University students' conceptions about familiar thermodynamic processes and the implications for instruction

Helen Georgiou, Manjula Sharma, John O'Byrne, Ian Sefton and **Brian McInnes**, School of Physics, The University of Sydney, Australia
georgiou@physics.usyd.edu.au, sharma@physics.usyd.edu.au j.obyrne@physics.usyd.edu.au, i.sefton@physics.usyd.edu.au, bmcinnes@pnc.com.au

Abstract *A large proportion of research in science education is either centred on or influenced by studies concerning conceptual change - in particular, the topic of students' misconceptions. This is justified by the observation that studies involving conceptual change or troublesome knowledge capture an aspect of science education that seems to be extremely significant for successful learning and vital for developments in instructional methods.*

This paper is an examination of conceptions about fundamental thermodynamic concepts held by university students. A 'pre-test' was developed and administered to 858 first year and 80 second year university students to probe conceptions and inform a subsequent study. Questions included both multiple choice and free response types. The results indicate that the first year students experienced varied and considerable difficulties with the thermodynamic concepts presented in the pre-test, particularly with respect to heat transfer and thermal equilibrium. It is significant to note that these particular concepts appear as part of formal instruction in science in NSW, and that they are embedded in familiar everyday situations. The results and analysis of this quiz are presented.

Introduction

The expansion of misconceptions literature has come to encircle a collection of disparate intentions and domains and is centred around constructivism, which describes that knowledge is not transmitted but assembled and developed by learners (Driver, Asoko, Leach, Mortimer & Scott, 1994). The field is fuelled by the persistent and confounding observations in science education that indicate that:

> Conceptions (or ideas) identify and relate factors that students use to explain intriguing or problematic phenomena. They also represent the knowledge, expressed in terms of solution strategies and their rationale, that constitutes the core solution to specific problems (Smith, diSessa & Roschelle, 1993, p. 119)

Physics has attracted a healthy serving of misconceptions research, especially in topics such as motion and thermodynamics which are heavily grounded in observable phenomena. Within each topic, there are specific concepts that continue to prove troublesome, some more robust and easily explained than others (diSessa, 2006). Although there is good reason to focus on misconceptions and troublesome knowledge in physics, extending this view offers new possibilities. Naturally, by broadening our scope from misconceptions to conceptions (or as one author labels it, 'resources' (Hammer, 2000)) we can expect broader insights. The aim for this study is to reveal university students' conceptions about familiar, everyday phenomena, and then to use this as a platform to broaden our understanding and inform the development of related practices and curricula.

Studies of this particular kind have been rare in tertiary education (Meltzer, 2004), even though this is where expertise is most actively initiated and developed. It is also evident that university students struggle with concepts in physics throughout their degrees, and graduate with epistemologies that do not match those representative of physics experts (Thacker, 2003). Improvements stemming from research are viable, promising, and often a case of merely having more information about students. For example, Dart and Clarke (1991) assert that lecturers who are simply aware of their students' beliefs and the structure of a learner's knowledge, would be able to use these insights to better structure their learning environment, and therefore encourage further progress and development.

The dominant method for probing conceptions, with considerations to scale, timing and reliability, is concept inventories (Thornton, 2003, p. 594). The Force Concept Inventory- which is currently the most widely established - has proven to be extremely useful, effective and reliable (Hestnenes & Halloun, 1995). The topics isolated for this particular exercise were presented in an inventory structure (the pre-test) and included heat, temperature, conductivity, heat transfer and heating and cooling rates. Within these topics, conceptions (mostly misconceptions) have already been extensively catalogued. Eylon and Linn (1988) summarise work from a number of authors which reports that students generally tend to: Think of heat as a substance, believe cold and heat are separate entities, not distinguish between heat and temperature, and think of temperature as a measure of hot and cold.

