund et al. (2015) stated that he agrees with Wei et al., 2014, who said that "association entropy with the disorder will alienate the student from the education targets which were based upon second law of thermodynamics."

Therefore, disorder relieved the entropy concept from the burden it has been carrying for so many years. This gap caused the scientist to stay away from one of the essential laws of the universe. In this context, many of the publishing houses declared that they were going to remove the disorder concept used in the explanation of entropy from the textbooks starting from 2013 and will only include energy concepts (Lambert, 2014). However, some people claimed that it would be unlucky to remove this concept since it would be a useable metaphor for the new-comers (Haglund et al., 2015; Haglund, 2017). It is not possible to agree with this point of view; although this topic is taught with new approaches higher education levels, it was reported that the students mainly stick to the disorder concept (Haglund et al., 2015).

3.5. The Approaches Used in Teaching the Concept of Entropy

Thermodynamic concepts and especially entropy, are fascinating subjects to study in natural sciences (Johnstone, MacDonald and Webb, 1977). However, it is high time we devised an approach to disprove the biased view that the entropy concept will never be fully understood. This view stems from the prejudice of the people that thermodynamics is one of the most challenging courses in science education (Ishida and Chuang, 1997). It was reported the thermodynamic concept in which students waged the hardest struggle is entropy, and it would be wise to give it a priority in future studies (Sözbilir (2001). In addition, there are approaches and metaphors mentioned alternative to the disorder concept in the explanation of the entropy concept. Among these macroscopic (thermodynamic)and statistical (microscopic) approaches the ones which reflect the meaning of entropy in the most realistic way is briefly mentioned

3.5.1. Macroscopic (Thermodynamic) Approaches

The macroscopic approach is mainly built upon the Clausius's views about entropy, and its main interest is the amount of change in total energy. If the first law preserves the total energy, it is not crucial that the total energy is taken as heat, work, or internal energy format. Although the total energy is preserved, maximum useable work shows a decrease according to II. Law and work is much more flexible than other thermodynamic concepts. The decrease in energy is particularly useful to introduce the irreversibility concept to explain the natural processes (Pinto, Couso and Gutierrez, 2005).

The students were interviewed to determine their approach to heat, temperature, energy concepts (Kesidou and Duit, 1993). The workers reported that the students have difficulty distinguishing heat and temperature. The workers claimed that after the introduction of new thermodynamic topics into curricula, an approach centered by the II. law based heat, temperature, and energy concepts must be adapted.

In a series of experiments in a Ph.D. study in the department of physics education investigating the cyclic process of heat engines, the students were observed to have difficulty in the application of the second law of thermodynamics. The problem was found to stem from the lack of knowledge of students in basic thermodynamic concepts such as heat and temperature. The authors also have strongly suggested that before the introduction of the microscopic quantities of thermodynamics, they must be equipped with firm knowledge on the macroscopic properties of the system (Cochran, 2005). In a similar study, Loverude (2002) suggested a familiar and straightforward macroscopic model of the heat generated when using a bicycle pump. He realized that students have difficulties in microscopic approaches as well—starting from the 19th century the entropy education has been given jointly with the macroscopic approach linked with the microscopic approach to explaining the heat transfer process (Baierlein, 1994).

In thermal physics, there was an entirely different macroscopic explanation of entropy where it was represented as heat form (Fuchs, 1987; Herman, 2000; Quoted by Haglund et al., 2015; Goggoli 2010). However, Strnad (2000) claimed that this approach might cause problems for the students as they will meet different thermodynamic evaluation of heat as the course is advanced. Similarly, Barrow (1988) advocated that heat and work were not system properties, and entropy could be linked to only to energy, according to the second law of without involving heat and work concepts.

Another thermodynamic concept used in the macroscopic explanation of entropy is Gibbs free energy. There are so many studies showings that the students are having difficulties linking entropy with other macroscopic concepts (Thomas and Schwenz, 1998; Haglund et al., 2015; Haglund et al., 2016). In a study carried out in the life sciences department, it was reported that Gibbs free energy is much easier to understand and acceptable than entropy. Therefore defining the relation between entropy and Gibbs free energy would be a highly appropriate starting point (Geller et al., 2014).

