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Research Article

Students' conceptual Difficulties in Thermodynamic

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Abstract
The learning difficulties for physical chemistry students from a multi-national, regional, tertiary education institution in Ethiopia where investigated using open-ended of questionnaires of diagnostic instrument contained 17 items followed up semi- structured interview distributed across basic chemical thermodynamics concepts. The research finding suggests that chemical thermodynamics is a topic fraught with conceptual difficulties and alternative conceptions based on the result from the study most physical chemistry students in our sample lack rudimentary understanding of thermodynamic concepts, there is no recognition of the fact that change in G of the system is directly related to change in S of the universe, there is uncertainty as to whether a spontaneous process requires entropy of the system or the entropy of the universe to increase, there is in certainty as to whether $\Delta G < 0$ implies that entropy of the system or entropy of the universe will increase. Based on the result of this diagnostic test instrument and structured interview based on the results, an alternative approach in which content – driven extra tutorials, are suggested for remediation that can partially tackle the source of learning difficulties in chemical thermodynamics

Keywords: thermodynamics concepts, learning difficulties, diagnostic test, entropy, enthalpy

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Introduction

Many students from secondary schools to universities in many countries, struggle to learn chemistry and many do not succeed (Reid, 2008). Research has now shown that many students do not correctly understand fundamental chemistry concepts and also many of the scientifically incorrect concepts held by the students go unchanged from the early years of the schooling to university and sometimes beyond (Sozbili, Pyanarbaby, and Nurtac (2010)). By not fully and appropriately understanding fundamental concepts, many students have trouble understanding the more advanced concepts that build upon these fundamental concepts (Thomas, 1997).

In Ethiopia studies have shown that a significant basic chemical concepts and reaction misconceptions were found by both teachers and students in primary and secondary schools (Abayneh, 2013, 2012; Sileshi, 2011; Temechegn, 2002, Temechegn and Sileshi, 2005). However, little or no work has been done in the country on thermodynamics.

Many high school and university students experience difficulties with fundamental thermodynamic concepts in chemistry (Carson and Watson, 2002). Despite the importance of thermodynamics in the foundation of chemistry, most students emerge from introductory courses with very limited understanding of the subject (Ochs, 1996). The physical chemistry course, where students tackle more advanced concepts of thermodynamics and kinetics, is perceived by many students to be one of the most difficult courses (Thomas, 1997). It has been suggested that many of the conceptual difficulties in thermodynamics could have an historical basis.

Physical chemistry comprises of three broad areas. The distinction between these areas has been explained by Atkins (1997) as quoted below

> *Physical Chemistry establishes and develops the principles that are used to explain and interpret the observations made in the other branches of chemistry. Physical chemistry is characterized by three main approaches; the discussion of bulk properties in terms of thermodynamics, the use of spectroscopy to explore the behavior of individual atoms and molecules, and the analysis of the rate and mechanisms of chemical change (Atkins 1997).*

In this definition, Atkins identifies three main divisions, which are 'equilibrium' 'structure', and 'change'. Equilibrium is mainly limited by chemical thermodynamics, structure is enclosed in quantum mechanics and spectroscopy, and change is the main domain of chemical reaction.

Thermodynamics is fundamental to physical science and the concept of energy and the distinction between intensive and extensive properties contribute to many domains in physical science (Linn and Songer 1991). Thermodynamics is the key to chemistry, physics and all natural sciences. Therefore, if we grasp its essence then we will be able to understand the concepts and principles and apply them in our daily lives, for example; conservation of energy in our houses, maintenance of body temperature, cooking with microwave etc., and we also can realize human behavior in terms of being free and rich (Nordholm 1997). Thermodynamics is a fundamental subject in the university level courses especially in engineering also in chemistry and physics. Thus, it is important to probe students' understanding capabilities in physical chemistry and their problems with grasping and applying the principles of thermodynamics to their everyday lives in terms of the development of industry and standards of human life. Perhaps the most important point is that the students who are the subject of this study will be chemistry teachers when they graduate. Their understanding of the fundamental thermodynamic ideas is crucial in terms of educating tomorrow's generations.

