9 Putting physics knowledge in the hot seat

The semantics of student understandings of thermodynamics

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Introduction

The study of students' ideas dominates efforts in science education research. Across the sciences and for all educational stages, more sophisticated approaches and methodologies have been developed which have helped result in improved instructional practices. Despite these significant developments, several fundamental issues remain underexplored, including questions surrounding the very nature of students' ideas, how they develop, and the values that should (or should not) be placed on them. Physics Education Research (PER) can be considered a specialism within the science education research agenda, comprising a relatively small but concerted initiative to support findings with theory in the hope of resolving these persistent issues. Mostly, theoretical frameworks utilized in PER have been based on cognitive science and aim to characterize the learning process, or what Maton (2014b) refers to as 'knowing'. This chapter instead turns the focus onto 'knowledge as an object' by looking at student ideas through the enactment of Legitimation Code Theory (LCT). In the first part of the chapter, limitations of current research on student ideas are discussed in the context of science education research. To illustrate the value of LCT as an potentially complementary approach, the chapter reports on a study conducted in a thermodynamics module in first year undergraduate physics which enacts the concept of 'semantic gravity' in analyses of student responses. Through this exemplar, the chapter illustrates how enacting LCT overcomes many limitations of existing studies to procure novel insights into the nature of student understanding.

Conceptions research in science education

Science education research is strongly characterized by its intense focus on students' ideas or conceptions (Chang *et al.* 2010; Tsai and Wen 2005). The term 'conceptions' is the name given to students' understanding of units of knowledge; 'misconceptions' or 'alternative conceptions' therefore represent erroneous or incomplete understanding (Liu 2001; Vosniadou

2008). These terms appear within a research agenda whose principal concern is with students' evident failure to emerge from science instruction with a more sophisticated understanding of science (Shaffer and McDermott 2005). Current 'conceptions research' is driven primarily by relatively new tools that reveal student difficulties (Hake 1998). These tools have facilitated ongoing research that aims to improve the development and assessment of instructional practices to help students overcome these difficulties (e.g. Treagust 1988).

Such is the perceived success of this programme that there exists in the science education field a conspicuous rejection of the necessity for conceptual frameworks (McDermott 1990). The unique culture and position of physics education researchers further encourages atheoretical research. They are often employed as part of physics faculties, are typically practising physicists (or have been), and are commonly working with students or educational issues within their institution. Inevitably, such research is not easily reinterpreted in different contexts. Reif (in Cummings 2013) argues that for real significant progress to occur, a coherent theoretical framework must be developed. diSessa *et al.* (2004) concur, arguing that even in the most dominant research concern, conceptual change, focused argumentation is limited.

At the periphery of Physics Education Research (PER), a specialism within the broader science education field, there exists a small but influential group of researchers that insist that theoretical frameworks must be utilized if research is to be influential and constructive. The theoretical framework employed by this group is known as 'the Resources Framework'. Advocates of this framework argue it is intended to specifically address persistent issues in science education research, particularly with respect to conceptions, and to provide a shared language through which disparate research findings may be grounded for greater explanatory power (Redish and Bing 2009; Sabella and Redish 2007). The relevant aspects of the Resources Framework are provided here as a way of exemplifying the need for a complementary approach (for a more comprehensive description, see Redish 2004).

The Resources Framework has its foundations in a view of learning based on cognitive science, one concerned with the content and structure of cognitive networks in the student's mind. The framework emerged from questions concerning whether students' knowledge was 'theory-like' or 'piece-like'. 'Theory theorists', such as Carey (1985) and Vosniadou (2002), believe students' conceptions are concrete manifestations of theory-like cognitive structures. However, it is the 'pieces' view that has come to dominate PER and which forms the basis of the Resources Framework. In this view, conceptions are 'nodes' (or pieces) that are embedded within a larger structure or network which in turn is organized and affected by more global influences such as motivation and context (more pieces). Questions for research include the examination of the structure of this network, how such a structure might develop, how the various nodes of this structure are activated and why, and how different contexts such as the subject studied, student background and motivational aspects affect the structure (e.g. diSessa 1993; Minstrell 2001; Sabella and Redish 2007).