Although the statistical and thermodynamic variations of entropy seem to be measuring different properties, they would not be separated from each other since the unit of Boltzmann constant (k_b) in statistical mechanics is (J/K), which shows that entropy is clearly linked with both heat and temperature (Haglund, 2010). Similarly, starting from the Joule/Kelvin unit, thermodynamic entropy shows the unused or unconverted energy into work within a certain temperature range (Popoviç, 2017). However, the thermodynamic entropy, which was personally disclosed by Clausius himself, has unfortunately not received any attention for 150 years and left to be forgotten (Popoviç, 2017).

3.5.2. Microscopic (Statistical) Approaches

The microscopic approach is generally concentrated upon a structure that is made of atoms, molecules, or particles. There are many known microscopic approaches, such as energy or distribution of particles, the number of microstates, and degrees of freedom instead of disorder. There are many microscopic approaches, such as the distribution of energy or particles, the number of microstates, and degrees of freedom instead of disorder. Also, the microscopic viewpoint is a predominating approach among the students coming from chemical disciplines (Christensen and Rump, 2008). Haglund et al. (2015) also obtained similar results in a similar study.

The energy distribution of the second law of thermodynamic (energy spreading or dispersal) can be described as "if there are no barriers, all the energy types tend to enlarge larger area than the localized situation." This process is generally measured as the increase in entropy (Lambert, 2006). In literature, strong arguments are going on about the use of "*energy dispersal* or *spreading*. Leff (1996, p:1261) proposed the use of "energy spreading" in place of "disorder" and described entropy as the measure of the unusable part of energy. In this regard, Wei et al. (2014) proposed the removal of the "*disorder*" term from the textbooks and used the *energy spreading* concept instead. He also claimed that since the letter S in "spreading" reminds one of the entropy, it could be used as its abbreviation. However, Philips (2016) said that business of insinuating entropy over the metaphor of spreading had gone too far because it determines the process as an action rather than a noun. Similarly, Jeppsson (2011) warned the scientific audience that the "energy spreading" metaphor is not free of problems because students may think energy dispersal as heat dispersal. He rationalized his idea by claiming both metaphors (heating and spreading) are in gerund form against the possibility of students thinking these two metaphors as the two parallel variables of the same approach. Therefore, Lambert (2006), suggested the use "dispersal," which has a much definite meaning in molecular thermodynamics in place of "spreading," a term which symbolizes the three-dimensional distribution in macro-thermodynamics. Philips (2016) stated that it would be more appropriate to use both these concepts together in the description of entropy.

On the other hand, Haglund (2010) claimed that decreasing entropy down to one single and definite description would be wrong because it would constitute a big problem of the beginners coming from different disciplines. He also claimed that this sort of description is suitable for only specific scientific groups. He said that it would be much simpler and acceptable to use the spreading of particle concept, which reminds us of the regulation of the components of the system rather than their dispersal (Haglund et al., 2015).

Another concept based upon the statistical approach of entropy is the microstates. Although many articles are suggesting that the use microstates in place of disorder in the literature (Reif, 1999; Kozliak, 2004; Lambert, 1999, 2002a, 2002b; Sözbilir, 2005), Haglund(2010) claimed that by using Gibbs' statistical approach one can obtain a more general expression applicable to a much wider range of systems by the use of Boltzmann entropy formula (2010).

Another concept suggested in the statistical explanation of entropy is the "degrees of freedom" (Styer, 2000; Brissaud, 2005; Amin, 2012). Styer (2000), who makes this suggestion in his study, states that although this concept is as vague as a disorder, the distribution of microstates leaves a positive feeling upon the person. Also, the students were observed to make more comprehensive microscopic and molecular interaction evaluations regarding the pre-course period. Some of the students described entropy as an action of the freely moving particles (Styer, 2000; Brissaud, 2005). In a study related to the degree of freedom, the students attributed entropy to the amount of action before the course. However, as the course ended, there was a vast variation in their ideas of entropy, and most of them linked it to the freedom of movement of the particles (Haglund et al., 2015). However, freedom of movement concept is not enough to describe entropy because students may easily relate the freedom concept is-conceptionally to disorder concept

4. Findings and Discussion

4.1. An Alternative Study Approach in Teaching and Definition of the Concept of Entropy

There is a relatively big controversy going on about the entropy concept, and this eventually is affected by the education field by aggravating the current problems. That is why a new educational approach in teaching the concept of entropy has been developed and an alternative description established by merging the appropriate macroscopic and microscopic approaches with each other. In this connection, first, an integrated education approach and entropy description have been developed. Below is the investigation of these integrated approaches used in the education of the entropy concept.

