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Multiple Representations in Calorimetry

by

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Program of Study Committee:
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This is to certify that the master's thesis of

Bruna Irene Grimberg

Has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy

For Fabian and Uriel

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ABSTRACT

The purpose of this study is to explore the use of multiple representational modes as a tool for understanding the concepts of temperature and energy transfer in calorimetry. The focus is placed on which type of representation promotes students' understanding of these concepts, and which representation(s) facilitates translations to other types. This study considers verbal, mathematical, and graphical representations. The statistical analysis of a problem set completed by 111 a freshmen college chemistry students and a semi structured interview on one-to-one basis to 23 students, is used to diagnose students' understanding of calorimetry and the use of representations. Based on these results a model for conceptual understanding is proposed.

INTRODUCTION

Scientific ideas cannot be abstracted from the language used to express them. Therefore, the limitation of the language[1] becomes the limitation of the science. The scientific language emerges from the intention to describe reality (or referent) with the purpose of finding an underlying pattern in nature (Krieger, 1987). The scientific language is in the most general sense, a representation. In particular, representations in physics can be conceptual or methodological tools having a symbolic (mathematical and diagrammatic), or rhetorical character. Many conceptual and methodological tools can be transferred from one field into another, given a sense of unity to scientific knowledge[2] and yet, representations are versatile depending on the reality that they attempt to represent. In other words, representations function passively as representational formats, decontextualized from the referent, and actively as meaning construction, or referent dependent (Posner et al. 1982).

The use of representations requires not only the skill of manipulating them, but also assessing which tool is appropriate to a specific situation. Similarly, a referent (a physical system or process) can be represented in different modes with the purpose of deepening in understanding and problem solving skill (Chi et al., 1981; Larkin, 1983; Janvier, 1987; Maloney, 1993). In the classroom, the use of diverse representations of a referent was shown to increase conceptual understanding of it (Reif, 1995; Hestenes, 1996) while mastering one form of representation could be beneficial for improving the use of other

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[1] The word language refers to any kind of expression to convey an idea.

[2] Reinforcing the idea of an underlying pattern.

modes (Lesh, et al. 1987). The transfer between different representational modes requires the identification of "core concepts" of the referent in order to guarantee its invariance through diverse representations. The identification of essential characteristics of a referent constitutes the conceptual understanding of it.

Several works address the use of multiple representations for learning and teaching different physics topics. The use of graphs in kinematics was thoroughly explored by Lillian Mc Dermott and collaborators (1987), and Beichner (1994 and 1996). Also topics such as particulate model of matter (Rhor and Reimann, 1998), mechanical systems (Dolin, 2001), and electricity (Frederiksen et al., 1999) were examined under the scope of multiple representations. However, in spite of well-known students' difficulties in dealing with topics of thermodynamics (Rozier and Viennot, 1991; Loverude et al., 2002; Granville, 1985; van Roon et al. 1994; Jasien and Oberem, 2002; Greenbowe and Meltzer, 2002), there are no studies that address directly the use of representations in that context[3].

The use of multiple representations in class constitutes a strategy to promote the evaluation of alternative explanations, and to solving problems. These teaching goals, as specified by the National Science Education Standards (1996), are crucial to any science class. Also the use of representations can make evident the inconsistencies that result from students' misconceptions. Indeed, different representations focus on different

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[3] Some works discuss students' difficulties with heat and temperature concepts and the use of multivaried formulas as in Rozier and Viennot (1991), or in different contexts as calorimetry of solutions (Greenbowe

aspects of the referent, such that a misconception can be associated with a specific representational mode and unmasked by using a different mode to represent the referent. However, in order to implement the use of multiple representations and their translations in class, several questions should be answered:

1) Which representation facilitates students' understanding of a referent?
2) Which representation(s) facilitates a translation to other ones?

The purpose of this study was to explore the use of multiple representational modes as a tool to understand a physical process by focusing on questions 1) and 2) for verbal, mathematical, and graphical representations of a heating process as a referent. In particular, students' understanding the specific heat equation in the frame of calorimetry was explored. The specific heat capacity equation is,

$$q = mc\Delta T \qquad \text{(eq.1)}$$

where q represents heat, m is the mass of the substance, c its specific heat, and ΔT is substance's change in temperature. This is a cause-effect equation, implying that a process takes place due to a causal relation between variables. A substance (of mass m and specific heat c) experiences an energy transfer in the form of heat (q), because its temperature changed (ΔT), and vice versa, the temperature changes because there is a transfer of energy between the substance and the surroundings. These functional and multivariate characters (meaning that relates more than one variable) makes the specific heat formula an interesting object of study that goes beyond its context of definition.

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and Meltzer; 2002). However these works do not recognize formulas of physical contexts as representations of a physical concept.

Physical equations[4] that describe a process are cause-effect (examples are Maxwell's equations in electrodynamics, Second Newton's Law in mechanics, etc...) and many of them are multivariate[5]. The relevant idea of cause-effect equations is that, in a specific context, each side of the equation cannot exist a priori from the other.

The present study addresses students' notion of cause-effect in the context of calorimerty and how this idea is expressed in diverse representational modes. Hence, the design of research tools and students' data analysis are oriented to determine students' concepts and working modes in calorimetry, and how conceptual understanding and representational modes are related.

The research tools were a quiz or problem set, and a semi-structured interview, both containing problems on calorimetry.

1. The problem set aimed to test the conceptual understanding of the specific heat equation: the cause-effect relation and its multivariate character. The problem set focused on the verbal and equation representations of the specific heat equation (eq. 1) and their translation, and on the concept of a thermodynamic system and the interaction between its components. A copy of the problem set with the solution of the analyzed questions (in italics) is attached in Appendix I. Freshmen chemistry students in a General Chemistry course completed the quizzes after instruction on calorimetry. A sample of 111 quizzes was randomly selected from a total of 450.

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[4] Cause-effect equations differ from mathematical equations in that the latter describe equivalences.

[5] An example of one variable cause-effect equation is Newton's Law, $F=ma$.

2. The interview questionnaire aimed to test the same calorimetry concepts as in the problem set, including text, equations and graphic representations, and their translation. A copy of the questionnaire with the solution of the non-graphical questions (in italics) is attached in Appendix II. 23 freshmen chemistry students were interviewed after instruction on calorimetry was completed.

The text of written responses of quizzes and interviews was analyzed. For the quiz the analysis focused on the problems referring to two different thermodynamic systems, isolated substances on a heating plate (Problem 1) and substances in a calorimeter (Problem 2). Different categories emerged from students' explanations, and a Chi-Square analysis was performed seeking a statistical relationship between the category of the explanation and the working representation (verbal or equation).

Interviewed students worked through the problems of the interview questionnaire. After the completion of each problem students were asked to explain their responses and justify each step. These interviews were semi-structured (Taylor and Bogdan, 1998); in spite of a "standard" set of questions students' ideas were probed with follow-up questions. The problems of the questionnaire and the follow up questions encouraged discussion of concepts and translations between modes of representations. The audiotaped interviews were transcribed and analyzed with the purpose of finding trends and patterns of students' reasoning in calorimetry.

The results from problem set and interviews can be grouped in modal and conceptual categories (or operational and explanatory for the statistical analysis). In what follows conceptual and modal results are summarized for both quizzes and interviews. The most relevant conceptual trends displayed by the students were:

1) Correct use of the energy conservation principle in a calorimeter
2) Associate energy transfer with the difference in the initial temperature of substances in a calorimeter, or bond breaking and forming for a chemical reaction
3) The idea of heat as a fluid
4) Use of the molecular theory to describe heat and temperature
5) Confusion between heat and temperature
6) Correct explanation of how the change in temperature depends on the specific heat
7) Recognize a direct relation between heat and the amount of substance.

The results emerging from the analysis of the working modes were the following,

1) The use of formulas is preferred for learning a new topic and to minimize the ambiguity found in textbooks.
2) Users of formulas required numerical values. Students displayed difficulties in using formulas in an abstract way, although they were able to do algebraic manipulations.
3) Users of formulas tended to omit verbal explanations.
4) Graphs were welcomed as facilitators of understanding. Many students claimed that they are "though provoking"

5) Users of graphs determined the critical points of the graph by using equations (as the calculation of the equilibrium temperature). Also, students associated the parameters of the graph with parameters given in the problem.
6) The use of graphs promoted extended responses from the students.
7) Use of words is preferred to express conceptual understanding
8) Words can be used in decontextualized problems that encourage conceptual understanding and self-reflection about the learned topics.
9) Students that correctly answered using words gave correct explanations; either based on the cause-effect character of the specific heat equation or on the values of the parameters of the problem.

Based on these results a model of conceptual understanding is proposed, the Stairway Model, based on the interplay between rhetorical and symbolic (in this case symbolic refers to equations and graphs) representations. Iterations of the translation between verbal and symbolic modes correspond to progression of the ability to make abstractions that lead to the organization of large structures of knowledge.

The chapters of this study are organized in the following way. Chapter 1 contains a literature review focused on relevant calorimetry topics (conservation of energy, heat and temperature and specific heat equation) and the use of representational modes in college classes for solving physics problems. A brief discussion on the difference in the use of representational modes between novices and experts is also included. Chapter 2 describes the research methods, the design of the research tools, the experimental conditions of this study, and the statistical analysis. Semi-structured interviews (see Appendix II) and quizzes (in Appendix I) allowed a qualitative and a quantitative analysis of students' understanding of calorimetry concepts and representational modes. Chapter 3 summarizes the results obtained from interviews and quizzes. A synoptic table of conceptual and modal categories that emerged from the analysis of the interviews is shown in Figure 2. The results of the statistical analysis of the relation between working modes and the displayed understanding of calorimetry topics are discussed in Chapter 3, while tables of the frequency distribution and statistical results are included in Appendix III. Examples of quiz problems coding are included in Appendix IV. Chapter 4 contains the conclusions derived from qualitative and quantitative results. Based on this study's results and conclusions regarding the interplay between textual and symbolic modes, a model for conceptual understanding is proposed, the Stairway Model. This chapter also contains some reflections on the weakness of this study and ideas for future work.

CHAPTER 1: LITERATURE REVIEW

Thermodynamics offers "simple" and "concrete" contexts through which to introduce and apply fundamental concepts of physics. The notion of system, energy conservation, and cause and effect relations are fundamental ideas in physics. Indeed, in college physics and chemistry, the study of classic thermodynamics including calorimetry, state functions, ideal gases, etc... takes place early in the instruction and has a character of "seminal ground" for the application of these ideas. Hence, the study of how students learn thermodynamic concepts could have impact in other contexts.

Calorimetry deals with the calculation of heat, or energy transferred, through the measurement of the temperature change produced by it when the pressure of the system is kept constant. In order to derive the energy transferred in a system, physical processes and chemical reactions take place in an insulating container. Three fundamental ideas can be introduced through calorimetry: a) the principle of conservation of energy within a system, b) differentiation between intensive and extensive properties of a substance (as temperature and heat respectively), and c) cause and effect relations. The last two ideas derive from the specific heat equation through which heat is linked to temperature change. Students' knowledge construction of physical ideas result from conceptual understanding (internal representation), and their way of expressing them (external representation) (Posner et al., 1982). Although both aspects are interwoven, here they are treated separately for sake of simplicity. In what follows research studies concerning students' understanding of these three thermodynamics concepts and their representations are reviewed.

About thermodynamic concepts

In the last twenty years educators realized that in order to teach physics it is necessary to ask what students know when they come to class and how they interact with the learning environment and content (Redish, 1994). A basic understanding of the notion of energy conservation requires understanding of the notions of energy degradation (Duit and Kesidou, 1990) and physical systems. Novices' understanding of fundamental physical concepts is strongly associated with the context in which they are introduced. As was indicated by van Roon and collaborators (1994) in a study that included university freshmen chemistry students, the concepts of system, surroundings, boundary and thermodynamic state, and their interrelations are better understood in context of thermodynamics. A similar result was found by other researchers (Summers, 1983; Se-Yuen and Young, 1987) for high school students.

Novice students find it difficult to define the concepts of heat and temperature (Erikson, 1980; Erikson and Tiberghein 1985; Kesidou et al., 1995; Greenbowe and Meltzer, 2002). In a study that included written answers from 653 students in four introductory-calculus based general physics courses, Meltzer (2001) found that students have difficulties in distinguishing heat and work (possibly because they share the same units); or that students viewed temperature as a measurement of heat. In some cases, temperature and heat are viewed as synonyms or as a unifying word to express ideas of cold and hot (Kesidou and Duit, 1993; Erikson, 1985; Loverude et al., 2002).