The Resources Framework focuses on describing a range of possibly meaningful units of knowledge where different units may be interesting or relevant for different reasons. Two such units include ‘facets’ and ‘p-prims’. Minstrell’s ‘facets’ (2001) are discrete and independent units said to characterize a student’s scientific repertoire. Such facets range from characterizing the ‘scientific method’ (e.g. experimenting is changing things and seeing what happens) to describing individual scientific ideas (e.g. heavier falls faster). The notion of facets allows for the identification of ideas in students’ ideas that are common amongst groups of learners and may affect understandings. Another unit is diSessa’s ‘phenomenological primitives’ or ‘p-prims’ (1993). These are characterized as pieces of knowledge in physics that students believe are an irreducible feature of reality, that is, requiring no further explanation. In general, p-prims are ‘concept groups’ that describe some aspect of a (supposed) physics mechanism. For example, if a student holds the p-prim ‘closer is stronger’, this could result in the mistaken belief that the Earth is closer to the sun in summer. Because ‘closer is stronger’ is both intuitive and true in other contexts, a justification is often not considered necessary, so the idea is quickly substantiated and subsequently difficult to alter.

Although both ‘facets’ and ‘p-prims’ are theoretical constructs developed outside of the Resources Framework, Redish argues they are most useful when part of a subsuming structure and recontextualizes both as ‘resources’ within the Resources Framework. In this way, he describes ‘facets’ and ‘p-prims’ as serving different purposes, related or connected, and activated in certain contexts and at certain times. This need for a more encompassing theoretical structure arises from criticisms of cataloguing which continue to be charged at notions of ‘facets’, ‘p-prims’ and misconceptions in general, namely that these ideas are not fixed, discrete or easily characterized through labels but are instead manifold and extremely sensitive to context. Redish (2004) makes a further amendment to the notion of ‘p-prims’ within his Resources Framework by suggesting they have internal structures. He argues that a p-prim comprises a ‘reasoning primitive’ that is abstract and which ‘mapping’ relates to ‘facets’, that are concrete and describe specific phenomena. This distinction draws the discussion away from descriptive labels and categories to a slightly more subtle model that suggests one way physics knowledge works is by connecting the abstract to the concrete.

These theoretical concepts have demonstrated utility within physics education research, raising the question for the Resources Framework of why stop at this characterization. That the level of abstractness (or concreteness) of ideas is significant suggests one could characterize the spectrum between these two extremes with a conceptualized organizing principle, rather than settle for two contestable, ambiguous and often morally charged categories of ‘abstract’ and ‘concrete’. Maton (2013, 2014b) highlights this issue when discussing ‘knowledge-blindness’. He explains that where knowledge as an object of study in its own right is seen by research (rather than reduced to knowing processes and mental states), as is the case in science and physics education, it is typically theorized in a highly segmented way as simple categories or constituent elements. Such a theorization reflects a vision of disciplines as simply an aggregation of concepts, relations and processes rather than a complex series of evolving constellations of meanings. As Poincaré stated, science is no more a collection of constituent parts than a pile of bricks is a house – it has an architecture based on organizing principles. From this perspective, it is apprenticeship into these organizing principles as much as specific atomic propositions that comprises the work of education.

More widely, Maton (2014b) highlights how ‘knowledge-blindness’ is endemic to educational research. Psychologically-influenced approaches, such as those employed in PER, typically focus on students’ learning processes, while sociologically-influenced approaches typically foreground how students’ experiences are shaped by power relations (whether with the teacher or the environment). Both largely obscure the nature of what is being learned, as if knowledge itself was homogeneous and neutral. However, a rapidly growing range of studies are showing that different kinds of knowledge take various forms and have different effects.

Types, categories, and a focus on the knower

As well as exploring the effects of knowledge, LCT is enacted to address several issues in science and physics education research. The general ambivalence toward theoretical reference has just been discussed. The following sections will focus on: limitations of available methodologies in physics education that result in typologies and categories of knowledge rather than exploring its organizing principles; and a tendency of existing theoretical frameworks to focus on knowers rather than knowledge.

Methodologies common in science education include survey research, quasi-experimental studies and evaluation studies. Many rely on some form of categorization (Otero and Harlow 2009). Multiple-choice surveys, for example, are largely used to identify misconceptions and assess conceptual understanding but have also been used to identify student attitudes, their learning to approaches and even their epistemologies.[1] The culture of categorization is also present in qualitative approaches. For example, one approach used widely for qualitative research of student conceptions is phenomenography (Marton 1981). Phenomenographic research involves the categorization of the content of student text (or speech) into groups of similar characteristics and has been useful in revealing the spectrum of student understanding under certain conditions (e.g. Sharma *et al.* 2004). A second example, The Structure of Observed Learning Outcomes or ‘SOLO’ framework (e.g. Boulton-Lewis 1994) analyses the 'quality' of student responses rather than their content. Student responses are assigned a level based on how 'relational' their responses are, and, over time, developments in the student may be tracked.