4.1.1. Tripod Approach

Although there are microscopic metaphors such as distribution index, microstates, degrees of freedom as an alternative of the entropy concept, these approaches neglect the macroscopic nature of entropy (the change of the type of energy). Unfortunately, it is not easy to understand the microscopic nature of entropy using a macroscopic structure, which corresponds to the statistical average of microstates. If we summarize the use of a microscopic (statistical) or macroscopic (thermodynamic) approach alone, it carries a critical risk for the students to misunderstand the entropy concept (Baierlein, 1994). Therefore, it is essential to have a solid perception of the macroscopic features of entropy before dealing with its microscopic properties (Loverude, 2002; Cochran, 2005). In this context, we carried out a group study related to the entropy concept with 11^{th}-grade students (Akbulut, unpublished Ph.D. thesis, 2020). In this study, the students were first briefed upon macroscopic explanation of entropy, and then they were asked to calculate the entropy change of the phase changes from the solid phase to the gaseous state. Most of the results were still based upon the disorder metaphor. However, when 50% of the phase change from solid to gaseous state takes place with energy exchange, and the unconverted energy appears as an increase in entropy (Akbulut, Unpublished Ph.D. thesis, 2020). Although some studies (Haglund, 2017) suggest starting the thermodynamic concepts at the secondary level with entropy and disorder, it is clear that this sort of approach will hinder the perception of the entropy concept. Because the students will only concentrate on disorder and neglect other related concepts, on the other hand, to start the education of the entropy, adapting a macroscopic approach will pave the way for the microscopic explanation of entropy and minimize the occurrence of misconceptions.

In order to overcome the problems and turmoil regarding how to teach thermodynamics and statistical approaches, a new educational approach is called the "*Tripod Approach*" based upon the macroscopic (thermodynamic) approach of Clasius and Kelvin, and the statistical or microscopic approach of Gibbs has been developed.

In Figure 2, the essential elements of the "*Tripod Approach*" have been illustrated. As seen from Figure 2, the first pot of the tripod represents the main concepts of energy and entropy, the second pod corresponds to the macroscopic (thermodynamic) approaches and unavailability, and the third pod illustrates microscopic (statistical) approaches and probability.

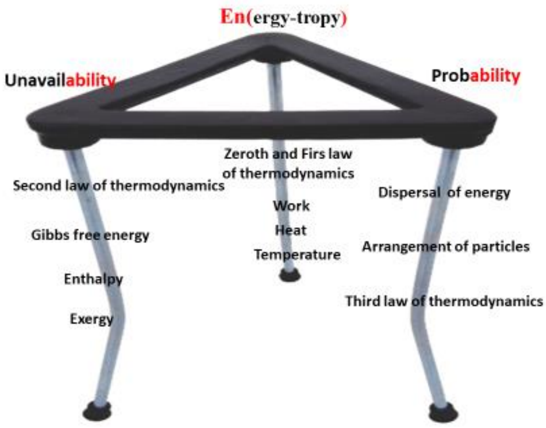

Figure 2: *Tripod Approach*

4.1.1.1. The First Pod: Energy/Entropy "En(ergy-tropy")

The major component of the "*Tripod Approach*" is entropy, which is based upon the conservation of energy. Because the physical means of entropy and energy concepts are so close to each other, it was purposely called entropy by Clausius. That is why the first leg of the tripod was constituted by "en(ergy-tropy)" (energy–entropy) concepts. Since preservation and devaluation of the energy and the complicated relations between heat, temperature, and energy cause great confusion, an in-depth examination of these concepts is of utmost importance. Two of the thermodynamic variables are heat and work that witnessed the birth of entropy defined with the zeroth and first laws of thermodynamics. Clasius contemplated on the fact that *why couldn't the whole energy be converted into useful work*. As seen from the mathematical expression of $dU= \delta Q+\delta W$ the first law of thermodynamics, the internal energy is also given by these two concepts. That is why the first leg of the tripod approach was defined as Energy-Entropy "En(ergy-tropy)."