Understanding the concept of heat requires a process of differentiation of related concepts as energy, temperature, and entropy (Kesidou et al., 1995). Students' difficulty in distinguishing heat and temperature can be attributed to the ambiguous understanding of heat. Initial knowledge is substance based, and it represents novice understanding of how objects function. Novices tend to attribute material properties to abstract physics concepts, such as heat, force, electricity, etc... Under this materialistic conception, heat and cold are inherent proprieties of objects and heat and cold accumulate and can be contained (Reiner at al., 2000). Students' materialistic ideas of heat, and lack of differentiation between heat and temperature, resemble the historical development of the concept of heat (Wiser and Carey, 1983; Kesidou et al.,1995).

Van Roon and collaborators (1994) suggested that a source of confusion encountered by university freshmen students with the (thermodynamic) concept of heat could be the use of a word that has a meaning in common parlance. They claimed that in order to assign a thermodynamic meaning to heat, it is necessary to develop a "thermodynamic context." Students develop an "energy conception" of heat, referring to "heat conservation," for the energy conservation principle, and "heat as a type of energy," in the context of the first law of thermodynamics and state functions. This is in contrast to a materialistic conception of heat, typical of a thermochemistry (calorimetry) context (van Roon et al., 1994). Also the microscopic context used to explain temperature interferes with the macroscopic context in which concepts of work, heat and internal energy are defined (Loverude et al., 2002)

Difficulties in recognizing the differences between temperature and heat are not overcome with the use of the specific heat equation (Gabel and Bunce, 1994), which links temperature change and heat. A study based on interviews of 16 college physical chemistry students found that many students have alternative conceptions or no conceptions at all of chemical equilibrium and thermodynamics. (Thomas and Schwenz, 1998). A study that included 421 participants with different backgrounds in physical sciences (physics students, organic chemistry students and in-service teachers) and different numbers of college physics courses, aimed to determine students' understanding of the concept of thermal equilibrium and its relation to temperature. Extended surveys were used to explore students' ideas about the physical basis for heat transfer and temperature change. The main results were: 1) no correlation between the number of college physics courses and the ability to answer correctly questions regarding fundamental principles of calorimetry. 2) A general confusion of specific heat with "heat per gram" held by a substance (Jasien and Oberem, 2002). Apparently failing to distinguish heat and temperature, one as energy transfer not inherent to a substance but depending on it, while the other as an intensive property of a substance, makes it hard to realize the cause and effect relation between temperature change and heat.

The specific heat equation is a multivariate equation linking heat and temperature change to two other variables: mass and specific heat. Multivariate problems are complex, and novices tend to simplify them (Rozier and Viennot, 1991). In a study that involved the analysis of written questionnaires of 2000 students, including science majors and prospective engineering students from the first four university years, Rozier and Viennot

(1991) were able to characterize the simplification process of multivariate problems. Theses authors indicate two main aspects: 1) a physical quantity that depends on several variables is treated as depending on only one variable. This reduction sometimes results from combining two variables, as if they were two different aspects of the same variable. 2) The application of a chronological argument to the many variables of the problem, instead of the consideration of the simultaneous change of several variables. This implies that there is an order in the action of the variables. Simplifications of multivariate problems interferes with the type of reasoning required for conceptual understanding (Luger, 1994).

About modes of representations

A range of diverse representations is required to expand the conceptual space associated with physical ideas into larger knowledge structures or models (Hestenes, 1996). Representations range from images of real objects (iconic representations) to entities that represent ideas (as language, mathematical symbols, graphs, diagrams, etc...) and their organization (or models). Different representational forms can refer to different aspects of a referent. Hence, the ability to link different representations contributes to conceptual understanding of a referent (Dolin, 2001).

The ability of transferring between different representational modes can be associated with problem solving. Good problem solvers tend to be flexible in their use of a variety of representations switching to the most convenient for emphasizing the desired characteristics during the solution process (Lesh et al., 1987). Transfer can be done for efficient manipulation of quantitative relationships or for conceptual understanding. Other studies explored the impact of the use of multiple representations on high school students' ability to solve problems in physics. The results show that use of representations not only enables students to successfully solve the problem, but also enhances conceptual understanding (McMillan and Swandener, 1991; Ping-Kee, 2001).

An example of conceptual transfer can be found in the use of analogies. Analogies work on the premise that the import of relations and operations from one domain to other further thinking (Greeno, 1983). The source of an analogy is a problem solution, an example, or a theory well understood, while the target is a non-familiar problem or system. Analogies either map elements from the source into the target, or is based on mutual alignment of partially known situations (Miao et al., 2001). In either case, analogies contribute to increasing conceptual understanding of scientific concepts through the promotion of inferential reasoning (BouJaoude and Tamin, 2000; Yanowitz, 2001; Baker and Lawson, 2001). Moreover, inferences people make vary according the analogies they use (Gentner and Gentner, 1983).

The differences in expert and novice performances can be related to use of different problem representations. Novices use a "naïve" problem representation, composed of objects that exist in the real world related through operations that occur in real time (as to push a spring, to move a block, etc…). Experts, in addition to this naïve representation have a "physical" representation that includes abstract entities such as forces, magnetic field, etc…(Larkin, 1983). These entities are related through the laws of physics, or physical operators and provide arguments on which general reasoning procedures about parts and whole can operate (Greeno, 1983). Experts usually use qualitative representational objects such as pictures, graphs, diagrams and bar charts, instead of only using quantitative representations (formulas) as novices do (Plotzner, 1994).

Indeed, students' ability to solve problems increases when emphasis is placed on the use of qualitative representational modes (Larkin, 1983; Hestenes, 1987). A study that involved students in an introductory university physics course indicates that qualitative representations build a bridge between words and equations and help students to understand mathematical symbols (van Heuvelen and Zou, 2001). In particular, these authors report on the benefits of the use of bar charts as visual aids for understanding the energy conservation principle and facilitating quantitative predictions in a classical mechanics context. However, the use of qualitative representations is productive when students understand what is being represented or how qualitative representations operate in problem solving.

The use of graphical representations, including the ability to construct and interpret them, is critical for scientific conceptual understanding (Berg and Smith, 1994). Graphs are viewed as representational objects that summarize functional relations between variables (Linn, 1987; Mokros, 1986; McKenzie and Padilla, 1986). However, students' graphing abilities are affected by both content knowledge and cognitive development (Berg and Phillips, 1994). In trying to identify learner "misconceptions" of graphing, many authors (Kerslake ;1977; McDermott et al., 1987; Shultz, 1986) found that students see graphs as a picture instead of a symbolic representation of data and its functional relationship. Results from a study conducted by Berg and Phillips (1994) indicate a strong correlation between logical thinking and graphing ability. Students who displayed evidence of mastering concrete operations related to the Euclidean space (Piaget and Inhelder, 1948/1969), such as conservation of distance, size, angles and parallels, and the ability to use coordinate systems, were able to construct and interpret graphs better than students with poor logical thinking.

CHAPTER 2: METHODS

Method I: Interviews

Selection of participants

A sample of twenty-three freshmen students of an introductory college course on General Chemistry was interviewed. All students were enrolled in the same semester course (total enrollment 650), attending the same lecture but different recitation and laboratory sections. All the interviewed students had at least one high school course in chemistry and physics, and 20 students out of 23 major in some area of engineering. Although students' grades were not a consideration in the selection of the sample, the grade distribution of the interviewed students is tightly concentrated on the high end of the scale, see Figure 1 at the end of this section. In order to enhance the accuracy of the study, the lecturer of the course was also interviewed.

Data Collection

The interviews were conducted in the university between two and four weeks after the instruction on calorimetry was completed. Each student was interviewed during one hour. The interview was conducted, audio taped, and transcribed by the same researcher. The interviews were semi-structured (Taylor and Bogdan, 1998) consisting of a written and oral part. The written part was based on a set of six problems including close-ended (definite response) questions (see Appendix I), while the oral component of the interview included follow-up questions aimed at exploring students' conceptual understanding and the procedure used for solving the problems of the set. The follow-up questions took place after the completion of each problem. Written and oral questions allowed a triangulation of the evidence emerging from the data.

The semi-structured oral interview of the lecturer took place after the analysis of students' interviews. The questions in this interview were intended to clarify some recurrent students' themes emerging from students' data. Indeed, the purpose of the lecturer interview was to provide a triangulation source to corroborate the evidence derived from students' interviews by comparing different population (students and lecturer) discourses. The questions included in the interviews allowed a qualitative analysis of the data.

Qualitative Analysis of the Data

The data was first segmented in units of information (or themes) and then each unit was labeled with a code regarding the content of the information. Codes that presented some overlapping in their content were grouped together in broader categories; these categories constitute the emerging themes of the data. This procedure was used with the oral and written components of each interview. The categories that are recurrent in at least 10% of the interviewed students were identified as emerging themes.

Qualitative research Tools: Interview Questions

The problem set included in the semi-structured interview (see Appendix I) was designed to answer the research questions of the present study: Which representation(s) facilitates students understanding of temperature and heat, and which representation(s) facilitates a translation to other ones? There are two main aspects included in the problem set, one aspect deals with the concepts of energy transfer and temperature change, while the other deals with the way these concept are represented (formula, words or graphs) and the transfer between these representational modes. Previous research results indicate that the understanding of some thermodynamic concepts strongly depends on the physical context in which they are presented (Greenbowe and Meltzer, 2002; Meltzer, 2001). The problem set includes four different contexts: non-reacting substances in a calorimeter, chemical reaction, substances on a heating plate, and a de-contextualized frame. A summary of the interview problems regarding different combinations of concepts, contexts, and representational modes is shown in Table 1. These problems are mostly conceptual; they do not rely on the numerical values of the parameters (the only exception is the value of the specific heat for water and copper) but are based on relations between the parameters. The ability to transfer between the different representations was explored during the oral part of the interview, asking the students about their working mode preference, and similarities or contrasts between the different modes.

Table 1. Combinations of concepts, contexts, and representational modes through the problems of the written interview

Concept	**Context**	**Representation**	**Problem number**
Temperature change	Calorimeter	Words; formula; graph	P1b; P1c; P4a, P4b, P6
	Chemical reaction	Words	P2b
	Heat plate	Graph; words	P3a; P3b
	De-contextualized	Words	P5b
Energy transfer	Calorimeter	Words; formula; graph	P1a; P1c; P4a, P4b, P6
	Chemical reaction	Words	P2a
	De-contextualized	Words	P5a, P5b, P5c
Specific Heat	De-contextualized	Words	P5c

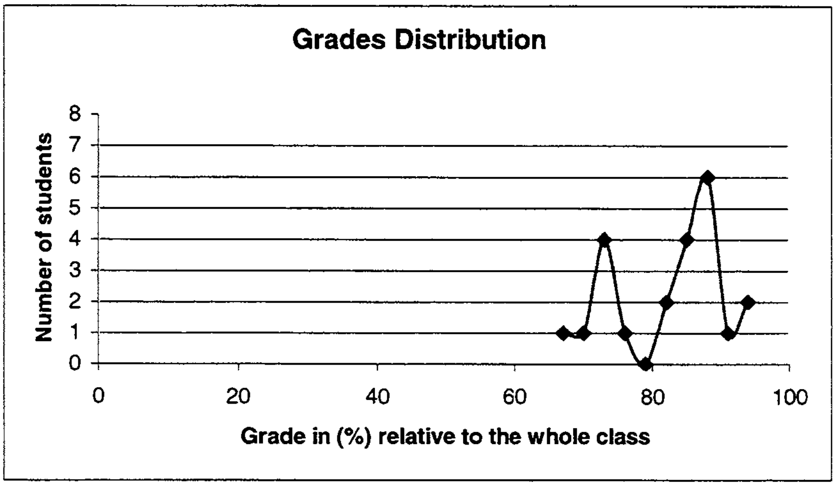

Figure 1. Grade distribution of the interviewed students. Only the score of 22 students is reported here.