While valuable starting points, these approaches are unable to capture the dynamicity of conceptions and heavily rely on the researchers' interpretation of student ideas – what is in their minds. In the Resources Framework, for example, 'development' is conceptualized as a movement along the spectrum between 'novice' and 'expert'. The expert–novice treatment involves the characterization of the novice learner, including how they approach and interpret problem-solving or how they understand a particular idea, and subsequent comparison to the expert's characteristics. The ultimate goal is for the novice to develop as far as possible into expertise (Chi *et al.* 1981; Larkin *et al.* 1980; Wu 2009). This is not to say such characterizations are not useful. However, there are questions left unanswered by the approach, including why novices think in this way, why the development into expertise is more difficult in some contexts and for some students, what explains differences among experts, and which expert is more 'expert' and why. Wolf *et al.* (2012) ask, for example, how do we know which group the subjects belong to? Without reference to a 'known' novice or expert, an analysis of conceptualizations of knowledge is unable to identify the level of expertise in a group.

In summary, we have a body of work in science education research that speaks of 'knowledge' (concepts, p-prims) and some work that hints at the organizing principles of that knowledge (such as relations between general principles and concrete facts). The next stage is thus to advance beyond categorization and atomic classification by conceptualizing these organizing principles. The justification for exploring new frameworks thus includes addressing the following concerns:

- Can a theoretical framework that focuses on knowledge as an object (rather than conceptions imputed to knowers) be useful in informing the teaching and learning of science, and if so, how?
- How can we advance beyond typologies for characterizing knowledge?
- How can we account for concepts having various possible 'types' of context-dependence?

These questions emerged as key theoretical and analytical issues for a major research project which aimed at assessing student understanding of a new teaching practice in the context of a first year module on thermodynamics. They led to the adoption of concepts from LCT in the study. For more on this study as a whole, see Georgiou (2009), Georgiou and Sharma (2010), Georgiou *et al.* (2014). Here I shall briefly introduce the LCT concept drawn on in the study before describing its enactment to analyse student responses to a problem on thermodynamics.

Legitimation Code Theory: Semantics

As Maton outlines in Chapter 1 (this volume), LCT is an explanatory framework for analysing and changing practice. LCT forms a core part of social realism, a broad 'coalition' of approaches which reveal knowledge as both socially constructed and real, in the sense of having effects, and which explore those effects (Maton 2014b; Maton and Moore 2010). LCT is a 'practical theory' and designed to be an open-ended endeavour that

> foresees its own repeated refinement, deepening and extension through dialogues with concepts inherited from existing frameworks, substantive studies that reveal new issues to be addressed, and complementary frameworks that shed light on different facets of phenomena.
>
> (Maton, Chapter 1, this volume, page 22)

As illustrated by this volume, LCT is rapidly growing as a basis for empirical research into education. The framework itself comprises a multi-dimensional conceptual toolkit, where each dimension offers concepts for analysing different organizing principles underlying practices (Maton 2014b; Chapter 1, this volume).

In this chapter, to illustrate how LCT may offer a way of building on existing approaches, I focus on one concept from the dimension of Semantics: *semantic gravity* (Maton 2009, 2011, 2013, 2014a, 2014b). This concept specifically addresses an issue already raised above when discussing the work of Redish: the context-dependence of knowledge. As Maton defines it:

> *Semantic gravity* (SG) refers to the degree to which meaning relates to its context. Semantic gravity may be relatively stronger (+) or weaker (–) along a continuum of strengths. The stronger the semantic gravity (SG+), the more meaning is dependent on its context; the weaker the semantic gravity (SG–), the less dependent meaning is on its context. All meanings relate to a context of some kind; semantic gravity conceptualizes how much they depend on that context to make sense.
>
> (Maton 2013: 11)

Here I shall simply note that, unlike typological conceptions of knowledge, the notion of 'semantic gravity' is not a homogenizing category into which diverse and changing practices are to be reduced. Rather, all practices are characterized by semantic gravity and the difference lies in their relative strengths. Thus the concept represents a continuum allowing both for infinite gradation among practices and for tracing change within practices over time. Dynamizing the continuum captures *weakening semantic gravity*, such as moving from the concrete particulars of a specific case towards generalizations and abstractions whose meanings are less dependent on that context; and *strengthening semantic gravity*, such as moving from abstract or generalized ideas towards concrete and delimited cases (Maton 2013: 11; Chapter 1, this volume). One can also describe the *gravity range* of practices (the difference between their strongest and weakest strengths) and the *gravity profile* that changes in strengths trace over time (Maton 2014b: 106–24).