Chemistry had been regarded as a difficult subject for students by many researchers, teachers and science educators (Carter and Brickhouse 1989, Nakhleh 1992 and Anderson et al 1999) because of the abstract nature of many chemical concepts, teaching styles applied in class, lack of teaching aids and the difficulty of the language of chemistry. All these cause students, from primary level to the university, to develop poor understanding and misunderstandings. Misunderstanding of concepts in chemistry has attracted attention over the last three decades (Skelly 1993, Ayas and Demirba 1997). A number of studies have been conducted on different topics in chemistry (Griffiths 1994, Garnett et al 1995), and in other areas such as biology, physics, or in general, in science (Drive 1981, Gilbert and Watts 1983, Duit 1987, Gil-Perez and Carrascosa 1990).
Thermodynamics was chosen for this study for two reasons. Experience of teachers and the literature have shown that thermodynamics is a difficult topic for students to understand. When students are asked to solve numerical problems they have the option of solving the problem by using some algebraic methods, however, most of them are unaware of the understanding behind the problems.

The above study is similar to the findings of the study by Taber (20002), An examination of studies on students' learning of basic physical and chemical concepts clearly demonstrates that most of the basic concepts were poorly learned (Sozbilir and Bennette 2007). Students' learning of fundamental concepts associated with chemical thermodynamics has not yet been the subject of educational research, especially at a more advanced level beyond the general chemistry (Thomas 1997). Relatively little research has been conducted at the tertiary level on students' understandings of entropy and Gibbs energy (Carson and Watson 2002). More research needs to be done to identify what sort of difficulties students face in the learning of physical and chemical concepts. Learning difficulties are important for both teaching and learning. Both science educators and cognitive researchers agree that efforts to understand and improve science education should be focused on fundamentally important knowledge domains (Ellis 1994). Hence, it has been concluded that it is worthwhile to conduct a research study about chemistry undergraduates' learning difficulties of fundamental thermodynamic concepts, which are a part of the physical chemistry course and the factor which may give rise to these learning difficulties.

Purpose of the Study

The purpose of this study was to identify and classify the chemistry undergraduate learning difficulties of thermodynamics concepts in physical chemistry and to determine the reason why students find these topics/concepts difficult. Finally a possible way to tackle these difficulties with an alternative approach, illustrated by the introductory physical chemistry courses in which structure, properties and energy are presented as there interconnected learning progression was described for understanding of concepts in thermodynamics for students studying chemistry in Ethiopia universities.

In the context of the forgoing the following research objectives were sequentially investigated:

a. Identify and classify the learning difficulties in thermodynamics principles experienced by chemistry undergraduate students in physical chemistry
b. Determine of the reasons why students find the thermodynamics principles identified in phase one of this investigation difficult to learn
c. Development of new alternative approach to tackle difficulties in learning chemical thermodynamics.

Research Question

The specific question that guides this study is: What makes physical chemistry difficult in selected universities in Ethiopia, and what are the factors that make these difficulties? In addressing this question, it is important that the thesis considers the following sub questions:

1. What are the learning difficulties on key chemical thermodynamics principles in physical chemistry second year Ethiopian chemistry undergraduate students?
2. Where do these learning difficulties arise? What are their sources?
3. What sorts of approaches are effective to remove learning difficulties in teaching and learning chemical thermodynamics in the classroom?

Research Methodology

The Data Collection

In this section, the sample will be described along with how the questionnaire was administered and how the interviews were conducted. The data collection was done in two phases. The first set of data was collected in October 2010, just after the beginning of the first semester in order to determine the students' knowledge of the selected concepts before the teaching started. This was important for this study, because what students knew affects the learning process for new concepts. It was thought that conducting a pre-test may help to identify students' understandings and learning difficulty of the selected concepts. The second set of data was collected in May 2011, just before the end of second semester.

The sample

In order to enhance the scope of the study, students from two different Chemistry Departments in East Ethiopia were chosen. Both of the participating departments are situated in eastern Ethiopia the first one was established before 50 years and the second one with in last six years. The physical difficulties in travelling inside Ethiopia and limited time available to collect data were also important factors which affected the decision in choosing the sample.

The departments which took part in the research were coded with the capital letter of the city where they were situated. Therefore one of them is coded as '*Department DDU*' and the other coded as '*Department HU*'. In both departments the academic year is composed of two 16 week semesters. The students in both departments are training to become chemistry teachers at high schools in Ethiopia and Chemist in different Sector.

The physical chemistry course is introduced in the second year of the undergraduate course in both institutions and the course content is also similar. The sample was the Second year chemistry student following the Physical Chemistry Course-I which was introduced in the first semester, the number of students who took part in the research study is given in **Table 1**.