Conceptions themselves are seldom considered in isolation. Context and dynamicity are vital aspects of theories and investigations involving how students learn. Eylon and Linn (1988) look at the structure and development of conceptions and compare different perspectives. For example, the "developmental perspective" (1988; p.252), is based on Piaget's research and will examine at what stage students acquire certain scientific conceptions. The 'problem-solving perspective' (1988; p.253), is based on literature about novice-expert characteristics and looks at how conceptions mould and affect problem solving ability. An example of the practical implications of research into conceptions and their development is presented in a study by Liu and McKeough (2005). The authors identify that a student who progresses through a standard US primary to university education is presented concepts related to energy in a predetermined and distinct order (due to respective curricula). The authors challenge this order, based on data obtained from a standardised national test that allowed them to trace the development of conceptions of students ranging from grade 3 to the last year of high school. The results identified that the order in which students tend to master certain energy related concepts was different to the order inherent in the national curriculum. The authors suggest that data on conceptions and their development should inform curricula structure to facilitate the comprehension of energy concepts.

Outline of paper

We outline the pre-test, sample, and administration and analysis in the section called Method. A more detailed method and results will then be presented separately for the Multiple Choice and Free Response Sections under these respective headings.

Method

The pre-test included 12 multiple choice questions and 3 free response questions. The participants were first and second year university physics students at the University of Sydney, see Table 1.

	Multiple Choice (and total number of responses)	**Free Response**		
	Q1-12	**Q13**	**Q14**	**Q15**
Fundamental	248	171	142	146
Regular	479	329	286	275
Advanced	131	100	92	88
2nd Year	80	43	45	40

Table 1: Number of responses for the multiple choice section and individual free responses according to group

The Fundamental, Regular and Advanced students are all first year physics students while the 2nd year group is the second year physics cohort. Generally, due to course specifications, the Regular and Advanced groups are required to have high school physics with the latter containing high achievers and the Fundamentals group is made up of students who have not completed senior high school physics, or have underperformed in it.

No one method has proven superior to another in terms of collating and interpreting qualitative data regarding student conceptions, although most authors will naturally employ some sort of categorisation (Liu, 2001). For the purpose of this study, it was most suitable to use a combination of phenomenography (Marton,1981) and SOLO (Structure Of Learning Outcomes) taxonomy (Biggs & Collis, 1982). Phenomenography is a mode of research whose aim is to describe and systemise *'forms of thought in terms of which people interpret significant aspects of reality.'* (Marton, 1981, p. 177). It highlights the characterisation of thoughts or concepts not as individual qualities, but as *'categories of description to be used in facilitating the grasp of concrete cases of human functioning'*. Marton highlights the importance of categories of conceptions by likening them to a representation of a collective intellect or mapping of development (1981). A phenomenographic approach in practice will group several responses based on similar characteristics and therefore result in a number of different bundles of like-responses. To complement this categorisation, a SOLO taxonomy was applied to provide additional information regarding the hierarchy of responses. SOLO categories allow the assignment of quality to responses by defining structured hierarchical levels, see Table 2. How both techniques were used for analysis will be further explained with reference to specific methods where necessary.

SOLO description	Description
Prestructural	Tautology, denial, transduction, bound to specifics
Unistructural	Can 'generalise' only in terms of one aspect
Multistructural	Can 'generalise' only in terms of a few limited and independent aspects
Relational	Induction. Can generalise within given or experienced context using related aspects
Extended abstract	Deduction and Induction. Can generalise to situations not experienced.

Table 2: SOLO taxonomy summary adapted from Biggs and Collis (1982)

Multiple Choice Section

The 12 multiple choice questions were selected and reviewed by a committee of physics experts to reflect the aims of this study, and were therefore associated with basic thermodynamic principles. Questions 1-6 were sourced from a thermal concept inventory (Yeo & Zadnik, 2001), Questions 7,8 & 11-12 came from a comprehensive study of thermodynamics conceptions amongst university students (Gray, 1998) and Q9 was adapted from a university topic test on thermodynamics (Sharma, 1995). The variety of sources assured a comprehensiveness of topics and a diversity of question types, which could help support reliably identifying misconceptions. The cost of this was the inherent inconsistencies in format and style, which included for example, a non unique number of alternatives throughout the test.