It should be emphasized that 'semantic gravity' is not the only concept in the dimension of Semantics, let alone in LCT as a whole. I focus on one concept for the sake of brevity. Nonetheless, this concept is being widely adopted in studies of education, including biology and History (Chapter 5, this volume), ethnographies (Chapter 6), design (Chapter 7), literary studies (Chapter 8), chemistry (Blackie 2014), law and political science (Clarence 2014), engineering (Wolff and Luckett 2013), and teacher education (Shalem and Slonimsky 2010). As this suggests, LCT concepts such as 'semantic gravity' have wide applicability, enabling research into knowledge practices in diverse contexts to cumulatively build on one another, as called for within PER and science education research more generally. Moreover, LCT reaches further than such calls would venture: within LCT studies of natural science inform and are informed by studies of the arts, humanities and social sciences, as well as research into informal learning contexts, such as museums (Chapter 4, this volume) and freemasonry (Chapter 11).

This flexibility is, however, not at the expense of empirical precision. LCT includes the notion of developing a 'translation device' for moving between concepts and empirical data that shows how concepts are realized within the specific object of study being explored (see Chapter 2, this volume). For example, a translation device for 'semantic gravity' defines what is meant by 'context' and how relative strengths are determined in the data under analysis. Having defined 'semantic gravity', I now describe the data, including the sample and educational context, and the translation device developed to enact semantic gravity in this study.

Method, sample and translation device

The study took place in 2011 with a sample of 133 first year physics students at a large metropolitan university in Sydney, Australia. It was conducted in a thermodynamics module, one of three modules in a first semester course. Students generally find the topic of thermal physics difficult but little is known about why. The students participating in the study completed four physics problems posed to them through the thermodynamics module. Their responses to one of these problems were collected and analysed to characterize student understanding.

Question

The question was administered at the beginning of selected lecture classes, during time allocated for their completion. Lecture observations and evaluation forms show the students completed the question largely autonomously and reported investing serious effort, taking 10–15 minutes to write their responses. The average length was three or four sentences with some use of equations and limited use of diagrams. The students in this sample are mainly taking Bachelors of Science, Medical Science or Engineering, with very similar high-school leaving marks that place them in the top ten per cent of the state of New South Wales. Students volunteered to be interviewed at the request of the researcher and course coordinator, providing data useful for illustrating or substantiating claims made in the analysis of written responses.

The question concerns a frosty cylinder:

> On a warm summer day a large cylinder of compressed gas (propane or butane) was used to supply several large gas burners at a cookout (the valve was open to release the gas). After a while, frost formed on the outside of the tank. In a few sentences, *explain at least one mechanism* associated with the frost formation.

The physics behind this scenario can be summarized as follows. The cylinder contains liquid fuel (propane or butane) and vapour fuel. As the gas exits the cylinder to supply the burners, some of the liquid fuel inside the cylinder evaporates to maintain constant vapour pressure (the same pressure that the vapour was at before it was released). Evaporation requires an energy input, which is achieved through heat transfer first from the cylinder walls to the liquid, then from the air outside the cylinder to the cylinder walls. Air contains water molecules and the heat transfer from the air is significant enough to result in the water condensing and freezing onto the outside of the cylinder.

This explanation assumes knowledge that the fuel inside the cylinder exists in a liquid-gas equilibrium state. However, failure to consider this assumption does not preclude a consistent response. For example, an explanation could instead state that an expanding gas does work and therefore requires heat transfer to it, the heat transfers from the cylinder, and consequently the surrounding air results in the condensation of the water molecules in the air and their ultimate freezing.

In their responses, students reveal both which concepts they deemed most relevant and an explanation of how those concepts applied to the provided scenario. The fact that the question assumed knowledge of the working of a gas cylinder that some students had and others did not, combined with the requirement to explain ‘at least one mechanism’, meant that there was an extensive range of physics content presented in the responses, providing rich data.

Analysis

Analysis of student responses to the ‘frosty cylinder’ problem occurred in a number of stages. Initially, LCT was not considered as a framework for the study. A collaborative attempt at coding using established methodologies, such as SOLO and phenomenography, ultimately failed. Although there was an attempt to code with respect to the different levels of quality that the SOLO framework offers (as determined by the relational structure of the responses), two senior researchers (S1 and S2) voiced concerns at the difficulty of doing so and produced highly conflicting analyses, agreeing on only 23 per cent of coding on responses. Alternative forms of 'categorization' suggested by the researchers included attempts to instead 'look at the logical structures' (S1) or attempt coding on the basis of the 'various physical principles evoked' and the 'nature of assumptions used' (S2).

The extent of the difficulty in coding necessitated a rethink of the theoretical approach being employed in the study. Cross-disciplinary consultations, including physics education researchers and scholars in both linguistics and sociology, resulted in the adoption of the LCT dimension of Semantics for the analysis of responses. I conferred with another researcher familiar with the physics in the question and the responses, physics education research in general, and the framework of LCT, to confirm the validity of the selection of three relative levels of semantic gravity. Coding was subsequently conducted primarily by myself. Validity, calibration and confirmation of coding were then achieved through a formal meeting with S1 and S2 followed by one-to-one correspondence. Agreement was reached at an inter-rater reliability of at least 90 per cent with alterations to coding characterization occurring where necessary. Such high agreement was unexpected given the complexity of the question and previous difficulties using the SOLO framework.