Table 1 The number of the students completed the questionnaires

Department Students	DDU	HU	Total
The number of the students who completed the OT_1	25	21	46
The number of the students who completed the OT_2	25	20	45
The number of the students who completed the ST_1	25	22	47
The number of the students who completed the ST_2	23	21	44

In Table 1; OT_1, OT_2, ST_1 and ST_2 refer to Pre-test-I, Pre-test-II, Post-test-I and Post-test-II respectively.

The administration of the questionnaires

The administration of the questionnaires was done in two stages. In the first stage, the questionnaires were administered in October 2010 as a pre-test. Although all the students on the physical chemistry course were asked to take part in the research, a few appeared not to do so voluntarily and they were eliminated from the study. Before administering the questionnaire, the questions in each set were put into different orders to ensure that every question got a similar number of responses.

Also, different sets of the questions were printed onto different colored paper to make them more easily distinguishable. The two sets of questions were also mixed together to ensure that they were answered by equal number of students in both departments. Students were allowed to answer the questions in one lesson, which was 50 minutes long. Before students started to answer the questions the research project was introduced by the researcher and they were assured that their personal information and responses would be kept confidential. The Pre-Test-I was answered by 46 students and 45 students answered the Pre-Test-II. At the second stage 44 students answered the Post- Test-I and Post-Test-II was answered by 47 students. The students who were not in the class at the time the study was carried out were not asked to answer the questions later.

Following the Post-Test, in order to find out students' perspectives on learning difficulties in physical chemistry and their thoughts about the how to overcome these difficulties they were asked to work in small groups, to discuss the reasons why they found it hard to understand concepts in physical chemistry. They were asked to write them on the sheet provided. They also were asked to discuss and write down how the learning difficulties might be overcome. Informal interviews were also carried out in which some of the students raised concerns and some anecdotal evidence was recorded.

Shortly after the questionnaires were completed, a surface analysis of the results was done and possible interviewees were identified. The interview strategies are reported in the following section.

The interviews

A number of interviews were carried out just after the pre-test and the post-test to support the data obtained from the questionnaires. The interviews held after the pre-test sought to reveal the students' understanding of the four selected concepts and related concepts such as internal energy, enthalpy, entropy and Gibbs energy. The interviews after the post-test sought to explore the students' understandings of a particular concept in detail. In total, 47 selected students were interviewed. In addition two lecturers were also interviewed about the possible sources of the students' learning difficulties and possible solutions to these difficulties. This section discusses the purpose of the interviews, describes how interviewees were selected and explains the interview strategy employed.

Pre-interviews (interview about all concepts): Pre-interviews with 22 students were carried out in October 2010. The purpose of the pre-interviews was to explore students' knowledge about internal energy, enthalpy, entropy, Gibbs energy and related concepts such as potential energy, kinetic energy, heat, temperature, work and spontaneity at the beginning of the course. Therefore, they have been called *interviews about all concepts* for the purposes of the study. This is important because students bring learning difficulty with them into the classroom and previous knowledge plays an important role in learning new concepts. *'The constructivist learning theory proposes that students actively construct new meaning by using their present conceptual frameworks to interpret new information in ways that make sense to them*' (Garnett *et al* 1995). Therefore it is important to establish what knowledge students bring into the classroom.

Post-interviews (interview about concepts): Post-interviews were carried out with 25 students in May 2011 following the post- test. These interviews explore the students' understanding of the one particular concept in detail. As there were four concept chosen to be studied, internal energy, enthalpy, entropy and Gibbs energy, interviews were focused on students' understanding of these concepts. Among the 25 interviewees, six of them were interviewed about internal energy, seven about enthalpy and entropy respectively and finally five of them were interviewed about Gibbs energy. The interviews were based upon the facts determined in section 3.3.1 and the students' understandings of the particular concepts were questioned in detail.

Interviews with the lectures: Two lecturers who had taught the physical chemistry course in the participating universities were interviewed after the post-test in order to establish their views of learning difficulties in physical chemistry and their possible solutions. The interviews were unstructured and started with an introductory question:

> *'What do you think makes it hard for the students to understand chemical thermodynamics concepts in physical chemistry?'*

Subsequently they were asked about the issues raised by during the interviews. The interviews were carried out in the lecturers' offices and lasted about an hour. One of the lecturers agreed to have the interview tape recorded and notes were taken in the case of the other lecturer.