Method II: Quizzes

Selection of Participants

The student population, from which the quizzes were sampled, was enrolled in the same General Chemistry course with the same lecturer, but two semesters ahead of the interviewed students. This could allow comparing the results of the interviews with those of the quizzes because they received similar instruction. A sample of 110 students' quizzes was randomly selected from a group of 450 quizzes corresponding to freshmen chemistry students. The students were enrolled in different laboratory sections with different instructors; fourteen instructors altogether. In order to minimize the effect of the instructors in the statistical sample through their impact in students' responses, a random sampling of the quizzes was done in a stratified way, per laboratory instructor, using a Random Number Table (Daniel, 1987).

The students that participated in this study attended a General Chemistry course in which the instruction of calorimetry included lectures, recitations, and laboratory experiments. In lectures, students had demonstrations that emphasized the different conditions for temperature change and energy transfer for physical processes and chemical reactions. In particular, systems like hot metal and cold water in an insulating container, the dissolution of a salt, and acid-based reactions were introduced either in lecture or lab to introduce the concepts of heat and temperature change. The lectures were mostly problem solving oriented, emphasizing the use of formulas, while in the lab the students used diverse representational modes such as graphs, tables, and formulas. In lectures and home works, the students were exposed to simulations of the molecular motion to represent the temperature of a substance. Calorimetry is taught before the laws of thermodynamics because it introduces the concept of thermal equilibrium; as the instructor of the course explained, "....I have started the thermochemistry chapter specifically with calorimetry, because they [the students] can see what happens and they can see it in the lab..."

The students that participated in this study had three laboratory sessions on calorimetry, including experiments with substances in calorimeters (metal and water) and chemicals reactions. In the lab, students record their observations in data tables and used graphs describing the temperature change of these systems.

Data Collection

A quiz on calorimetry (see Appendix II) was given to the students two weeks after completion of instruction on that topic. The quiz was mandatory for all the students enrolled in the course, and its grade contributed to the final student grade. Student's responses to three problems of the quiz (problem 1, 2d, and 2g) were analyzed to explore any possible relation between the mode of approach to a problem (operational variable, O) and the display of conceptual understanding (explanatory variable, E).

Quantitative Data Analysis

In order to find any relation between the operational and explanatory categorical variables, the quantitative analysis was based on the chi-squared test. This test compares the observed frequency distribution to frequencies that one would expect if the data follow a particular distribution. The statistical test retrieves a value χ^2, which is a measurement of the extent to which the observed and expected frequency distributions disagree; the smaller the value of χ^2 the better the agreement between the frequencies (Daniel, 1987).

When two categorical variables describe a set of entities, the resulting two-way classification can be summarized in a table with the categories of one variable as columns and the other variable as rows, the contingency table. If O and E are independent variables, the probability that a given category of O happen along with a category of E (the joint probability) is equal to the product of the individual probabilities for these two categories. In this way, the resulting frequency table represents the expected frequencies for independent variables.

By comparing the observed frequencies with the expected ones, the null hypothesis that the two variables are not dependent can be rejected or sustained depending on the discrepancy of the chi-square distribution. If the chi-square test indicates that the variables are dependent (null hypothesis rejected) an analysis of adjusted standardized residuals (Agresti and Finlay, 1997) was performed in order to find the related categories between the two variables. This analysis indicates if the distribution of each category of one variable follows a normal distribution centered on zero, with respect to the categories of the other variable. Two categories are related if their residual is not within two standard deviations of the normal distribution (r_{ij} not belong to $[-1.96, 1.96]$ interval, with r_{ij} the residual of the ij categories of variable O and E respectively). Examples of this statistical analysis applied to the data are included in the Results chapter, Chapter 3, and in the Appendices IIIa, IIIb and IIIc.

Quantitative Research Tools: Quiz Questions

The focus of the quiz (see Appendix II) is on the concepts of energy transfer, temperature change, and the different parameters in the specific heat equation. The representational modes included in the quiz are formulas and words, while the physical context for all the problems is non-reacting substances in a calorimeter. Problem 1 centered on the use of the specific heat equation while problem 2 focused on the process that takes place when two non-reacting substances are put together in a calorimeter at different initial temperatures. In particular, problem 2d deals with the ideas of energy conservation and the change of temperature due to the energy transferred between the substances, and problem 2g deals with the effect of the mass on the temperature change. In order to complete each of these problems, students were required to perform an operation and to explain it.

CHAPTER 3: RESULTS

The objectives of this investigation are to find which representation(s) promotes students' understanding of the concepts of heat and temperature, and which ones facilitate translations to other representations. In order to work toward this goal, the research instruments (interview and quiz) contained questions and problems aimed at conceptual understanding, and the use of representational modes when dealing with heat and temperature. The interviews and quizzes have been analyzed under the scope of conceptual and modal categories. In the following sections trends emerging from the interviews and statistical results from the quizzes are presented.

Trends from the interviews

The results obtained from the students' interviews included oral and written parts. The categories and subcategories that emerged from the interviews, including the percentage of the interviewed students that correspond to each subcategory are summarized in the diagram of Figure 2 at the end of this section. The main subcategories emerging from the interview with the instructor are triangulated with those from students' interviews in Table 2. Both the diagram and the table are included at the end of this section. The information from the written responses given during the interview is supplemented with quotes from dialogs between the interviewer (I) and students (S).

Conceptual categories

Energy issues

90% of the interviewed students correctly invoked the principle of conservation of energy to balance the energy transferred between the two substances in the calorimeter and in a chemical reaction. They recognized that the cold water should gain the same amount of heat lost by the hot metal in a calorimeter, as well as that the heat lost by the reactants should be equal to the heat gained by the solution.

52% of the interviewed students justified the transfer of energy between the substances in the calorimeter because of the difference in their initial temperature. However, 30% of the interviewed students think of heat as a fluid flowing from one substance to another. For example one student said:

> S: … the copper transfer its heat to the water, so when transfer enough heat they reach the same temperature.

This view contradicts the scientifically accepted notion of heat as energy transfer (or change in internal energy). Most of the students that held a materialistic picture of heat were able to correctly operate with both conservation of energy and specific heat concepts. Nonetheless, the idea of heat as a fluid could impact the perception of a heating process; as a student explained when she/he was asked about the temperature change rate of water when the mass of hot metal in the calorimeter was doubled:

> I: Which process [with the original amount of copper or double amount] will take longer to heat the water?
> S: The second one [twice the original mass] because there is more heat to exchange.

In the case of the chemical reaction, 65% of the students associated bonds breaking and forming as the source of temperature change of the combined solution.

The problem of heat and temperature

Through the interview students were asked to relate the concepts of heat and temperature. Two types of relations can be distinguished; one focuses on the nature of heat and temperature, while the other is an operational relation. 35% of the interviewed students defined temperature and energy transfer based on a molecular explanation, as is illustrated in the following quote:

> S: copper molecules are moving really fast, water molecules are moving no so fast, so the copper molecules are causing the water molecules to move fast and therefore there is an increase in temperature.

However, only 25% of the students who invoked the molecular model correctly stated that temperature is the averaged kinetic energy of the particles, and that heat is related to energy transfer or is a “kind of energy”.

Another group of students, 30%, referred to an operational relation between temperature and heat indicating, "temperature measures heat." This idea contradicts the statement of the First Law of Thermodynamics, in which heat is related to the change in internal energy, while temperature is proportional to the molecular kinetic energy. In some cases, the source of this operational relation seems to arise from the fact that students are familiar with the use of thermometers to measure temperature, as one students explained:

> S: Temperature is a measurement, is a device to measure heat.... is an instrument for making calculations. Is a way to measure relative heat, is like you compare the temperature of two substances, one at 0C and the other at 100C, the relative difference is 100C....T is a reflection of the relative heat.

As can be seen from the above quote, some students, while supporting the idea that temperature is a measurement of heat, confused heat with temperature. In particular, 42% of the students who indicated an operational relation between heat and temperature confused thermal equilibrium with equal heat distribution, as follows form this quote,

> S: When two substances at different temperature are in contact reach equilibrium.
> I: When you say "reach equilibrium," equilibrium of what?
> S: Of heat distribution

18% of the interviewed students thought that temperature and heat are the same because of the energy balance, as was answered by one student

> The temperature of Cu(s) will go down by the same amount as the $H_2O(l)$ goes up because the Cu(s) is losing heat to the $H_2O(l)$.

In particular, 10% of these students used only the equation of conservation of energy ($q_1 + q_2 = 0$, with q_1 and q_2 the heat transferred to substance 1 and 2 respectively) to explain the temperature change of the substances. Another 10% of the interviewed students indicated that temperature represents heat average: "Temperature is a measurement of heat, is like the average." In general, students who stated an operational relation between heat and temperature see them as interchangeable concepts, as is indicated by this student,

> S:... heat can be measured. You can take a thermometer and see how much heat is in the substance.

Dependence of the temperature change

Problems 1b, 4a, and 4b aimed for the inverse relation of the temperature change of a substance with its mass and specific heat, as is indicated by the specific heat equation (eq. 1). Students recognized the specific heat and the mass of the substances as the main factors affecting the temperature change. 78% of the students based their explanation of the difference in temperature changes for water and metal, on the meaning of specific heat. They clearly pointed out a functional relation between the specific heat and the change in temperature,

> S: Since water has a higher specific heat, it takes more heat to heat it up than copper. Copper has more of a temperature change than water

17% of the students described the problem of two non-reacting substances in a calorimeter in terms of a chemical reaction taking place in a calorimeter, and they could not apply the specific heat equation to the "reactants and products" of the system. A smaller portion of the interviewed students, 13%, associated the difference in temperature change with heat conductivity.

The fact that the mass of the substances affects the amount of heat gained and lost was indicated by 70% of the interviewed students. As an example this is what one student said:

> S: ... because copper is doubled will cool less, and water heat more because there is more copper. So there is less water to absorb the heat.

Other students were able to relate the change in the mass of copper to the amount of the heat, and subsequently to the rate of temperature change of the water,

> S: Copper will lose heat at the same rate but water will rise faster because there is much copper....is just given off twice as much heat, because there is more [copper].

The difference between the transfer of energy and temperature change for a physical process and a chemical reaction was emphasized in problems 1 and 2. 73% indicated that the physical context impacted on the understanding of these concepts. 52% of the interviewed students referred to the system of hot metal and cold water as the simplest one in which the variables can be identified, and for which people are more familiar. As one student said,

> S: Chemical reactions can be difficult because there is no mass and could be confusing to know how something that you really cannot see or grasp can transfer energy.

Modal categories

The representational modes presented in students' interviews were formulas, graphs, and words. Students were interviewed on the use of these modes and the interrelations between them.

Characteristics of the use of formulas

48% of the interviewed students preferred to work with formulas as a first approximation in order to understand a topic. One of the reasons students prefer the use of formulas to the use of words, is their specificity. As one student explained,

> I: How you understand [a new topic] better, with a formula or a text?
> S: Usually with a formula, because sometimes the text in books is written funny, but mathematical symbols mean the same.

Some students preferred the use of formulas as a language in order to express or retain their ideas,

> S1: To understand I still need the formula. Helps things in perspective, formulas lay out what variables you have, and what will change. Formulas help to explain your understanding.
> S2: To see it in an equation form helps me to retain better [the idea]....

Other aspect of the use of formulas is that formulas reinforce students' conceptual understanding. Some students referred to formulas as an "evidence for your ideas"; as one student explained,

> S: The concept comes from the formula. I understand what's going on and the formula justifies it.

Students who operated with formulas, chose a specific formula "because matched the information given by the problem", and requested quantities be assigned to the variables of the formula in order to operate with them. Indeed, 72% of the students who used equations requested numerical values for the parameters involved in the formula of specific heat in order to demonstrate the difference in temperature change. However, 35% of these students got numerical results that contradicted their thoughts.

In some cases the use of formulas is preferred to avoid difficulties encountered with the written mode. In what follows three different students addressed issues related to the audience, or people that could read the text, to the reading, and to the reflection process required with the use of text.

> S1: To write is difficult because you need to put things in a way that people would understand while math is more concrete.
> S2: Is easier to use equations. I do not like English. Charts are easier than to read, it is visual and is not like reading books.
> S3: I like the formula most because for the formula the only thing that can go wrong is the math. But when you are thinking, you can confuse yourself by thinking. So the formula is probably better.