The translation device developed in order to enact the concept of semantic gravity in analysis of student responses is shown in Table 9.1. This describes three levels that represent relative strengths of semantic gravity. The most 'abstract' level (SG−) comprised general principles used to justify the reasoning made in the response. The most 'concrete' level (SG+) contained descriptions of the objects in the question, including tautology or repetition. The intermediate level (SGØ) comprised the causative reasoning of the student, often linking more abstract ideas to more concrete facts. Although responses were coded into categories of distinct levels of relative semantic gravity, this is not to suggest responses within each category are homogeneous. For example, the sections coded in Table 9.1 within the 'SG−' category (discussed in the results section below) are all general principles, but some are clearly more general than others; for example, '(viii) (the first law of thermodynamics)' compared to '(iii) ($E = mc\Delta T$)'. Thus, enacting the LCT concept enables *both* categories to be employed *and* a more continuous and nuanced analysis of differences within categories.

Results

The findings of the study will first be situated within existing research on conceptions. Then, an illustration will be offered of how the concept of semantic gravity was able to reveal insights into how students approach a problem in physics and how and why they are successful or otherwise.

Table 9.1 Translation device for semantic gravity of student responses in thermal physics

Semantic gravity	Coding categories	Description of coded content	Examples of student responses (including original grammatical and spelling errors)
Weaker	SG–	Student is describing a physical principle, law, concept or theory, without reference to a specific situation	i an expanding gas absorbs energy ii as the state changes from liquid to gas; heat absorbed from surrounding iii $E = mc\Delta T$ iv the gas undergoes an adiabatic process v thermal equilibrium vi the second law of thermodynamics vii $PV = nRT$ viii the first law of thermodynamics ix the mechanism is pressure x the ideal gas law
↕	SGØ	Student is describing object(s) but referring to physical process(es), either explicitly or implicitly providing some explanation or embedding some cause. (Often 'links' SG– and SG+ levels)	i therefore it absorbs the heat from the surroundings, decreasing the temperature ii P stays the same. V decreases and therefore temperature decreases iii this causes the heat in the surrounding the cylinder to drop iv so heat flows into the surface, cooling the gas v it is expanding because the pressure outside the cylinder is less than inside vi and so the expanding gas removes heat from the nozzle of the cylinder vii work is done by the system – it loses energy in the form of heat viii in this situation, heat leaves the tank as the gas is released
Stronger	SG+	Student refers to the object or its characteristics, or rephrases or extends the question	i the gas is released from the cylinder ii when gas is released it meets a cool surface iii so it sticks to the wall of the tank iv there is a greater density of gas in the cylinder at the start v the formation of frost was a direct result of the gas leaving the cylinder vi frost formed vii propane and butane are gases at room temperature viii as gas is released the volume of gas decreases ix the pressure in the tank decreases, however, the volume remains constant

Augmenting conceptions research

Conceptions, alternative or otherwise, were identifiable in student responses. These conceptions were identified to reside in the SGØ level and revealed the reasoning of the student. It was where the student provided, implicitly or explicitly, the supposed mechanism which led to the frost formation. These mechanism(s) are termed 'emergent conceptions'.[2] Emergent conceptions are not necessarily wholesale statements from the students, although they have been summarized as such in the list below for illustrative purposes:

- Decrease in pressure leads to decrease in temperature
- Decreased temperature leads to frost forming
- Heat flows from warm to cold
- Increased disorder results in decreased heat which results in decreased temperature
- An expanding gas absorbs heat from surroundings, leading to a decrease in temperature
- Heat transfer from something makes that object colder
- Objects in contact reach thermal equilibrium with each other
- Heat transfer from air results in condensation and freezing
- Decreased order increases entropy and decreases temperature

Many of these emergent conceptions, particularly those identified as alternative conceptions (or misconceptions) are widely catalogued in the existing literature. Take, for example, 'decrease in pressure leads to decrease in temperature'. In general, this extensively reported idea has been associated with an over-reliance on algorithmic or inappropriate use of formulae (Boudreaux and Campbell 2012). The reports also reveal that holding such alternative concepts may impact further learning and are notoriously difficult to fully master (Lin *et al.* 2000; Meltzer 2004, 2005). However, Boudreaux and Campbell (2012: 710) also add that 'In reporting student difficulties, we do not necessarily imply that student ideas are stable and coherent, as a "misconceptions model" of student reasoning would suggest'. Through enacting the concept of 'semantic gravity', these emergent conceptions, 'residing' in the SGØ level, cannot easily be misconstrued as isolated and discrete. Using this concept, researchers are forced to consider the context of the student's response. The rhetoric of a student 'holding' a specific conception can therefore be replaced with an emphasis on the conditions of its emergence. The next two sections discuss the significance of this reconceptualization.