4.1.1.2. The Second Pod: Unavailability

One of the concepts located on the unavailability pod of the tripod approach is enthalpy. As seen from the Clausius non-quality ($dS \geq dQ/dT$) the macroscopic changes in entropy are associated with the change of the enthalpy of the system and the temperature of the medium (Thomas and Schwenz, 1998; Haglund and Jeppsson, 2014; Loverude, 2015). Also in the unavailability leg of the "*Tripod Approach*", there are the macroscopic (thermodynamic) concepts such as the second law of thermodynamics, which is used in the calculations of the change of energy due to the interaction of the system with its environment, Gibbs free energy, enthalpy, and exergy. Since the students found Gibbs free energy much more accessible, it is much better to start entropy education, revealing its relationship with Gibbs free energy (Geller et al., 2014). However, the change of Gibbs free energy should be introduced after the clarification of the entropic relations with other macroscopic properties because Gibbs free energy is a concept related to entropy, heat, work, temperature, and exergy concepts. According to Haglund(2016) Gibbs free energy is an easy way to define entropy where the enthalpic and entropy parts between the system and the medium are given in an integrated format. One other concept related to the entropy in the framework of unavailability is the exergy. According to Dincer and Cengel (2001), the change of the type of energy can only be understood by the exergy concept covering entropy and first and second laws of thermodynamics. It is believed that using an exergy concept would make the second law and entropy much more understandable (Jones and Dugan, 2003).

4.1.1.3. The Third Pod: Probability

The probability related third pod of the "*Tripod Approach*" is based upon the microscopic statistical approach in the framework of the probability of the Gibbs free energy and included the possible arrangement of the particles such as atoms and molecules, dispersal of energy, the third law of thermodynamics.

The starting point of the microscopic explanation of entropy for the newly acquainted people would be the arrangement of the particles and continue with the soft transition to the energy dispersal metaphor since some of the students have hard times to understand and evaluate this abstract molecular approach. In some studies which support this thesis that the degree of understanding of a concept is not related to how it is told but how the students evaluate it. In a study related to entropy with the students from various departments, chemistry students are much more successful in the molecular point of view, while the students coming from the physics department are much better in the macroscopic approach (Christensen and Rump, 2008; Haglund et al., 2015).

During the application stage of the tripod approach, based upon both the macroscopic (thermodynamic) and microscopic (statistical) analysis of entropy in the light of all the data obtained, it will be beneficial to take the following criteria into account:

The pre-knowledge of the students about thermodynamic concepts such as heat, energy, work, and temperature must be resurfaced in order to correct all misconceptions. Cotignola et al. (2002) and Erickson and Tiberghien (1985) reported that the students have intuitive ideas about heat and temperature, and most of the students could not distinguish heat, work, and internal energy. They also could not figure out why such a distinction should be made (Meltzer, 2004).

The perception of the energy concepts is a critical stage, and the students should adopt an approach either at the molecular stage or in mechanical energy format ($\Delta E_{system}=\Delta U+\Delta KE+\Delta PE$).

In a Ph.D. study concerning the difficulties encountered in the education of the thermodynamic laws (Pinto Casulleras, 1991), the students' incapacity to realize the similarities and differences between heat, temperature, and energy concepts were attributed to the fact that these concepts were not previously subjected to an in-depth analysis.

The education of the entropy concept must be started giving the quantitative macroscopic approaches top priority. In a Ph.D. thesis research (Cochran, 2005), it was reported that the students have problems understanding the basic thermodynamic concepts. That is why it is recommended that the education of the thermodynamic concepts must be started from the macroscopic approach first (Baierlein, 1994; Loverude, 2002).

The students must perceive the relationships between entropy and other thermodynamic concepts using techniques such as mind maps (Figure 3).

4.1.1.4. The Mind Map of Entropy and Related Thermodynamic Concepts

We must remember that in the evaluation of the concepts, the students encounter in a science course is closely related to their perception of the terms indicating them (Haglund et al., 2016). Only under these conditions will the entropy concept mean something depending on the number of correct relationships with other thermodynamic concepts. On the other hand, it is a known fact that what the students mainly understand from the entropy concept is disorder. That is why there was a mind map established to improve their understanding of the entropy concept. (Figure 3).

As seen from Figure 3, the mind map developed is an integral part of the Tripod Approach and facilitates to establish much more meaningful relations between the thermodynamic concepts. Therefore, the education of these concepts is to be carried out in three distinct stages as follows:

1. **Stage:** Teaching the energy-based concepts related to the zeroth and first laws of thermodynamics.
2. **Stage:** Teaching the macroscopic concepts related to the change in the type of energy**.**
3. **Stage:** Teaching the probability-based microscopic approaches.