The interview strategy: The interviewees were selected on a voluntary basis including the consideration of their responses to the questionnaire. The respondents who did not answer the questionnaire at all were also eliminated because it was considered that they may not have enough knowledge of the concept/s being studied.

Once the interviewees were selected, appointments were made with individual students by the researcher. They were not told about the content of the interviews, but in general, they were aware that the interviews would be in the same vein as the questionnaire.

Interview took place on a one-to-one basis, usually in an office or in an empty laboratory and students' permission to tape-record the interview was sought in each case. Interview times varied between half an hour and 45 minutes. At the beginning of each interview, students were given a brief explanation of the aims of the interviews and they were put at their ease by adopting a relaxed approach. With a few exceptions, interviewees were willing to talk and did so freely; others needed encouragement and gentle prompting. As the interviews aimed to explore students' understandings of particular concept/s, students were encouraged to talk in a non-confrontational way. Interviews were semi-structured, and no prepared sets of questions were used.

The interviews provided a rich source of data. As well as supplementing the questionnaire data they also revealed several learning difficulties which had not emerged from the questionnaire data. Although the interviewees were asked not to reveal the content of the interviews to the following interview candidates, some of the interviewees appeared to come to the interviews prepared. This was not considered as a threat to the reliability and validity of the interview since students did not know which particular questions they were going to be asked about in their interviews.

Research Findings and Discussion

The purpose of this study was to identify and classify the chemistry undergraduate learning difficulties of thermodynamics concepts in physical chemistry and to determine the reason why students find these topics/concepts difficult. Finally a possible way to tackle these difficulties with an alternative approach, illustrated by the introductory physical chemistry courses in which structure, properties and energy are presented as there interconnected learning progression was described for understanding of concepts in thermodynamics for students studying chemistry in Ethiopia universities. The main findings of this research study will be discussed in relation to the aim of the study and the research questions proposed. The first research question which was 'what are the learning difficulties on key chemical thermodynamics principles in physical chemistry?' second year Ethiopian chemistry undergraduate students will be answered and a concise summary of the Learning difficulties which were identified will be given. Then the second research question, where do these learning difficulties arise? What are their sources? Will be answered and the possible sources of the students' difficulties in learning these concepts will be discussed. Finally, what sorts of approaches are effective to remove learning difficulties in teaching and learning chemical thermodynamics in the classroom? It will be discussed in the light of the literature.

Results of chemistry diagnostic test

Once the first data collection had been done, the responses needed to be analyzed. Every page of an individual's response was given a number to uniquely identify it and questionnaire pages were detached and the responses given to the same questions were put together. Then the responses were skimmed and possible coding schemes were considered. From this superficial analysis it emerged that there was a considerable number of responses which included both understandings and learning difficulty. This section summarizes the identified learning difficulties in order to answer the first research question.

Difficulties related to mathematical representations

- There is confusion regarding the fact that in the equation $\Delta G = \Delta H - T\Delta S$, all of the variables refer to properties of the system (and not the surroundings).
- Students seem unaware or unclear about the definition of ΔG (i.e., $\Delta G = G_{final} - G_{initial}$)
- There is great confusion introduced by the definition of standard free-energy change of a process: $\Delta G^{o} = \Sigma\, n\, \Delta G_{f}^{o}$ (products) $- \Sigma\, m\, \Delta G_{f}^{o}$ (reactants)

Lack of awareness of constraints and conditions

- There is little recognition that ΔH equals heat absorbed only for constant-pressure processes
- There appears to be no awareness that the requirement that $\Delta G < 0$ for a spontaneous process only holds for constant-pressure, constant-temperature processes.

Overall conceptual Gaps

- There is no recognition of the fact that change in G of the system is directly related to change in S of the universe (= system + surroundings)

- There is uncertainty as to whether a spontaneous process requires entropy of the system or entropy of the universe to increase.
- There is uncertainty as to whether $\Delta G < 0$ implies that entropy of the system or entropy of the universe will increase.
- In our sample, the majority of students held incorrect or confused conceptions regarding fundamental thermodynamic principles following their introductory courses in physical chemistry.
- The tenacity and prevalence of these conceptual difficulties suggest that instruction must focus sharply upon them to bring about significant improvements in learning.
- Most students in our sample lack rudimentary understanding of thermodynamic concepts.
- Most students in our sample either (1) misunderstand process – dependent nature of work and/or heat, or (2) do not grasp process – independent nature of ΔE (=Q-W), or both (1) and (2).