Semantic gravity range of student responses

By moving beyond a focus solely on discrete categories, one can also explore further characteristics of the knowledge being expressed by students. With

LCT one can analyse the range embraced by the relative strengths of each relation, their reach from strongest to weakest. Here one can explore the semantic gravity ranges demonstrated by students' responses. Most students' (85 per cent) responses employed at least two of the three strengths of semantic gravity being used here. This includes, in approximately equal measures, responses coded to both SG– and SGØ and the SGØ and SG+ level. Such responses indicate that students attempted to link general principles or use established physics mechanisms to explain a concrete physical phenomenon.

Although the employment by students of more than one level of semantic gravity in their responses sounds fairly obvious (or it would be to physics instructors and educational researchers), it is a distinct quality in response to a somewhat unique knowledge structure. According to the novice–expert literature, students begin to develop distinct characteristics as they become more expert learners; they are able to see past the surface features of a question, successfully link theory to examples and use the correct terminology. However, these characteristics are becoming increasingly ambiguous and difficult to confirm (Mason and Singh 2013). This first insight, therefore, provides a stronger theoretical basis to support part of these claims. The novice and the expert's approaches can be made explicit by referring to the presence of different strengths of semantic gravity in their responses. For example, students less exposed to physics, when asked to explain a physics phenomenon, are more likely to give concrete answers or answers resembling opinions, responses that reflect a narrower semantic range (Georgiou 2009).

Figure 9.1 presents a visual representation of different relative strengths of semantic gravity and therefore gravity ranges. Students lacking experience in science present a very limited gravity range in explanations, often remaining at the very concrete levels of stronger semantic gravity (A1). Students with a strong background in physics, although not necessarily successful in the content of their explanations, appreciate that a broader gravity range is necessary (B1, B2), one that reflects the depth of different degrees of context-dependence across the knowledge structure of physics. As such, the analysis here makes transparent characteristics that would have been missed in an approach which focused instead on 'content' or 'correctness'. That is, the *structure* of the response is evidence itself and a valuable supplement to analysis of the content. The tangibility of using the concept of 'gravity range' facilitates the production of further questions, such as how the semantic range of responses changes with different levels of 'expertise' or, as will be discussed in the next section, how the range relates to the success of a response.

Moving beyond conceptions: the Icarus effect

Maton (2013: 18) draws attention to the importance of context-dependence for knowledge-building as the latter 'requires both upwards shifts from specific contexts and meanings, and downward shifts from generalized and

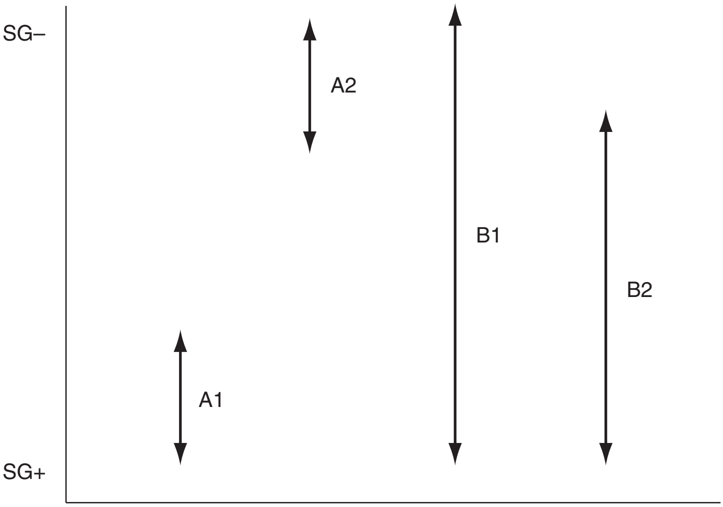

Figure 9.1 Examples of different ranges of semantic gravity in student responses.

Note
SG+ refers to stronger semantic gravity; SG– refers to weaker semantic gravity.

highly condensed meanings'. In physics education, transfer of skills and knowledge is a priority; it is desirable for students to learn to apply a principle to a context outside of that which it was introduced. The frosty cylinder problem requires the appropriate selection appropriate and enactment of physics knowledge to answer successfully. In terms of semantic gravity, it is 'where the students reach', rather than solely what conceptions they portray, that determines how successfully they answer the question. Students that 'reach too high' or exhibit responses with weaker semantic gravity (range B1 in Figure 9.1) are more likely to fail to make the appropriate connections in their explanations. They have reached too high, into abstract principles that are not necessarily required for answering the specific question. A discussion of the explanation of the nature of the ideal gas equation as the students' understanding of it will evidence this assertion.