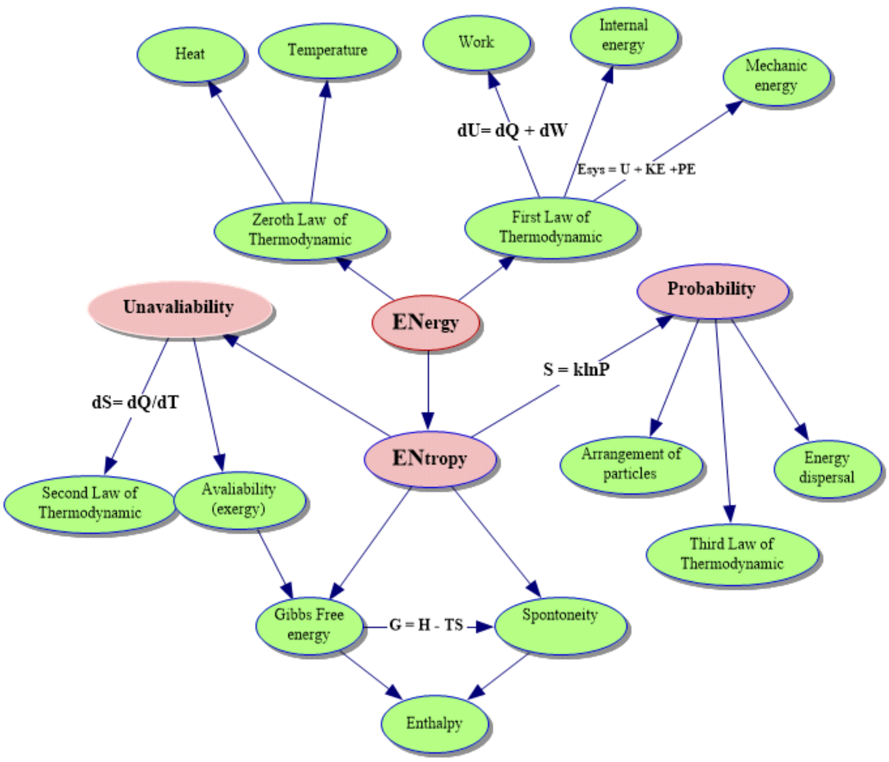

Figure: 3 *The mind map of entropy and related thermodynamic concepts*

We must mention that the tripod approach is the result of the need for macroscopic and microscopic focused integrated approaches for the explanation of the entropy concept.

4.2. An Alternative Definition to Entropy

The most significant difficulty in teaching entropy is the how-to integrate the macroscopic (thermodynamic) and microscopic (statistical) approaches to each other

Some opinions in the related literature are as follows:

- It is complicated for students to see how macroscopic quantities such as heat, temperature, enthalpy, or Gibbs free energy related to microstates and probability (Haglund et al., 2015, Haglund et al., 2016).
- It is quite difficult for students to see how much various aspects of entropy are related to a single physical quantity (Kozliak, 2004).
- Students need both basic microscopic understanding and the ability to solve phenomena-related problems on a macroscopic level, and the main difficulty lies in combining the two levels (Baierlein, 1994).

So far, there is no study to overcome this difficulty in the literature. Apart from that, leaving the macroscopic description of entropy, which goes back to Clausius and lack of relations between these two approaches of entropy, resulted in a dramatic increase of the studies based on microscopic explanations, which were thought to reflect the entropy in a much better way. However, this situation bears important risks for the understanding of the entropy concept (Baierlein, 1994; Haglund et al., 2010). For instance, in a study, it was reported that students were not capable of establishing any relation between entropy and macroscopic concept or problem-solving capacities and conceptional skills. Again, in the same study, the students predominantly related the entropy concept with the disorder concept. The least related thermodynamic concept was Gibbs free energy, followed by the second law of thermodynamic and enthalpy concepts (Haglund et al., 2016).

Leff (2012) claimed that entropy is an energy-related concept as seen in both Clausius algorithm ($dS=dQ_{rev}/T$) and Boltzman ($S=klnW$) formula and therefore, as was the case for disorder metaphor, the energy-independent descriptions would be an oversimplification of the entropy concept. In a similar approach, the heat and work are not the property of the system, and entropy and the second law of thermodynamics would be derived solely on an energy-dependent concept without touching heat and temperature (Barrow 1988).