Characteristics of the use of graphs

Most of the students welcomed the use of graphs because of their visual aspect, and successfully responded to the questions that required their use (problems 3 and 4). 10% of the students failed in her/his graphical description of the rate of temperature change of two substances on a heating plate, in problem 3. 52% of the students viewed the use of graphs as "helpers for understanding" or as a way to be more accurate in their explanation of a physical process. When students used a graph they extended their response beyond what was asked in the problem. For example, 26% of the students described the rate of temperature change at and after the boiling point of the liquids on the heating plates. Indeed, some students claimed that graphs give a whole picture of the process, that "a graph helps understanding because you can see what temperature is doing all the time." 44% of the interviewed students referred to a graph as "thought provoking" leading to conceptual understanding.

The operation with graphs, as was displayed in these interviews, involved the identification of critical points (for example, in problems 4a and 4b the point at which both materials reach the equilibrium temperature), the assignation of a physical meaning to the slope of the graph, and the requirement for quantities (a data table). The identification of critical points required the integration of different modes, either by the use of equations (the specific heat and energy conservation equations was used by 60% of the interviewed students to calculate the equilibrium temperature) or by estimations based on the information given in the problem (e.g. the estimation of the equilibrium temperature based on the values of specific heats). In both cases students needed to assess the results obtained for these critical points. Here is an example of what a student said regarding problem 4a,

> S: Equations make sense when you calculate an amount and [you are] thinking about. Like the final temperature, needs to be between 473 K and 313 K. A graph helps you to see an idea in a visual form.

70% of the students correctly identified the specific heat dependence of the slope of the lines that represented the rate of temperature change in problem 3 (with larger slope corresponding to a smaller specific heat), and also assigned a constant slope to the lines corresponding to the constant heating rate of the heating plates. 10% of the interviewed students correctly identified the slope dependence with the specific heat but the explanation they gave for a constant slope to the lines in problem 3, was based on the constant value of the specific heat of the liquids, ignoring the heating process. 35% of the students made explicit, graphically and verbally, the difference between the slopes of the lines in problems 3 and 4 due to different heating processes. In one case, the function that described the rate of temperature change was linear (due to the constant heating rate of the heating plate, problem 3). A non-linear function was used to describe the temperature change rate in the calorimeter, because " I will assume that the rate will decrease as they [the metal and water] will get closer to the final temperature" (problem 4).

18% of the students that used a graph either ask or wrote themselves a numerical table for the dependent and independent variables, because "it will make the graph accurate." As one student explained,

> S: Graph is adding to understanding, depending how accurately the graph was done. If it is a quick sketch it does not help to understand, but if it is accurate I can look at it and will help.

Characteristics of the use of words

The use of words and text was explored as a tool for conceptual understanding in both, contextualized (problems 1 through 4) and de-contextualized problems (problem 5a, 5b, and 5c). 52% of the interviewed students claimed that conceptual understanding comes first by using words. Their conceptual understanding of the topics was mostly based on the use of words. Only 10% of the interviewed students based their explanations on the values of the specific heats given by the problem omitting a conceptual response, while 13% of the students used analogies for explanations. Following is a transcription of how a student used an analogy to answer problem 3ii) referring to the difference in the specific heats of liquids A (higher specific heat) and B (lower specific heat) and the effect on temperature change,

> Liquid A "holds" more energy per mass than B. This is analogous to two similar airplanes, airplane A differing in that it has more seats. More people fill the plane and thus take-off is slowed.

An alternative use of words as a working mode is the use of de-contextualized problems, in which concepts are probed out of a physical context. 83% of the students who were interrogated on the usefulness of de-contextualized problems, such as problem 5, answered that this type of problem helps in their conceptual understanding, either because it forces them to reflect on what they do and do not understand ("helps me to know what I do not understand") or because "... if you see the concepts together, you can compare them and connect all of them."

Interrelations between different representational modes

Formulas and words

Formulas and conceptual understanding expressed through words are tightly related or "complemented" as was claimed by the interviewed students. In particular, formulas can unveil relations between variables that were ignored at a conceptual level. As an example, 13% of the students were not able to distinguish heat from temperature at a conceptual level, but they successfully explained the difference in temperature change between the metal and water when using the specific heat equation. Nonetheless, there appears to be a hierarchy between numerical results derived from the use of formulas and conceptual understanding as displayed by the fact that the students who obtained numerical results that contradicted their ideas about the change in temperature (18% of the interviewed sample) disregarded the numerical results.

Formulas and graphs

Most students viewed the use of graphs as complementary to the use of formulas; for many students, graphs "back up formulas." However, 30% of the students indicated that graphs add in their understanding of formulas. As one student explained,

> S: It is easier to graph than to deal with formulas. You can visualize better. Think how the temperature will change, plot this in a graph and after graphing come out with a formula.

At the same time, 18% of the students viewed graphs and formulas as two unrelated representational modes, "as independent from formulas." The relation between formulas and graphs emerged in two ways. One way refers to the use of formulas in order to make a graph, as in the case of critical points of a graph (discussed above), while the other is related to the translation of a formula into a graph. Although 30% of the students recognized that the lines of the graph should be related to a physical formula, only one student out of 23 was able to propose a formula that relates the temperature change with time (problems 3 and 4). The interviewed students had no difficulty in assigning a mathematical equation to the lines in problem 3, but were not able (with exception of one) to explain the equation in physical terms.

Graphs and words

As was discussed above, graphs are mainly viewed as conceptual tools; graphs "reflect my thoughts." However, 2 students out of 23 drew graphs that contradicted their conceptual explanation of thermal equilibrium by extending the lines that represented the temperature change for both substances in the calorimeter beyond the equilibrium temperature. On the other hand, students who ignored the difference in rate of temperature change of the substances in problem 1b (9% of the interviewed sample) correctly estimated the final temperature (closer to the initial temperature of water, showing that the temperature of water changed in a lesser amount) when drawing a graph.

The last problem of the interview was formulated in terms of bar charts. Although the problem aimed to ask about the change in temperature and internal energy of two objects in an insulating container, five out of the six students that tried to solve this problem, viewed it as an ill-defined problem. In an ill-defined problem the problem is not clear, therefore, finding a solution requires finding first what the real problem is (Newell and Simon, 1976). Only 26% of the interviewed students (six students) reached problem 6 within the time of the interview and one was able to solve it successfully. In this context, students contradicted their previous statements in such ways as: a) energy transfer between bodies A and B had the same sign and different magnitude (33% of the students that did problem 6), b) equal initial temperature for bodies A and B respectively, but different final temperatures (33%), c) no energy transfer but equalization of the final temperature given different initial temperature for A and B (50%).

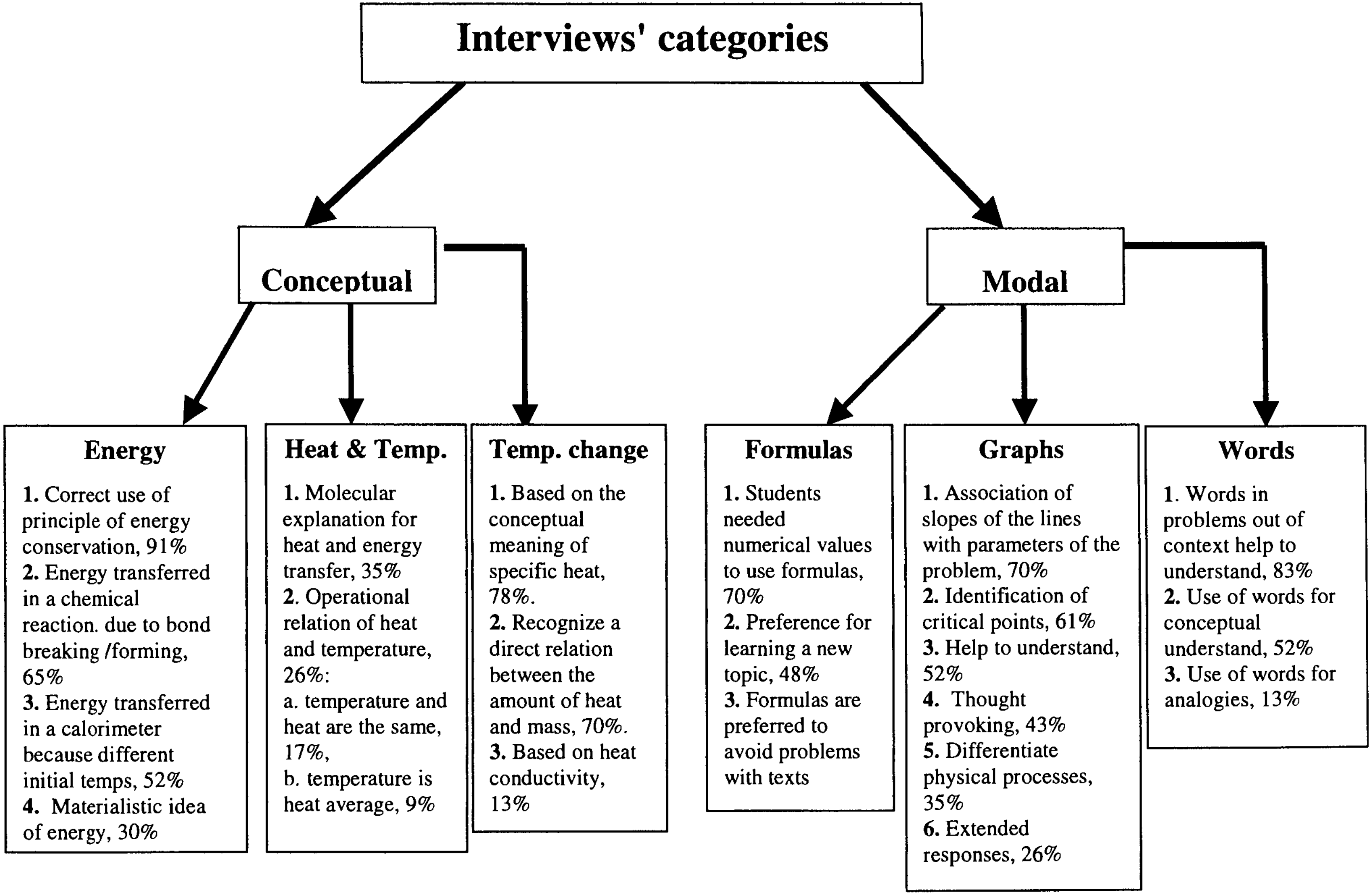

Fig. 2 Diagram summarizing the conceptual and modal categories emerged from the interviews. The main trends within each category are indicated, along with the percentage of students that addressed them.

Table 2. Triangulation of students' and instructor's interviews subcategories.

Students' Categories	Instructor's Categories
Better understanding of temperature change and energy transfer, in the case of hot metal in cold water because the system is simple and variables can be identified.	Emphasis on the difference between a physical process and a chemical reaction.
Conceptual meaning of specific heat for explaining difference in temperature change.	Hot metal in cold water: discussion of the meaning of specific heat.
Direct relation between heat and mass through the specific heat equation.	Manipulation of the variables of the specific heat equation such as the mass of the substance.
Identification of bond breaking-forming as the temperature change source.	Chemical reactions: difficulties with the source of heat and the mass of the reaction
Formulas are the favorite mode of work to introduce a new topic	The class is mainly focused on problem solving skills, while try to integrate both concepts and problems.
Changes in temperature are equal because heats gained and lost are equal.	Difficulty in distinguishing between heat and temperature.
Molecular explanation of temperature and energy transfer.	Use of the molecular model to explain what is temperature in simulations.
Not able to operate with ill-defined problems.	Not enough ill-defined problems in the lectures, only two open inquiry labs in the whole course.

Trends from the quizzes

Problems 1, 2d and 2g of the quiz (see Appendix I) were analyzed in order to explore whether there is any relation between the mode of work and the displayed conceptual understanding of a topic. A chi-square test was performed in problems 1 and 2g, to test if the operational mode, (variable O) was independent of the type of explanation (variable E). The categories of the operational mode variables were "verbal" or "equation," referring to the use of text or formulas to approach the problem, while the categories of the explanatory variable varied depending on the problem. The analysis of standardized residuals was performed for problems 1 and 2g, in order to identify the related categories between the two variables. The observed and expected frequency tables, and the analysis of standardized residuals for each problem are presented in the Appendix III. A summary of the results is presented in Table 3a, Table 3b, and Table 3c for problems 1, 2d, and 2g, respectively at the end of this section. Examples of the coding sheets containing the subcategories of the explanations are included in Appendix Iva, and Appendix IVb for problems 1, and 2d respectively.