Common Basic Learning difficulties analyzed from diagnostic test

- No clear concept of state or state function
- No clear idea of what is meant by net change
- Difficulty interpreting standard diagrammatic representations
- Association of enthalpy with heat even when pressure is not constant
- Do not recognize that work done by the system is equal to P ΔV
- Do not recognize that work done on the system is negative if P $\Delta V > 0$
- Are unable to make use of the relation between Q,W, and ΔE (i.e., First law of thermodynamics)
- Believe that $W \propto \Delta E$ regardless of ΔV
- Believe that $Q \propto \Delta E$ regardless of ΔV

Believe that $Q \propto \Delta V$ regardless of ΔE

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Student Interviews

- Twenty five student volunteers were interviewed within three days.
- The average course grade of the eight students was about the class –average grade.
- Interviews lasted 40-60 minutes, and were videotaped.
- Each interview centered on students “talking through” a six – part problem sheet.
- Responses of the eight students were generally quite consistent with each other’s

Students’ guiding conceptions
(What they “know”)

- ΔH is equal to the heat absorbed by the system.
- “Entropy” is synonymous with “disorder”
- Spontaneous processes are characterized by increasing entropy
- $\Delta G = \Delta H - T\Delta S$
- ΔG must be negative for a spontaneous process.

Difficulties interpreting Meaning of “ΔG”

- Students often do not interpret “$\Delta G < 0$” as meaning “G is decreasing” (nor $\Delta G > 0$” as “G is increasing”)
- The expression “ΔG” is frequently confused with “G”

- "$\Delta G < 0$" is interpreted as "G is negative," therefore conclusion is that "G must be negative for a spontaneous process"
- Frequently employ expression "ΔG [or ΔS] is becoming more negative" (or "more positive")

Examples from interviews

Q: Tell again the relationship between G and "spontaneous'?
Student #21: I guess I don't know, necessarily, about G; I know ^G.
Q: Tell me what you remember about ^G.
Student #21: I remember calculating it, and then if it was negative then it was spontaneous, if it was positive, being no spontaneous.
Q: what does that tell you about G itself? Suppose ^G is negative, what would be happening to G itself?
Student #17: I don't know because I don't remember the relationship.
Student Conception: If the process is spontaneous, G must be negative.
Student #11: If it's spontaneous, G would b negative … But if it wasn't going to happen spontaneously, G would be positive. At equilibrium, G would be zero … if G doesn't become negative, then it's not spontaneous. As long as it stays in positive values, it can decrease, but (still be spontaneous).
Student #1: Say that the Gibbs free energy for the system before this process happened … was a negative number … (then) it can still increase and be spontaneous because it's still going to be a negative number as long as it's increasing until it gets to zero.
Student's confusion: Apparently confecting criteria for spontaneity

The Possible Sources of the Learning difficulties

This section summarizes the possible sources of the learning difficulties in order to answer the second research question. Various reasons were considered as possible sources of the learning difficulties. These can be grouped into the following recurring themes:

> (a) lack of knowledge of fundamental thermodynamic concepts, (b) application of algorithms without conceptual understanding, (c) using thermodynamic data to explain situations involving kinetics, (d) memorization of scientific laws and statements without understanding, resulting in inappropriate over-generalization, (e) confusion of fundamental ideas, (f) defining fundamental ideas according to their usage in everyday language, (g) the effects of everyday experiences, and (h) socio-economic and methodological aspects of the teaching and learning environment.

Implications for Teaching

The results of this study suggest that many students in an advanced undergraduate class have difficulties in acquiring some the most basic chemical concepts as well as having difficulties in acquiring advanced thermodynamics concepts. Conversations with colleagues at other institutions of higher education suggest that it is likely that many of these learning difficulties identified in this study would be found among physical chemistry students in general, although the students in this study were from only two chemistry departments in Ethiopia. Therefore, the findings of the present study may provide some clues about the quality of student learning in typical Chemical thermodynamics classes.