The macroscopic state of a process is the statistical average of microscopic states. For instance, the macro variables of pressure and temperature are statistical average values. The relations between the microscopic structure and thermodynamic data are investigated under a new discipline called "Statistical Thermodynamics." Since it is not possible to observe the movement of the individual atoms, the values we use are practical average values (Çetinkaya, 1986). If we look at the same picture, the total entropy is made of two types of entropy, namely, thermal entropy measure of unusable energy and residual entropy due to the orientation of the molecules. Although both the residual and thermal entropy measures the uncertainty, they are different due to the type of uncertainty they measure. Residual entropy measures the uncertainty of the molecular arrangements, while the thermal entropy is related to the uncertainty of the energy and momentum of the particles (Popoviç, 2017). That is why if the statistical concepts are linked with the microscopic information of the atoms and molecules, it is possible to make statistical entropy or probability estimations about the microscopic world (Çetinkaya, 1986).

In conclusion, the fundamental mistake, which caused entangled problem ball of entropy rolling down to our time, was the insertion of the button to the wrong hole at the start, just as case of "disorder." In this context, we will have made peace with the entropy concept, which has terrorized the scientific world for more than a century.

Based on the data obtained from this study, since all the processes take place in the universe with uncertainty in the energy dispersal and the type of energy, we can easily say that the metaphor which links the macroscopic (thermodynamic) and microscopic (statistical) nature of the entropy concept is "probability." That is why the entropy concept should be analyzed with an integrated approach by the use of probability and energy metaphors, which formed the essential components of the new description of energy.

In this context, entropy was described as **a "probable measure of unavailable energy or energy dispersal."** The differences between the newly proposed and current description of energy can be listed as follows:

- The entropy descriptions in the literature were predominantly based upon the microscopic approach, which is believed to reflect the content of the concept much better than the macroscopic approach, so the macroscopic part of it is usually ignored. However, in our alternative description, both approaches have been given adequate attention.

- Lambert (2006) stated that there are two critical concepts, namely energy, and probability, which is be stated in entropy changes. It is seen that while the concepts such as disorder, freedom, information theory are based upon the probability factor only, the alternative description contains both metaphors.

- The current descriptions explaining the entropy in energy and probability concepts are established according to the microscopic approach. Although microscopic and macroscopic approaches are a different component of the same root, the significant difficulty here is how to integrate them. The current descriptions are based upon the microscopic approach, and energy and probability concepts. In the alternative description, entropy is assumed to be dependent upon both macroscopic and microscopic approaches of the energy and probability concepts.

5. Conclusion

Scientists have brought so many explanations for the thermodynamic concepts, especially for the entropy concept. However, some of the approaches in the description of entropy caused the student to be puzzled. That is why the thermodynamic concepts, especially the entropy, were found to be complicated by most of the students. Although many press houses decided to remove the disorder concept from the new printed textbooks from 2013, some of the studies (Haglund et al., 2015) reported that the disorder is still the most popular concept. In the explanation of entropy, a highly abstract and mysterious concept, there were various metaphors developed in place of disorder (Leff, 1996; Styer, 2000; Lambert et.at, 2011). However, in most of these approaches, the macroscopic nature of entropy has been neglected. Because of this, there were so many problems encountered in the education stage of the entropy concept. In the face of the problems that occurred in entropy education, an entirely new education approach has been developed known as the "Tripod Approach."

The target of this "Tripod Approach" (Figure:2) is establishing an integrated outlook on the entropy concept. It is based upon both the thermodynamic (macroscopic) approach developed Clausius, Kelvin, and the probability (statistical) approach of Gibbs. Also, entropy and related concepts were illustrated on a mind map to determine the criteria of the education concepts to ameliorate the adverse opinion about it. Especially in-depth investigation of the energy concept, which plays a crucial role in the microscopic and macroscopic features of entropy, should be carried out.

On the other hand, since the description of the entropy was usually made on microscopic focused approaches, the macroscopic nature of entropy was neglected, and as a result, entropy was fixed in our brain as a complicated and vague concept. It was first realized by Bairlein (1994) and reported this problem prevailing in the scientific word. However, there were no studies to obviate or overcome this difficulty in the literature. Finally, with an undeniable contribution of the "Tripod Approach" system, integrated energy and probability-based description of entropy was developed. According to this study, entropy is described as **"Entropy is the probability measure of unavailable energy or energy dispersal."**

As a result of this study, we expect investigating the entropy concept in a much detailed manner, and the development of alternative education approaches will put an end to the turmoil existing in that area.

6. Conflict of Interest

The authors declare that there is no conflict of interest.

7. Ethics Committee Approval

The authors confirm that the study does not need ethics committee approval according to the research integrity rules in their country.

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