Results from Problem 1

The categories of operational variable were: "verbal" and "equation." For the explanatory variable the categories were: Gf, meaning "good functional" and corresponds to correct explanations based on the conceptual meaning of specific heat; Gp, meaning "good parametric" and corresponds to correct explanations based on the given values of the parameters of the problem omitting any reference to the relation between the specific heat and temperature change; W, meaning wrong explanations, and N, referring to no explanation.

The observed frequency table for problem 1 (Appendix IIIa) indicates that 81% of the sampled students (89/110) approached the problem using words. 39% of these students gave a parametric explanation, 30% gave a conceptual explanation based on the meaning of specific heat, and 28% gave a wrong explanation. Only 2% of the students that approached problem 1 using words avoided an explanation. 52% of the students that approached the problem using equations answered correctly based on the values of specific heat for water and copper (good parametric), 19% gave conceptually rich explanations, while 14% either gave incorrect explanations or did not complete the explanation part. Apparently there is a larger tendency to omit explanations among the students that preferred equations than for students that used words.

The result from the chi-square analysis indicates that there is a marginal dependency between the operational and the explanatory variables in problem 1. The probability to fail in the rejection of the null hypothesis was 0.043. Also, the obtained discrepancy between the observed and expected frequency distribution is marginally higher than the discrepancy obtained when a probability of 0.05 of failing to reject the null hypothesis (α) is tolerated. The residual analysis shows dependence between the use of text or equation with the omission of explanation. Students that approached the problem using equations tend to omit, more than what is expected, the explanation.

Results from Problem 2d

The operational categories of problem 2d were V and E corresponding to "verbal" and "equation," respectively. The explanatory categories were based on the physical concepts included in students' responses. For examples of these categories, please see Appendix IVb. The main categories are,

Category I: correct use of principle of conservation of energy, and the concept of thermal equilibrium

Category II: confuse temperature and heat

Category III: confuse thermal equilibrium and the specific heat equation.

A category is such that it includes more than 5% of the total sample (111) responses. Therefore, categories for which there were fewer than 5% responses were excluded from the statistical analysis, and the resulting sample of problem 2d consisted of 89 quizzes out of 111. The observed frequency table for problem 2d (Appendix IIIb) indicates that 91% of the students approached the problem using words, 69% of these students gave a category I explanation, while 18% displayed some confusion regarding heat and temperature (category II), and 12% of the students are confused about the specific heat equation (category III). The overwhelming use of text to approach problem 2d can be due to the way in which it was formulated asking for what students think about the change in temperatures (see Appendix I). This type of question stimulates a response using text interfering with the statistical assumption that the operational variable has a priori an equal probability to be "verbal" or "equation". Therefore a statistical analysis is not appropriate in this case.

Results from Problem 2g

The operational categories of problem 2g were V and E corresponding to "verbal" and "equation," respectively. The explanatory categories are based on the physical concepts included in students' responses. The main categories are the following,

Category I: correct use of the principle of conservation of energy, and the relation between heat and mass

Category II: confuse temperature with heat

Category III: ignores the effect of the mass in the specific heat equation

The criterion for the inclusion of a category is as before (more than the 5% of the total sample responses), and the resulting sample of problem 2g was 93 quizzes out of 111. The observed frequency table for problem 2g (Appendix IIIc) indicates that 91% of the sampled students approached the problem using words, of which 53% answered and explained correctly relating mass and energy transfer and its effect on the temperature change. 22% of the students who approached the problem with words omitted the explanation. 9% of the sampled students approached the operational part of the problems using formulas; 50% of them did not complete the explanation part. The result from the chi-square analysis indicates that both, O and E variables are independent for problem2g. Indeed, the probability to failing to reject of the null hypothesis is 0.127 and the obtained discrepancy of the chi-square distribution is much smaller than the tabulated discrepancy for $\alpha=0.05$.

Table 3a. Frequency distribution of operational and explanatory variables for Problem 1

Mode	Explanation*
Verbal: 81% of the total sample	39% (parametric) 30% (functional) 28% (wrong) 2% (none)
Equation: 19% of the total sample	52% (parametric) 19% (functional) 14% (wrong) 14% (none)

Table 3b. Frequency distribution of operational and explanatory variables for Problem 2d

Mode	Operation*	Explanation*
Verbal: 91% of the total sample	69% correct answers	100% Category I
	31% incorrect answers	60% Category II 40% Category III
Equation: 9% of the total sample	50% correct answers	100% Category I
	50% incorrect answers	100% Category II 0% Category III

*. The percentages reported in these columns are relative to the population of the previous column

Table 3c. Frequency distribution of operational and explanatory variables for Problem 2g

Mode	Operation*	Explanation*
Text: 91% of the total sample	53% correct answers	75% Category I 25% None
	47% incorrect answers	12% Category II 72% Category III 16% None
Equation: 9% of the total sample	87% correct answers	43% Category I 57% None
	13% incorrect answers	100% Category II

* The percentages reported in these columns are relative to the population of the previous column

CHAPTER 4: CONCLUSIONS

Conclusion from the interviews

Heat and Temperature

Two main ideas are embodied in calorimetry: the principle of conservation of energy applied to heating of different bodies, and the idea that heat is linked to temperature change (through the specific heat equation). These ideas, which only include heat and temperature, could imply some sort of equivalence between them as was claimed by 65% of the interviewed students. Two main arguments for supporting equivalence between heat and temperature emerged from the interviews: one is through an operational relation between them ("temperature measures heat," 20%, and "temperature is heat average," 10%); while the second is based on the nature of heat and temperature, both associated with molecular motion (35%). Both notions could imply that heat is a property of a substance instead of transfer of energy: in the first case, the materialistic idea is indirect (temperature is an intensive property of a substance, therefore if heat is like temperature, heat is also a substance characteristic), while in the second case heat is a directly associated with matter through the motion of its molecules. Indeed, many researchers (Erickson, 1980; Guesne, 1985; Fuchs, 1987; Rogan, 1988) agree that physics and chemistry novices have a materialistic concept of heat that resembles the "caloric theory." The dominant theory of heat at the beginning of the 19th century treated heat as a substance (caloric) that flowed from a hot to a cold body. Under this theory, temperature was a measurement of how much "caloric" a body contained. This theory was abandoned when it was observed that mechanical work[6] on a body could raise its temperature, or more formally, an equivalence between mechanical work and heat was found[7] .

Moreover, the apparent materialistic nature of heat accommodates in students conceptual frameworks of thermodynamics for the examples treated in lectures. In the case of two substances in the calorimeter at different initial temperatures, the microscopic theory of temperature explains the process of temperature change, which in some cases was thought as equivalent to heat. This confusion between the microscopic idea of temperature and its further extrapolation to the concept of heat could result from working with microscopic and macroscopic thermodynamics contexts at the same time, as was indicated by several researchers (Se-Yuen and Young 1987; van Roon et al.,1994; Loverude et al., 2002). While, from the use of chemical reactions as examples, interviewed students responded, "When bonds form and break, molecules move." This idea of heat as a substance's property seems very resistant to change. Students that held this conception successfully operated with the specific heat equation, as was also found by Gabel and Bunce (1994). However, when students were asked to compare heat and temperature in contrasting pairs (problem 5 of the interview) most of them established a sort of equivalence between these concepts. When the interviewer asked about the units used to designate heat and temperature, all the students recognized that they are different but could not resolve the conflict between the equivalence of the concepts and the difference in the units. The strong commitment that college students have to a

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[6] Initial observations were carried out by Count Rumford, in which he noticed that friction occurring when boring cannons increased their temperature.

[7] The quantitative equivalence was discovered by Joule.

materialistic idea of heat was also found by other researchers (Fuchs, 1987; Reiner et al. 2000) as well as the idea that heat and temperature are interchangeable (Wiser and Carey, 1983).

When introducing the First Law of thermodynamics, in which heat is related to the difference between the change of internal energy (referring to kinetic and potential energies at a molecular level) and mechanical work, heat can be seen as the balance resulting from the interplay of different types of energies in a given system and as a transfer of energy. Another situation that clearly shows the difference between heat and temperature is when changes in the phase of a substance take place. In this case heat is added to the system without temperature change but with a change of state[8]. Although calorimetry has the advantage of being very "concrete" in terms of simple laboratory experiences, it could lead to the simplistic idea that heat and temperature are equivalent. Indeed, van Roon and collaborators (1994) named thermochemistry as a "proto-thermodynamic" context in which work and heat are not related, and heat can be explained by a materialistic notion. While in a thermodynamic context, the idea of heat as energy change is reinforced because of the First Law of Thermodynamics, which relates heat and work. A more elaborated meaning of heat requires other frames in which the concept of system, and diverse type of energies are in place. Systems in calorimeters (as used in college courses and texts) represent a particular example of the energy conservation principle, and of the causes for a substance's temperature change.

The use of representational modes

The study of physics and chemistry relies on the use of symbolic representations. As was indicated by some of the interviewed students and by numerous research studies, symbolic representations are not only carriers of meaning but also they may serve to catalyze improved understanding of a concept (van Heuvelen and Zou, 2001; Radford, 2000; Fosnot, 1996; von Glasersfeld, 1987; Posner at al. 1982). The ability to transfer between different representational modes is associated with the capability of problem solving. Indeed, good problem solvers tend to be flexible in the use of a variety of symbolic representations switching to the most convenient in order to emphasize a desired characteristic during the solution process (Lesh, et al. 1987), or because some representations more efficiently show quantitative relations (Kaput, 1987). Also, the manipulation of representational modes and translations are relevant in understanding scientific models (Janvier 1987; Hestenes, 1996). Models require a "representational phase," in which relevant characteristics of the referent are identified and there is a correspondence between the original situation and the representational mode(s), and a "translation phase," in which the model is probed in conditions different than the original ones in order to make viable predictions.

In the present study, the use and transfer between graphs, formulas and conceptual understanding expressed with words, were tested. As is reported in the diagram of

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[8] This process is the reverse of the chemical reaction, in which two substances of equal temperature react producing heat that changes the temperature of the product.

“Trends from Interviews” section, the main trends emerging from student’s interviews were:

a) Graphs contribute to conceptual understanding of the system as a whole
b) Words contribute to conceptual understanding of specific elements
c) Formulas are preferred to learn a new topic
d) Although formulas are easier to use than words, both are strongly connected
e) Students displayed an unclear understanding of the connection between physical formulas and graphs.

Conclusions from studies of expert/novice differences in mastering scientific concepts strongly rely on the differences in the organization of structures of knowledge (DiSessa, 1983; Glaser, 1990). Experts take and use information in chunks that require organizing and integrating knowledge in patterns, while novices rely on individual pieces of information of the system elements (McDermott, 1984; DiSessa 1988; Glaser, 1990). In general, experts use qualitative representations, such as graphs, pictures, diagrams and bar charts, in order to understand a problem, while novices use formulas to approach a problem (Plotzner, 1994). The use of modes that promote conceptual integration could contribute to scaffolding students' expertise in science. Therefore, the use of graphs as a way to integrate information about the system under study is desirable.

Highly organized structures of knowledge require the recognition of the fundamental principles that underline diverse pieces of information. Experts initially approach problems from a qualitative perspective prior to the retrieval of equations, while novices rush into quantitative manipulation of formulas (Larkin et al., 1980). Therefore, emphasis on conceptual aspects of a problem could be very beneficial to scaffold novices into expert levels.

Interviewed students had a good predisposition to the use of graphs, and used them effectively for conceptual reasoning. Indeed, van Heuvelen and Zou (2001) recommend introducing qualitative representations before mathematical equations. However, in most of college science courses the use of formulas and the ability to solve problem through their correct use is the main goal of instruction. Formulas should result from conceptual understanding, as a way to display variables and their relations in a non-ambiguous and with a condensed language. Deeper understanding requires the use and transformations between formulas, graphs, and texts (written or oral) in order to achieve highly organized structures of knowledge. As students indicated in the interview, formulas are easier than the use of words, "…when you get to think you can confuse yourself"; apparently the mere use of formulas could reduce conceptual thinking.

The interviewed students had difficulty to associate graphs with physical formulas, although they were able to translate concepts into the graph (e.g. different slopes corresponding to different specific heats). This could indicate that the transfer between formulas and graphs is an indirect transfer (Janvier, 1987) requiring more than two representational modes such as formulas-words-graphs. However, students and instructor indicated that different representational modes were introduced in different contexts: the use of formulas and some conceptual remarks were used in lectures, while the use of graphs was mostly limited to the lab. The association of representational modes to specific contexts could interfere with the ability to integrate them.