Constructivist theories of knowledge are based on a fundamental assumption that knowledge is constructed in the mind of the learner (Driver, 1989). This suggests that students construct their own meaning by assessing and assimilating the new knowledge to that which they already have. Therefore students' previous knowledge plays a vital role in learning. Chemical thermodynamics lecturers sometimes overestimate their students' understanding of basic concepts. If lecturers recognize the possibility of learning difficulties or no understanding concerning fundamental concepts, they will be better able to organize the teaching and learning environment by addressing and attempting to overcome student learning difficulties (Thomas 1997). As Ribeiro (1992) points out, university lecturers would provide better teaching if they begin with the question '*what do students see, do and know?*' Discussion of students' concepts amongst themselves and with lecturers may bring out what they already know and do not know and may provide a way forward for better teaching. Beall (1994) argues that informal in-class writing also provides clues to students' previous knowledge. Overestimating students' previous knowledge and misunderstandings makes the difficulties even more chronic.

In order to improve the students' understanding of important thermodynamic concepts lecturers might concentrate more on the quality than the quantity of material covered during the course, as Thomas (1997) points out. In doing this, some of the students may need extensive help to change their way of thinking about fundamental concepts and replace incorrect beliefs with the scientific ones. Otherwise, if student learning difficulties are not addressed by the lecturers, students might continue to hold them even if they successfully complete the requirements of the course. In addition, as Pushkin (1998) argues, exposure to many concepts at a time promotes memorizing and enhances algorithmic skills instead of conceptual learning.

Since this study provides evidence that students' explanations of scientific phenomena are based on the macro physical world and they have a very limited level of microscopic level thinking, lecturers should check that students have acquired the correct scientific meanings of concepts taught and that they can apply the concepts learned in different situations, whether it is an everyday phenomenon or theoretical one (Selepe and Bradley, 1997). In addition, university lecturers should pay attention to everyday, out-of-class concepts associated with the scientific terms they use. They should also be checking if students have understood in the way they intend Ribeiro (1992). As Ribeiro *et al* (1990) argue the best way of becoming aware of the shortcomings of one's own knowledge is to rub it up against that of others. Discussions with students may provide a better chance of knowing their shortcomings.

In order to overcome the difficulties of confusion among concepts, students might be helped to see clearly the contextual differentiation of their knowledge. This is a major source of student's difficulties. It was argued by Ramsden (1997) that a context based approach, using scientific applications and context as a starting point, in teaching may provide better help for students in developing an understanding of some areas of chemistry as compared to traditional approaches. In addition, as Carson and Watson (1999) point out, it is important that thermodynamic entities are defined qualitatively and their effects talked about before they are defined quantitatively. Therefore, it is suggested that there is a need to reverse the usual procedure where numerical problem solutions are set first and then understanding follows. The results of this study support Carson and Watson's (1999) findings that students were not able to draw out the meaning attached to the thermodynamic entities defined quantitatively, therefore teaching thermodynamics requires new perspectives rather than traditional teaching methods. It is evident from the literature that traditional teaching methods are ineffective in tackling the students' learning difficulty (Bodner, 1991).

In summary chemical thermodynamics course coverage is fragmented, not connected to students earlier Knowledge, and typically not set in a meaning full context .The three core energy concepts the macroscopic, which involve thermodynamics and mathematical treatments, the molecular, which describes the origins of energy changes in terms of bonds, and the quantum mechanical, which provides the basis for understanding of periodic trends, bonding and interactions of matter and electromagnetic radiation are not well connected, and there is often no attempt to make an explicit connection between them most assessment for chemical thermodynamics courses still emphasize rote problem solving and factual recall rather than understanding, and there is little opportunity for students to synthesize and connect the energy concepts there is ample evidence that students lack of a coherent framework of energy concepts on which they can hang their understanding of energy changes associated with chemical change in fact many of the leading text books introduce these topics indifferent orders, so it is clear that there is no consensus on how to develop and connect energy concepts or even why it is important as a result this thesis develop an intervention strategy to tackle some of the learning difficulties.

Recommended intervention strategic program

It is clear from our analysis of the traditional approaches to the integration of energy concepts into the chemistry curriculum, that the three approaches to energy are rarely well integrated. That is, the macroscopic phenomena that are the purview of thermodynamics are taught separately from the molecular-level and quantum phenomena from which they arise. Discussion of quantum mechanical factors typically begins and ends with the structure of atoms (and while this may be a start, most chemistry does not in fact take place between atoms, but rather between molecules, ions, and networks of atoms). Our approach to an energy learning progression must reconcile these different aspects and explicitly recognize connections and places where energy is best treated by one or more of the approaches. We need to provide students with a relevant toolkit of energy concepts that integrates the three levels and allows students to make sense of energy phenomena.

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