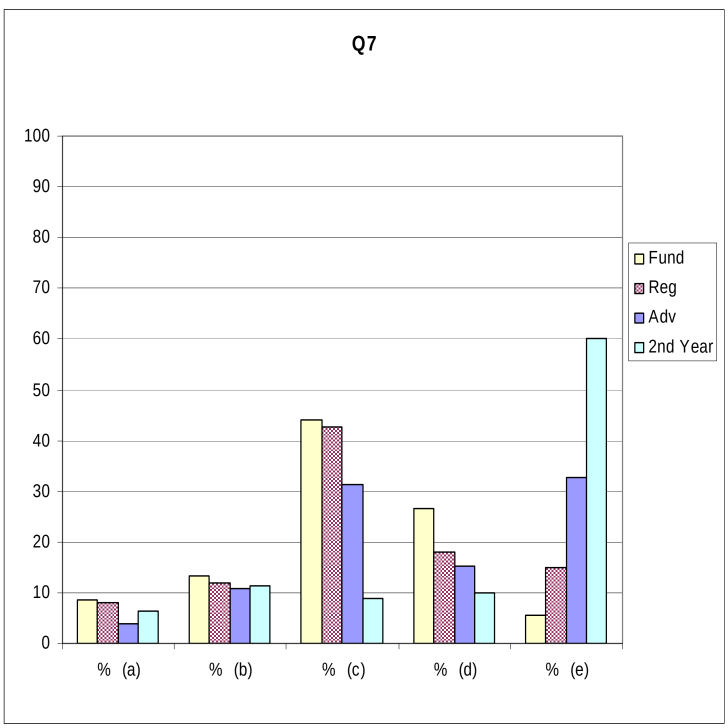
A representation of the concepts in the pre-test and their related questions is shown in Table 3. The topics on the left are accepted thermodynamics topics and are listed as such in many textbooks. Further divisions were made to improve specificity; these are found in the second column. A definition of the non standard terms is provided.

Thermodynamic Concepts		Specific Topic	Question
Thermodynamic Processes		Phase change and latent heat	4,5,6,8
Zeroth law	Zeroth Law	Contact temperature	1,2,7
		Thermal equilibrium	1,2,3
		Temperature	1,2
	Thermal conductivity	Thermal contact	1,3,5,7
		Temperature as a measure of hotness	2,5,7,8
Cooling and heating rate		Rate of cooling	9,10
Heat transfer		Heat transfer	3,12

Table 3: Classification of concept areas in Contact temperature: Bodies or systems in thermal contact have the same temperature. Thermal contact: When, if the temperature of two bodies or systems are different, heat (or energy) can be transferred from the hotter body to the colder body.

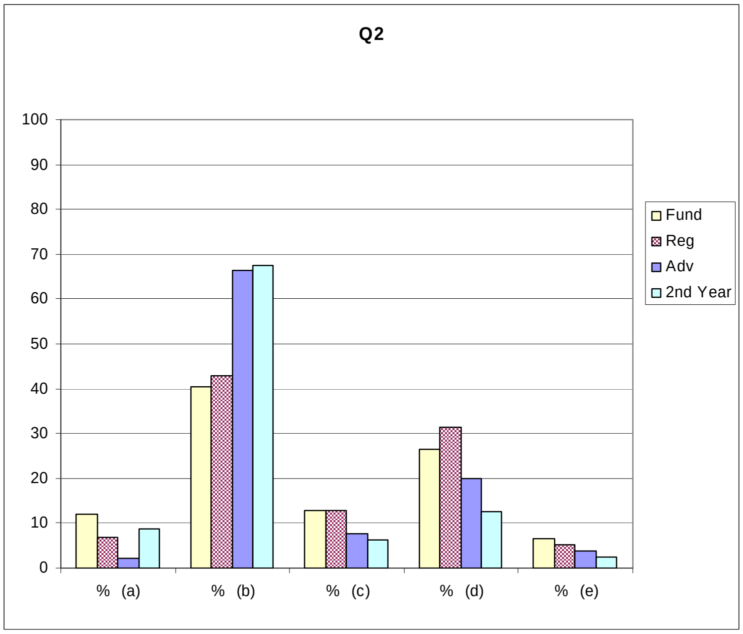
Preliminary analysis of the section revealed interesting results that could address various aims. Q2 and Q7 are presented here as they were the most interesting, relevant and noteworthy:

- A large proportion of students made errors regarding application of thermal equilibrium in Q7. Responses indicated that the perception of 'coldness' was associated with temperature, even though this contradicted the notion of thermal equilibrium and did not take into account the different conductivities of the objects. (See Figure 1).
- There was also evidence of the lack of or difficulty in transferring a similar concept between different contexts. The same concept was recognised in Q2 more readily than Q7, where there were fewer errors.