The problem of ill-defined problems

Ill-defined problems are problems in which the given information is vague and in general are different problems than those for which solutions follow a pattern. Interviewed students displayed a very low proficiency in dealing with these types of problems. In particular, students found the presentation of a bar chart to report the information of the problem "very confusing." Their reasoning and predictions derived from this representational mode conflicted with previous results obtained for a similar physical problem when using different representations. The difficulty encountered with bar charts in the context of thermochemistry contradicts the findings of van Heuvelen and Zou (2001) on students' deeper understanding with the use of bar charts in an introductory classical mechanical course. This can be an indication that the chemistry students have a poor understanding of the energy conservation principle (the represented concept) or of the use of bar charts.

An effective way to develop problem-solving and critical thinking skills is through the use of ill-defined problems because it requires the evaluation of different possible paths to find a solution to the problem (Reed, 2002). The way experts proceed with ill-defined problems can be summarized as follows: a) choice of plausible constraints, b) imposing values on the parameters of the problem, c) search for analogies, d) identify the fundamental principles that underlie the problem in order to pursue similar solutions of well-defined problems (Glaser, 1990). Therefore, a class practice that is based on the implementation of these steps could facilitate the ability to solve ill-defined problems. In particular, it can be desirable to use schematic and conceptual representational modes, such as graphs or diagrams, for which constraints and values of parameters are not critical for their use. The approach to ill-defined problems exposes students to practices that encourage the organization of knowledge structures based on fundamental principles, and the transfer between known and novel situations. I strongly believe that the ability to solve ill-defined problems closely resembles the scientific thinking, stimulating creativity.

Conclusions from the quizzes

The purpose of the quizzes was to test students' understanding of the basic ideas of calorimetry: the principle of conservation of energy within the calorimeter, and the relation between heat and temperature change through the application of the specific heat equation in relation to the working mode. Working modes (equation, text or graphs) were not specified in the problems and students had the freedom to choose any one. From the analysis of the quizzes the following can be concluded,

1. Most of the sampled students approached the problems of the quiz verbally: 81% for problem 1, and 91% for problems 2d and 2g.

2. The use of words or formulas could depend on the formulation of the problem Questions that focus on students' opinions or thoughts could imply the use of text. An example is question 2d of the quiz, which targeted the use of the principle of conservation of energy along with the specific heat equation; nonetheless, 91% of the students answered using text.

3. The use of words or formulas could depend on the ability to integrate "new knowledge" (through accommodation or assimilation) with prior knowledge. Question 2g intended to test students' understanding of the effect of the mass on heat and temperature change. Although question 2g was formulated similarly to question 1, 10% more students used words here than in the first problem. For problems 1 and 2g, 69% and 53% of the verbal answers were correct, respectively. Both problems require the use of the specific heat equation, however students indicated that they were not as familiar with the idea of the dependence of heat and mass, as with the idea of temperature change in relation to heat. Indeed, 22% of the verbal responses to problem 2g lacked an explanation, while only 2% for problem 1. Also the language that students used to explain problem 2g was less specific than in the case of problem 1. Despite the fact that the quiz was given two weeks after instruction on calorimetry in lectures, the specific heat equation and the relations implied by its parameters seems to be new to most students. Apparently novice students approach problems using words first, unless an equation is explicitly requested. The inclusion of a formula in the response requires recognition of formulas as tools for conceptual understanding, and this seems to occur with ideas that are familiar to students.

4. The independence of the explanatory (E) and operational (O) variables depends on the topic of the problem. If students are familiar enough with the topic, as in problem 1, some of them will explain the functional relations implied by the formula, and the use of words will lead to richer explanations than the mere use of words without the notion of the formula. Once the formula is used, the use of text could lead to higher conceptual understanding. In that case, a marginal dependency between the O and E variables could be found because the operational variable would correspond to a stage in understanding. The use of words could correspond to students that either understand the topic very well and can formulate explanations based on the idea implied by the formula, or to students whose understanding is rather basic and has not reached the formal stage (pre-formula). Students who used a formula to answer the problem reached a formal operational level, but not necessarily a deep understanding of it. Therefore, in this case the mode of operation could correspond to a depth in understanding. On the contrary, if the topic is new to the students, as in problem 2g, most of them are in the first stages (pre- or formal operation); the operation is mostly verbal but does not corresponds to the internalized meaning achieved after the abstraction of the formula. In that case how students approach a problem does not reflect a deeper conceptual understanding and the E and O variables are independent.

5. The use of equations tends to diminish the inclusion of explanations. For both problems 1 and 2g students who used words have a lesser percentage of omitted explanations than students who used equations to approach the problems. In problem

1, the percentage of omitted explanations was 2% and 14% for the use of words and equations respectively, and in problem 2g, 22% and 50%. This situation could be due to the fact that the students that used equations reached a formal stage but not deep conceptual understanding, derived from "reading" of the formula. Therefore, richer explanations can be found in students that approached the problem verbally. An example can be found in problem 1, in which "functional" explanations were distributed as follow: 19% in equation responses, and 30% in the case of verbal responses. Students that rely only on formulas apparently see them as the justification of their thoughts (see in Results from the Interviews/Modes Categories).

Stairway Model for Conceptual Understanding

Symbolic expressions (as formulas) are abstractions of meanings derived from concrete experiences and students' prior knowledge. Experiences are the referent to be represented seeding the ground for further higher order abstractions that lead to different representational modes, such as written or verbal texts, reading, graphing and formulas. The transition between the naïve verbal descriptions of experiences to the codification in a symbolic expression requires identification of the elements of the experience and their mutual interactions, with symbols and operations. This correspondence process constitutes an abstraction. Progressing in understanding implies explaining the meaning of a symbolic expression and "re-covering" the ideas fostered by the concrete experience. This internalization of meaning is critical in order to achieve a structural knowledge of a topic as experts do. The internalization of meaning takes place after a process of synthesis similar to the mechanism of production of utterances (Galbraith, 1999). Only when the learner can verbalize the "story" of the symbolic expression, conceptual understanding is increased.

Translations between verbal, symbolic (here referring to mathematical notation and graphs) and verbal again, in the re-conceptualization stage, iterate. A model of this iterative process, the Stairway Model, is presented in Figure 3. Each iteration represents a higher abstraction level. The transition from verbal to symbolic requires an abstraction, while the transition from symbolic to verbal stages requires a synthesis that produces a deeper understanding of the referent. The higher conceptual status achieved by the textual recovery of the symbolic expression implies a hierarchy between results obtained from the use of formulas and students' conceptions. As was indicated before (see Results/ Trends from the interview) students will commit to their ideas if they contradict their numerical results.

The transition from a verbal expression to a symbolic one requires an abstraction that increases the organization of knowledge. The symbolic stage (and re-conceptualization stage associated with it) in each abstraction level corresponds to a larger structure of knowledge, ranging from a single formula in low levels to reach the formulation of a model in higher abstraction levels. The role of science instruction should be to stimulate students through the stairway of deeper understanding and higher levels of abstractions.

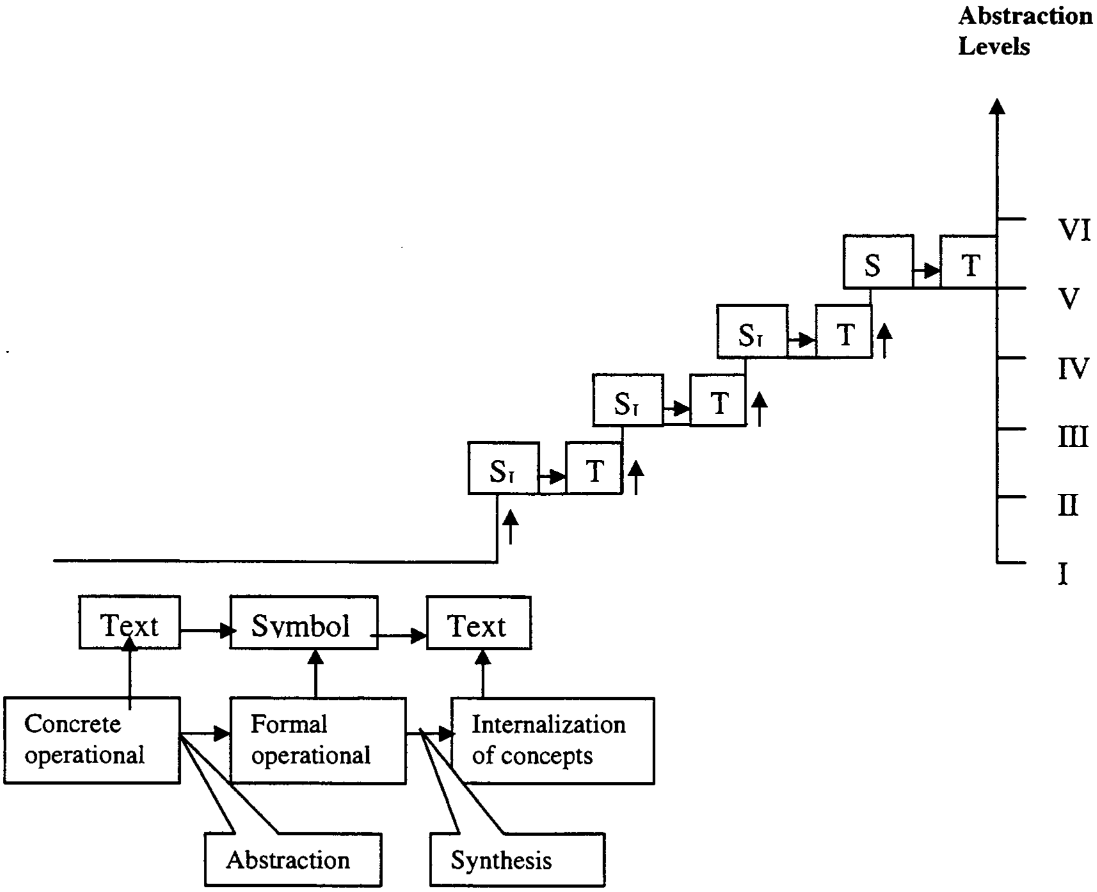

Figure 3. Stairway Model for conceptual understanding. The transition from textual (here the same as verbal) to symbolic expressions requires abstractions, while from symbols to text requires a synthesis. S_i (i=I, II, ...) corresponds to the symbolic expressions of different abstraction levels.

Limitations of this study

Difficulty of combining interviews and quiz results

Interviews and quizzes are two different methods, each of them with benefits and limitations of their own. Interviews allow an in-depth exploration of students' thoughts and emotions, and the effect of the researcher's perception of interviewee's discourses can be minimized through clarification questions during the interview. Although a researcher can have an agenda for the interview (semi-structured interview) the outcome is less predictable. On the other hand, quiz outcomes are more specific but the impact of a researcher's perception on students' responses cannot be avoided. Nonetheless these methods are different in nature, and they complement each other. A comparative list of interview and quiz problems is included in Table 4 at the end of this section, in which problems are matched regarding different working modes of the same calorimetry topic. A weakness of this study is the difficulty of combining both interview and quiz results, because it fails to fulfill some methodological conditions

1. Comparable students' grades distribution between interview and quiz populations. Students' grades were very different between two samples. Interviewed students mostly had high grades, while for the quizzes, students' grades displayed a broader distribution. This interferes with the possibility of drawing conclusion from interviews and quizzes altogether, because the proficiency that students displayed in the use of a specific mode could be due to their higher level of achievement and not to an attribute of the mode itself.

2. Comparable instruction for students that participated in the interviews and quizzes. Although interview and quiz populations attended lectures given by the same instructor two semesters apart, the instruction of both groups is quite different. The quiz was given two weeks after a lecture on calorimetry, but for many students, before the laboratory session, while all the interviewed students completed their calorimetry laboratory experiment a few weeks before the interview.
3. Comparable time on task. Quizzes were completed during 20 minutes in lecture; while interviews lasted up to one hour, and each student worked on each problem on her/his own pace.

Problems arising from the design of the research tools

1. Awareness of the impact of the context of the research tool (quiz or interview) on individual problems. Issues like the order of problems in the research tool, based on the same topics and requesting different working modes, could impact the proficiency displayed in the responses. Therefore, the design of the order of the problems in the research tools and the inclusion of the variable "order" in the statistical analysis is recommended.
2. Include questions that specify the working mode (in the quiz) in order to have a better matching between quiz and interview problems.