The ideal gas law is as follows:

$$PV = nRT$$

Where P = pressure, V = volume, n = number of moles of gas, R = gas constant 8.314 $\mathrm{J \cdot K^{-1} mol^{-1}}$, T = temperature

This is a general law which applies to an 'ideal gas' and, like all physical laws, it involves a set of assumptions. Most real gases can be considered as ideal gases and so the ideal gas law can be applied to determine characteristics of interest for gases used in a wide variety of contexts. This law can help describe, for example, what might happen if you have a gas confined in a fixed volume and increase the temperature (the pressure will increase), or if you compress a gas at a fixed temperature (the pressure will increase). Although the idea gas law has great explanatory power, it has been reported that students often find the interpretation of this law difficult and are not successful in its application to different circumstances. Most commonly, the law is misunderstood as a two-variable equation, such as Ohm's Law ($V=IR$) or Newton's Second Law ($F=ma$), rather than a three-variable equation. It is therefore overlooked that only one variable will change in response to another; i.e. that the change of more than one variable, unlike the two-variable situation, will not result in predictable outcomes (increases or decreases in the dependent variable), at least without the specific quantitative information.

In the responses analysed for this chapter, all uses of the ideal gas law in response to the frosty cylinder problem, implicit or explicit, were scientifically inaccurate either by contradiction or by failing to account for the three-variable situation. Explicit mention of the ideal gas law occurred in 39 of the 133 responses, while 40 additional responses implied a reference meaning around 60 per cent of responses deferred to the ideal gas law as the mechanism explaining the frosty cylinder phenomenon. Here is the most common explanation for how the ideal gas law was used to explain the frost formation:

> Due to the pressure decreasing as a result of gas leaving the cylinder, the temperature decreases.

In and of itself, this explanation is a typical example of mistaking a three-variable problem for a two-variable problem. A strong causal link would depend upon a statement about the other variables. In this case, if the gas is leaving the cylinder, the number of moles of gas should also be affected. The number of moles, the pressure and the temperature cannot be related in this way without more information.

Therefore, students attempting to link changes in pressure, volume and number of molecules to a change in temperature in this way confirm the difficulty of reasoning attached to a three-variable problem. But it is more than that. Students were not provided with a question about an ideal gas under certain conditions, a ubiquitous question in first year thermodynamics; they had a choice. This result does not involve merely providing students with the content and asking them to work through it, it required a decision to be made by the student on which concept(s) they were going to use in their explanations. The question therefore becomes why they chose to use the three-variable problem in the first place. They did need to employ 'SG–' reasonings in their responses but in fact accommodated them by making spurious or sometimes unreasonable assertions.

Interview data suggests students suppressed an impulse to 'reach higher' and apply the ideal gas law to the situation. The student's justifications for these choices were compelling. Six students in total were given the question and asked to provide a verbal explanation. All but one explained the question using the ideal gas law. All students were asked why they drew upon the ideal gas law to provide an explanation for the frost formation. Answers included: 'Because we saw it a lot'; 'Equations are easier and more convenient to use compared to a conceptual understanding'; and 'It's one of the first things you look at when you look at gases and it has a lot of things in it and it uses the word gas in it'.

Students were then prompted to consider alternative explanations:

T: Can you think of another way to explain this?
S: When the gas is expanding … it's doing work on its surroundings…
T: So if a gas is doing work, how does it do this work?
S: Well … the work … heat is equal to work.… So, if … the energy of the work has to come from somewhere. That comes from the container, so the temperature of the container decreases because the particles of the container are moving slower and gave lower energy.

A second student came to the same conclusion. When arriving at the explanation that an expanding gas requires energy the student commented that: 'I'd say the second one [explanation] was clearer because like you can visualize it better … it's less abstract'.

Although it is possible to use the ideal gas law to explain what is happening with the frosty cylinder, it is not actually necessary or appropriate in this case. Students were tempted by the equation to reach up to a higher level of abstraction than required and this may be a reflection of student attitudes toward physics or a consequence of the way that physics is taught throughout school and university (general principles first (A2), examples later (A1 in Figure 9.1), and not necessarily with an intermediate link).

In essence, the results showed there is an appropriate semantic range associated with successfully answering the frosty cylinder problem (B2) and that students who were not successful drew on explanations that were too weak in semantic gravity (A2, B1). It was not only that students had problems understanding that three-variable equations could not be manipulated as two-variable equations, or that they were unable to successfully use the ideal gas law, it was also that they were compelled to reach up to a more general equation when it was not necessary.