7. In a bathroom, not exposed to direct sunlight, what can you say about the temperature of the ceramic tiles on the floor compared to the temperature of a bath mat made of a thick towel-like material?

a) The mat is at a lower temperature as it does not absorb energy well.
b) The tiles are at a lower temperature as they conduct energy well.
c) The tiles are at a lower temperature as they do not store energy well.
d) The tiles are at a lower temperature as they do not conduct energy well.
e) They are both at the same temperature as they are in contact with each other.



2. Sam takes a can of cola and a plastic bottle of cola from the refrigerator, where they have been overnight. He quickly puts a thermometer in the cola in the can. The temperature is 7°C. What are the most likely temperatures of the plastic bottle and cola it holds?

a) They are both less than 7°C
b) They are both equal to 7°C
c) They are both greater than 7°C
d) The cola is at 7° C but the bottle is greater than 7°C
e) It depends on the amount of cola and/or the size of the bottle

Figure 1: Results presenting responses for Questions 7 and 2. Bold represents correct answer.

Free Response Section

There were three free response questions in the test. Q13 will not be considered for this report as it was analysed in a slightly different way due to the nature of the question (less free response and more quantitative). Q14 and Q15, sourced from Gray (1998), were both of a similar style and encouraged essentially qualitative responses. Initial examination of the data revealed common patterns that facilitated the categorisation of student responses. Although the characteristics of the categories were specific for this study, the general arrangement roused similarities with other established categorisation methods; phenomenography and SOLO taxonomy, which were subsequently used to guide further analysis.

Questions 14 and 15 appear below. Their associated classification and specific examples are presented in Tables 4 and 5 respectively.

Question 14: Explain why we are comfortable in 15°C air but find swimming in 15°C water unpleasant.
Question 15: Explain why it is suggested that blowing over hot tea may make it cool faster.

A sample of 160 responses from the regular group was initially analysed and sorted into broad categories. The categories were constructed initially in an untailored phenomenographic manner, dividing responses by common characteristics. The authors and other physics experts reviewed and verified the characteristics and boundaries of the categories and minor adjustments were made. Column two lists the characteristics which were developed to represent each group of categories we constructed. The corresponding SOLO levels are presented in the leftmost column. These levels were used to refine and substantiate our own categories. The relational and extended abstract level of the SOLO taxonomy was collapsed to one for this purpose. This is because the questions were not intended to encourage particularly comprehensive responses, and therefore only a few students autonomously provided such responses. When our groups were established and accepted, full samples of the other groups were classified accordingly. The results are presented below.

Level	Characteristics of questions 14 and 15 for each category	Percentage of Reponses in each category							
		Q14				Q15			
		F	R	A	2nd	F	R	A	2nd
Prestructural	Messy, random responses that made little sense.	19	12	1	6	11	7	1	-
Unistructural	Real world links with tendencies of naïve beliefs (some p-prims (diSessa, 1996)). Some mention of unrelated biology or chemistry references.	27	25	6	9	39	19	15	-
Mulitistructural	Use of Physics concepts, but these were either not primarily related to question, or incomplete	26	20	22	4	32	27	40	25
Relational/ Extended Abstract	Understanding of physics behind question. Errors mainly in use of language, expression.	28	43	71	81	18	47	44	75

Table 4: Response Classification and SOLO comparisons for Q14 & Q15 for the fundamental (F), regular (R), Advanced (A) and second year students (2nd)

Level	Q14 response examples	Q15 response examples
Prestructural	"The water is too cold"	"Blowing removes the heat"
Unistructural	"Water doesn't allow heat to escape, causing colder conditions"	"Cool air from your breath will cool it down because the air is cooler than the liquid"
Multistructural	"Air has less density than water molecule which means that each atoms*(sic)* move more freely in air state"	"Blowing over hot tea will make the water molecules be blown away thus less heat will be left on the tea"
Relational/ Extended Abstract	"Water conducts hear*(sic)* more efficiently than air. As such, our outer body loses heat more quickly in water than in air, This rapid change in temperature is perceived as discomfort. In air, the heat transfer occurs slowly, which is less unpleasant"	"Remove hot air from surface of the tea, allowing cooler air to replace. Letting the heat from the tea transfer quicker to the colder air. Cooling tea faster"

Table 5: Examples of typical responses for each level or classification

Some interesting aspects of analysis are discussed:

The similarities of categories despite question type The characteristics of all four student response categories' were common for both questions. For example, 'Real world links with tendencies of naïve beliefs' was a category that was clearly present and well defined for Q14 and Q15.