Problems arising from the student's sample

The results found in this study are based on college students' ability to solve problems in thermochemistry. Most of these students are engineering or life science majors and constitute a limited portion of the learning population. In particular, the interviewed students are high achieving students with a relative total score of 80% and up. This characteristic of the sampled population does not allow generalization of the results concerning the use of representations and conceptual understanding of calorimetry to the general learning community of non-science students.

Table 4. Correspondence between interview and quiz problems for calorimetry concepts but requiring different working modes.

Interview	**Quiz**
3 (graph)	1 (text or formulas)
1b (text) 1c (formula) 4a (graph)	2d (text)
4b (graph)	2g (text or formula)

Future study

a) Replicate this present study improving the experimental conditions and design of the research tools based on the points discussed above in order to integrate both interview and quiz results.

b) Quantify the parameters that are involved in the Stairway Model and test their sensitivity.

c) Replicate this study (with improved design of the research tools) to probe the Stairway Model for conceptual understanding in different areas of physics (thermodynamics, mechanics, etc…) and for different levels of students' expertise.

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APPENDIX I: PROBLEM SET ON CALORIMETRY

The specific of water is 4.184 J/g C and the specific heat of copper is 0.71 J/g C

1) Consider equal masses of water and copper at the same initial temperature. If we add 100 Joules of heat to each (water and copper), which will achieve the highest temperature? Explain.

   Copper will achieve the highest temperature because it has lowest specific heat, meaning it requires less energy to increase in one degree centigrade one gram of mass.

2) Copper metal of mass m_1 at temperature T_C is placed in a calorimeter which contains water of mass m_2 at temperature T_W, where T_C is less than T_W. The calorimeter is really made of good insulating material and it has a lid. Assume that no energy transfer occurs between the walls of the calorimeter and the water. There is no energy transfer between the calorimeter and the room where it is located.
   a) Draw a diagram of the system. Identify its components.

   b) Do you expect a change of the water temperature (ΔT_W)? If so describe the change.

   c) Do you expect a change of the temperature of the copper metal (ΔT_C)? If so describe the change.

   d) Do you think that there is any connection between ΔT_W and ΔT_C? Explain your answer.

   Yes, the temperature change of water is related to the temperature change of cooper because both are in contact in an insulating container. The amount of heat gained by the copper is the same as the amount lost by the water, therefore water temperature change is,

$$\Delta T_W = (c_{pC}/c_{pW})\, \Delta T_C$$

   with c_{pC} and c_{pW} specific heats of water and copper respectively.

e) If a transfer energy occurs: What type of energy is it? Is this energy different than ΔT? Explain which object or objects are gaining energy and which object or objects are loosing energy. If no energy transfer occurs, explain how you know.

f) Would you expect a change of the total energy of your system as the time goes on? Why?

g) In a second experiment and double the amount of water, keeping the initial water temperature the same, and the mass and temperature of the copper the same. What would you expect ΔT_W of this experiment to be: MORE THAN, LESS THAN or THE SAME with respect to ΔT_W of the first experiment? Explain.

Less. The ratio of temperature change of water to copper will be half with respect to the ratio in the first experiment because there is more mass (twice as much) per Joule to change the temperature.

h) In a third experiment and double the amount of water, keeping the initial water temperature the same. We use a different piece of copper metal at the same initial temperature, and we observe a change in the water temperature ΔT_W, is the same as in the first experiment. What is different about the new piece of copper metal? Be as exact, write a formula if you can.

APPENDIX II: INTERVIEW QUESTION ON CALORIMETRY

The specific heat of water is 4.18 J/g °C, and the specific heat of copper is 0.71 J/g °C.

1) A calorimeter is made of very good insulating material and it has a lid. We can assume that no energy transfer occurs between the walls of the calorimeter and any material contained within it, and also that there is no energy transfer between the calorimeter and the room where it is located.

A piece of copper metal is put into a calorimeter which is partly filled with water. The mass of the copper is the ***same*** as the mass of the water, but the temperature of the copper is ***higher*** than the temperature of the water. The calorimeter is left alone for several hours.

a) Does energy transfer occur? Please explain your answer.

Yes, energy transfer occurs between copper and water because these substances are in an insulating container at different initial temperatures.

b) Is there a temperature change in either the copper or the water, or both? If no, explain why not. If yes, is the temperature change of the copper greater than, less than, or equal to the temperature change of the water? Please explain your answer.

There is a temperature change in both, water and copper because the energy gained by one substance is equal to the energy lost by the other. Cooper will change its temperature the most because it requires less energy to change in one degree one gram of mass, as is indicated by its lower specific heat relative to the one of water.

c) Try to give a mathematical justification for your answer to parts (a) and (b). That is, use a relevant equation in each case and explain how the mathematics proves your answer.

a) In a calorimeter there is no heat transfer with the exterior then:

$$Q_W + Q_C = 0 \Rightarrow Q_W = -Q_C$$

b) Using the specific heat equation:

$$mc_W \Delta T_W = -mc_C \Delta T_C \Rightarrow \Delta T_C = -(c_W/c_C)\, \Delta T_W$$

2) In an insulated constant-pressure calorimeter with negligible heat capacity, hydrochloric acid solution is combined with ammonia solution. The temperature of the combined solution is observed to rise several degrees.

(a) Explain what causes this increase in temperature.

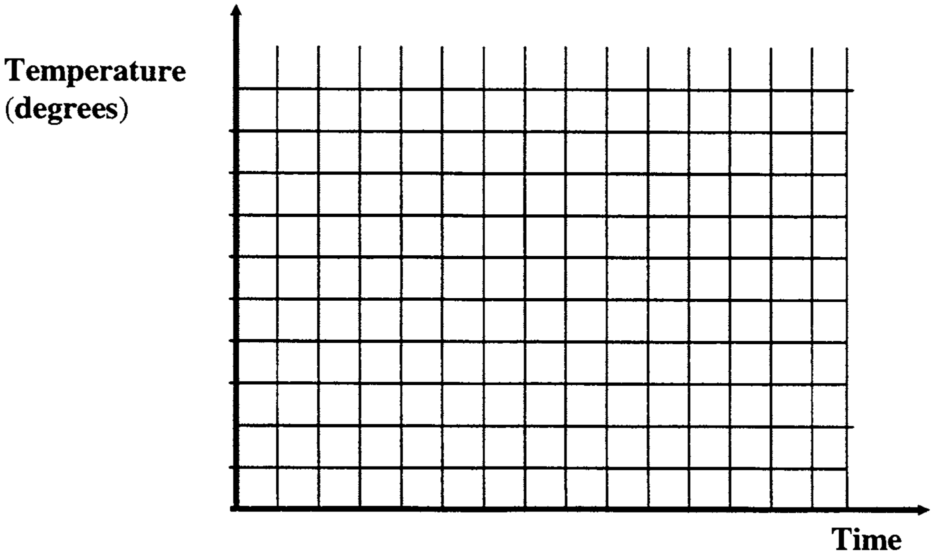
The chemical reaction causes the temperature of the combined solution to increase.

(b) Is there any energy transfer during this process? Please explain.

Yes, the energy transfers from the reactants to the combined solution; the bond forming process releases energy.

3) Suppose we have two ***separate*** containers each containing ***different*** liquids with different ***specific heats***, liquid A specific heat is three times bigger than the specific heat of liquid B, but with the same mass and initial temperature. Each container is placed on a heating plate that delivers the ***same rate of heating*** in joules per second to each liquid.

i) Below please graph the temperature of each liquid as a function of time.

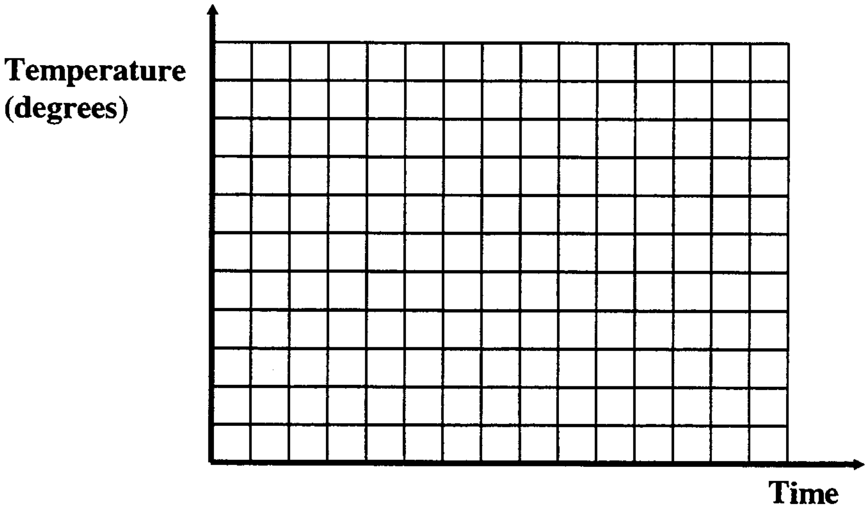


ii) Please explain the reasoning that you used to determine how you chose to draw the graph as you did.

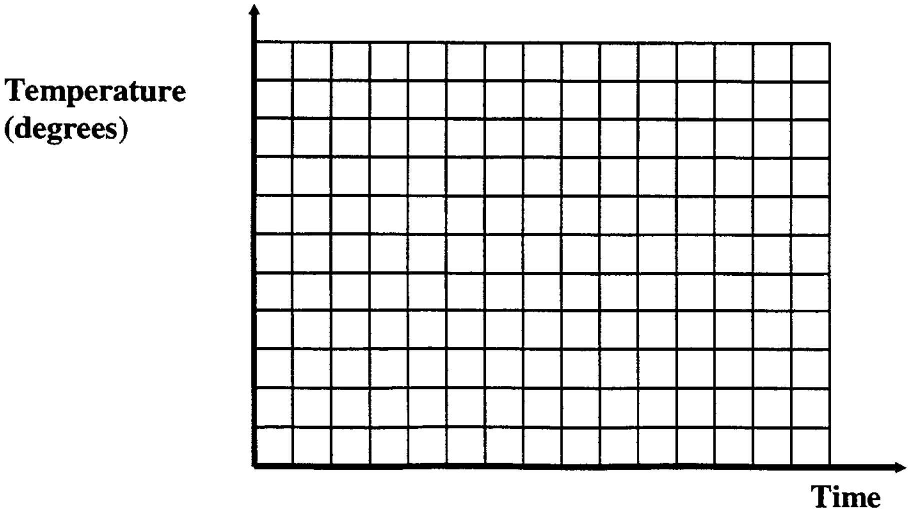
(Graph before reaching the boiling point: two straight lines with different slopes: line B has a slope three times larger than line A). The rate of the increment of temperature is constant due to the heat plates delivering the same rate of heating. Line B has a slope three times larger than A because substance B increases its temperature three times faster due to the fact that its specific heat is three times lower than the specific heat of A.

4) Suppose that a mass of copper is heated to 473 K initial temperature. Suppose then that is placed in a insulated container of water that is at 313 K initial temperature.

a) Graph the temperature of the copper and water if they both have the ***same mass***.



b) Graph the temperature of the copper and water if the mass of the copper is ***double*** that of the water.



5) Please briefly compare and relate to the best of your understanding the following concepts:
    a) Enthalpy and Heat

    Enthalpy is heat transferred under constant pressure. Enthalpy is a state function, meaning does not depend on the way the heat under constant pressure was transferred but on the initial and final values. Heat is energy transfer and it is not a state function.