Discussion

Research in concepts and conceptual development has helped make sense of students' understanding in science. However, many researchers are arguing that we must move beyond simply identifying and describing conceptions. The direction most scholars have taken thus far is to focus on the individual mind (the knower) and generic processes of 'knowing', leaving behind issues surrounding the nature of the knowledge itself. Yet, as Erduran and Scerri (2002: 22) put it, citing Schwab (1962):

> expertise in teaching requires both knowledge of a content of a domain and knowledge about the epistemology of that domain. Teachers develop the necessary capability of transforming subject into teachable content only when they know how the disciplinary knowledge is structured.

Context dependence is one aspect of disciplinary knowledge structure focused on in this chapter through the concept of 'semantic gravity'. The first step in the analysis identified the presence of combinations of different strengths of semantic gravity – the gravity range – in student responses and it was clear that students with more experience with physics produce answers with a definite structure. They are more likely to exhibit a larger gravity range.

Most significantly, when both the structure and content of responses are considered together, the conclusion is that, in this instance, students employing knowledge with relatively weaker levels of semantic gravity – signalled by use of the ideal gas law – were more likely to be unsuccessful, leading students down the wrong path. This result suggests that there is an appropriate semantic range for success. The chapter also examined why students were favouring concepts with weaker semantic gravity. Students are tempted by more abstract principles for a variety of reasons and often went to extraordinary lengths to try to make them work.

Moving from the structure of responses to their content, and drawing on the conceptions literature, the concept of the emergent conception was also introduced. Emergent conceptions are conceptions, alternative or otherwise, that reside in the intermediate level of semantic gravity. This distinction emphasizes the need to consider the entire student response rather than identifying similar words or phrases and labelling them as 'misconceptions' or 'alternative conceptions'. This is particularly important when comparing students of different levels of expertise and when taking into account whether responses are correct or incorrect is not illuminating.

While the primary purpose of this chapter is to show how a concept from the LCT dimension of Semantics offers an insightful approach for PER, it is also worth noting its potential contribution to teaching. The concept of semantic gravity provides a language with which to interpret institutional practice in thermal physics. For example, many of the questions that are designed for use in conceptual surveys and first year examinations in thermal physics that ask questions about the ideal gas already include various assumptions (e.g. consider a fixed volume cylinder). Effectively, such questions, popular because there is usually a unique and unambiguous solution, provide a scaffold which lifts the context-dependence away from the very concrete. That is, typical physics questions involve weakening semantic gravity and removing the need for students to discuss more concrete behaviours or practice selecting which more general principles are appropriate. Therefore, is it not surprising there are reports that students are unable to effectively transfer the learning of general principles to other, unfamiliar contexts (Atkinson *et al.* 2003). This is particularly salient when considering fundamental understanding, which can remain underdeveloped despite increasing in expertise in physics more generally (Meltzer 2005). Semantic gravity thus provides a valuable meta-language for instructors and course designers. For example, the instructor may wish to focus on strengthening the semantic gravity when presenting the concept during instruction, perhaps by introducing Boyle's Law, Charles' Law and Avogadro's Law before the Ideal Gas Law, in order to strengthen the links across the gravity range. Alternatively, an analysis of the semantic gravity implied by the problems could help clarify certain objectives of instruction by exploring which semantic gravity range is being activated. The identification of this structure could thus allow for greater understanding (or even prediction) of both successful and unsuccessful attempts in teaching these concepts. (Compare Blackie 2014 on using Semantics in chemistry teaching.)

Conclusion

This study showed how 'semantic gravity' conceptualizes an organizing principle of knowledge and reveals its consequences for research, teaching, and learning. Specifically, this example provided insight into student understanding: that it is not just a matter of whether students are providing correct answers, it is also a matter of whether they grasp that there is an appropriate range of semantic gravity for their answers, that learning physics includes learning how abstract and how concrete one needs to be. More generally, enacting the concept of semantic gravity also addresses limitations of science and physics education research. It addresses a methodological limitation that leads to an over-reliance on categorization and it enhances theoretical perspectives by turning the focus onto knowledge as an object. Given the discipline of physics is typically considered an archetypal knowledge structure, one can expect to understand more about the teaching and learning of physics if one also pays closer attention to knowledge practices. Physics does not just consist of physics content, and physics content does not reside solely inside a student's mind, just as semantic gravity is not a piece of content – it is not inside physics – it is describing an organizing principle of physics as a knowledge structure.

Notes

1 A comprehensive selection with references to published papers may be found at www.flaguide.org/tools/tools_discipline.php.

2 They 'emerged' from the SG0 level.