The clear progress of conceptual development through increasing ability groups It is clear that the higher order categories (multistructural and relational/extended abstract) have a higher population of responses as we move through the 'ability' groups (Fundamentals, Regular, Advanced, 2nd year). The largest adjustments occurring between the Fundamental/Regular students and the Advanced and 2nd year groups. Although this is not surprising, it offers some insight into the evolution of conceptions.

A deeper insight into certain misconceptions Some misconceptions that were only superficially identified in the previous section were more deeply revisited in the responses to the free response questions. For example, in Q15, the notion that cold is a substance and can be transferred was explicitly evident in 7% of total responses.

This preliminary study has probed student conceptions. Subsequent research will use these results to investigate their underlying structure and development in further detail.

Conclusion

This aim of this study was to examine conceptions. The existence of certain conceptions amongst university students was indicative of a lack of conceptual mastery of basic and familiar thermodynamic concepts, particularly the concept of thermal equilibrium. The road to mastery was also in a sense captured by the development of conceptions throughout the different first year physics groups. Identification of problematic conceptions may help identify students who would benefit from further assistance.

References

Biggs, J. B., & Collis, K. F. (1982). *Evaluating the Quality of Learning: The SOLO taxonomy*. New York: Academic Press.

Dart, B. C., & Clarke, J. A. (1991). Helping students become better learners: A case study in teacher education. *Higher Education, 22*(3), 317-335.

diSessa, A. A. (1996). What do "just plain folk" know about physics? In Olsen and Torrance (Ed.), *The Handbook of Education and Human Development: New Models of Learning, Teaching and Schooling* (pp. 709-730). Cambridge: Blackwell.

diSessa, A. A. (2006). A history of conceptual change research: Threads and fault lines. In K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences*. New York: Cambridge University Press.

Driver, R., Asoko, H., Leach, J., Mortimer, E., & Scott, P. (1994). Constructing scientific knowledge in the classroom. *Educational Researcher, 23*(5), 5-12.

Eylon, B.-S., & Linn, M. C. (1988). Learning and Instruction: An examination of four research perspectives in science education. *Review of Educational Research, 58*(3), 251-301.

Gray, A. (1998). *Developing a prototype thermal concept inventory.* The University of Sydney, Sydney.

Hammer, D. (2000). Student resources for learning introductory physics. *American Journal of Physics, Physics Education Research Supplement, 68*(S1), S52-S59.

Hestnenes, D., & Halloun, I. (1995). Interpreting the Force Concept Inventory. *The Physics Teacher*(33), 502-506.

Liu, X. F. (2001). Synthesizing research on student conceptions in science. *International Journal of Science Education, 23*(1), 55-81.

Liu, X. F., & McKeough, A. (2005). Developmental growth in students' concept of energy: Analysis of selected items from the TIMSS database. *Journal of Research in Science Teaching, 42*(5), 493-517.

Marton, F. (1981). Phenomenography - Describing conceptions of the world around us. *Instructional Science, 10*(2), 177-200.

Meltzer, D. E. (2004). Investigation of students' reasoning regarding heat, work, and the first law of thermodynamics in an intriductory calculus-based general physics course. *American Journal of Physics, 72*(11), 1432-1446.

Sharma, M. (1995). Therodynamics practice test. Sydney.

Smith, J. P., diSessa, A. A., & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences, 3*(2), 115-163.

Thacker, B. A. (2003). Recent advances in classroom physics. *Reports on progress in physics, 66*.

Thornton, R. K. (2003). Uncommon knowledge: Student behavior correlated to conceptual learning. In V. Redish (Ed.), *Proceedings of the international school of physics 'Enrico Fermi'* (pp. 591-608). Amsterdam: IOS Press.

Yeo, S., & Zadnik, M. (2001). Introductory thermal concept evaluation: Assessing students' understanding. *The Physics Teacher, 39,* 496-504.