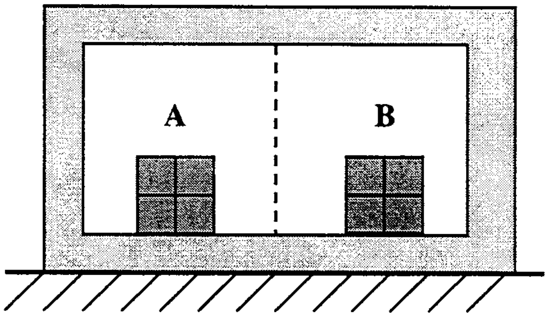
    b) Heat and Temperature

    Heat is energy transfer, and depends on the amount of substance. Temperature is related to the kinetic energy of the substance's molecules and is independent of its amount.

    c) Specific heat and Heat

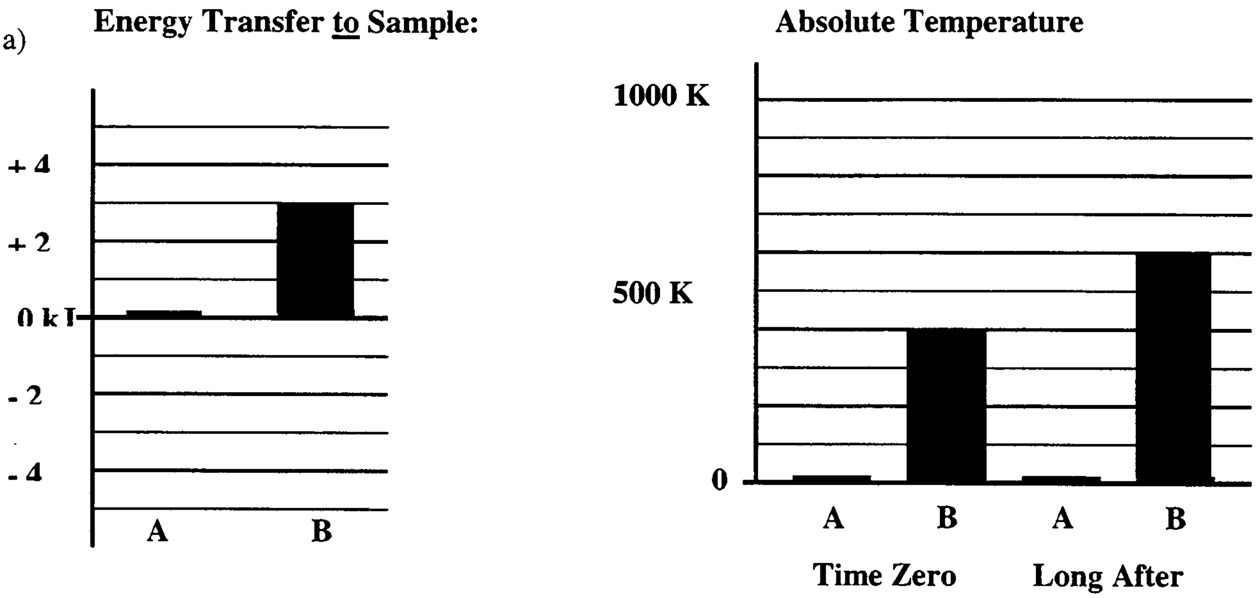
    Specific heat is a property of a substance, indicating the amount of energy needed to change one degree of temperature of one gram of mass. Heat is proportional to the specific heat as is shown in the specific heat equation.

6) Suppose we have two samples, **A** and **B**, of the **same** material placed in a partitioned insulated container of negligible heat capacity. Sample **A** has the **same** mass as sample **B.** Energy but no material can pass through the conducting partition. The atmosphere in the container can transfer energy but has a negligible heat capacity. Assume specific heat is independent of temperature.

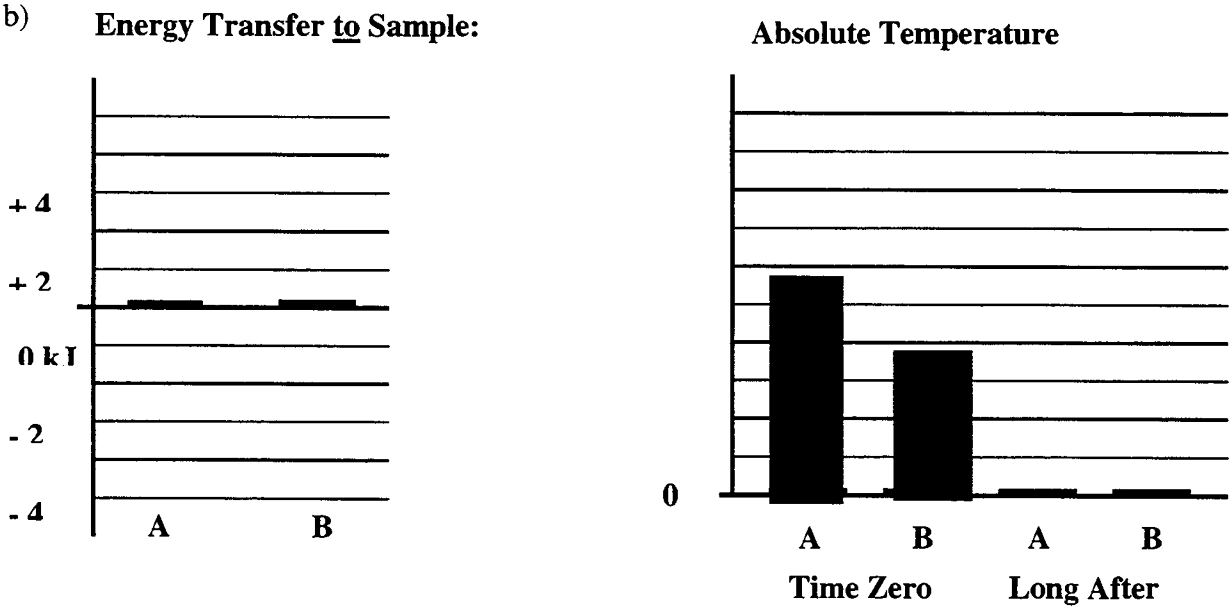


Complete the bar charts below for temperature and energy transfer. If any quantity is zero, label that quantity as zero. Explain your reasoning below.

a)


Energy Transfer to Sample:
+ 4
+ 2
0 kJ
- 2
- 4
A
B
Absolute Temperature
1000 K
500 K
0
A
B
A
B
Time Zero
Long After

b)


Energy Transfer to Sample:
+ 4
+ 2
0 kJ
- 2
- 4
A
B
Absolute Temperature
0
A
B
A
B
Time Zero
Long After

APPENDIX III: FREQUENCY TABLES OF THE QUIZ PROBLEMS

Appendix IIIa. Problem 1

Contingency Table

	Gf	Gp	W	N	
Words	27	35	25	2	89
Formulas	4	11	3	3	21
	31	46	28	5	110
Expected Frequency Table					
	Gf	Gp	W	N	
Words	25.08182	37.21818	22.65455	4.045455	
Formulas	5.918182	8.781818	5.345455	0.954545	

chi-test=	0.043008
chi-square(0.05, 3)=	7.814725
chi-square(0.04, 3)=	8.150584

The mode of operation is
marginally dependent
on the quality of the response

Standarized Adjusted Residuals

	Gf	Gp	W	N
Words	1.034379	-1.09097	1.306247	-2.38229
Formulas	-1.03438	1.09097	-1.30625	2.38229

	Gf	Gp	W	N
Words				less
Formulas				more

The dependency arises from the fact that people that used words tended to omitt explanations less than expected, while those using formulas omitted more than expected. There is not dependency of the operation with the quality of explanation but on the omission of it.

Appendix IIIb. Problem 2d

Contingency Table

	I	II	III	
Verbal	56	15	10	81
Equation	4	4	0	8
	60	19	10	89

Categories of Explanations

I: correct notion of conservation of energy and thermoequilibrium

II: confuse heat and temperature

III: do not display idea of thermoequilibrium in a calorimeter

People that approached the problem verbally displayed understanding of conservation of energy and thermoequilibrium.

People that used equations did equally in the category (I) than in (II)

Appendix IIIc. Problem 2g

Table of Contingency

	I	II	III	N	
verbal	45	3	18	19	85
equation	3	1	0	4	8
	48	4	18	23	93

Categories of Explanations

I: correctly relate mass, energy transfer and thermoequilibrium

II: confuse heat and temperature

III: ignore the relation of mass and heat

N: None

Expected Frequency Table

	I	II	III	N
verbal	43.87097	3.655914	16.45161	21.02151
equation	4.129032	0.344086	1.548387	1.978495

chitest:	0.12939
chitest(0.13, 3):	7.236612
chitest(0.05, 3):	9.487728

The obtained chisquare test distribution (7.237) is samller than the tolerated discrepancy (9.487), when the probability to fail in rejecting the null hypothesis is 0.05.

I obtained a probability of 0.13 and a chi-square discrepancy of 7.237

Thefore the variables are independent!!

APPENDIX IV: CODING SHEET OF THE QUIZ PROBLEMS

Appendix IVa. Problem 1

s's#	Oper.	Oper. Type	Expl.	Expl. Type	Comment
145	G	verbal	G	parametric	correct sense of Cp and DT
148	G	numerical	G	parametric	uses formula q=mcpdT
269	G	verbal	G	functional	concept of Cp
173	G	verbal	G	parametric	no mention Q and DT
285	G	verbal	G	functional	concept of Cp
303	G	verbal	G	parametric	no mention Q and DT
358	G	verbal	G	parametric	no mention Q and DT
375	G	verbal	G	parametric	correct sense of Cp and DT
88	W	verbal	W	parametric	T prop to Cp
131	G	numerical	G	parametric	uses formula q=mcpdT
186	G	verbal	G	functional	no relation to Cp, heat conductivity
187	W	verbal	W	parametric	T prop to Cp
207	W	verbal	W	parametric	T prop to Cp
215	G	verbal	G	functional	concept of Cp
221	W	verbal	W	parametric	T prop to Cp
235	G	verbal	G	parametric	no mention Q and DT
19	G	numerical	N		uses formula q=mcpdT
289	G	verbal	G	parametric	correct sense of Cp and DT
302	G	numerical	G	parametric	correct sense of Cp and DT
314	G	verbal	G	parametric	correct sense of Cp and DT
323	G	verbal	G	parametric	correct sense of Cp and DT
325	G	verbal	G	parametric	correct sense of Cp and DT
354	G	verbal	G	parametric	no mention Q and DT
359	G	verbal	G	parametric	correct sense of Cp and DT
61	G	numerical	G	functional	concept of Cp
85	G	numerical	G	parametric	no mention Q and DT
28	G	numerical	G	parametric	correct sense of Cp and DT
37	G	verbal	G	parametric	no mention Q and DT
151	G	verbal	G	parametric	no mention Q and DT
189	W	verbal	W	functional	Density no relation with Cp
213	G	verbal	W	functional	no Q pro. Cdt, relate w/solid propert.
390	G	numerical	G	parametric	no mention Q and DT
266	G	verbal	W	parametric	T prop to Cp

Clues

s's#: resulted from the random selection of the samples of different laboratory sections

Operation G (good) or W (wrong) refers to the correct or incorrect answer to the problem

Type of Operation: numerical (formulas) or verbal

Type of Explanation: parametric (rely on the parameters values of the problem)
or functional (rely on the concepts)

Comments: categories extracted from students responses; they are not verbatim

Appendix IVb. Problem 2d

s's#	Oper.	Oper. Type	Expl.	Comment	Category
145	G	verbal	N		
148	G	verbal	N		
164	G	verbal	G	final T the same for both	I
173	G	verbal	G	final T the same for both	I
285	G	equation	W	adiabatic condition for T	II
303	G	verbal	G	final T the same for both	I
358	G	verbal	N		
375	G	verbal	G	gain and lost Q	I
88	G	verbal	N		
131	G	verbal	G	final T the same for both	I
186	G	verbal	N		
187	G	verbal	G	final T the same for both	I
207	G	verbal	G	gain and lost Q	I
215	G	verbal	W	average of Ti's	III
221	G	verbal	G	final T the same for both	I
235	G	verbal	G	energy transfer	I
19	G	verbal	G	gain and lost of Q	I
289	G	verbal	G	final T the same for both	I
302	G	verbal	G	gain and lost Q	I
314	G	verbal	N		
323	G	equation	G	adiabatic cond. For Q	I
325	G	verbal	N		
390	G	verbal	G	gain and lost Q	I
359	G	verbal	G	gain and lost Q	I
61	G	equation	W	DT the same for both	II
85	G	verbal	W	relates to mass only	III
28	G	verbal	G	gain and lost of Q	I
37	G	verbal	W	DT the same for both	II
151	G	equation	G	adiabatic cond. For Q	I
189	G	verbal	G	final T the same for both	I

Clues

s's#: resulted from the random selection of the samples of different laboratory sections

Operation: G (good) all students of this example answered that the temperatures are related

Type of Operation: equation or verbal

Comments: categories extracted from students responses; they are not verbatim

Category: conceptual categories grouping students responses