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Recovering knowledge for science education research: Exploring the "Icarus effect" in student work

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Abstract

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Keywords

recovering, knowledge, student, science, exploring, icarus, effect, education, work, research

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Recovering Knowledge for Science Education Research: Exploring the "Icarus Effect" in Student Work

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Abstract: Science education research has built a strong body of work on students' understandings but largely overlooked the nature of science knowledge itself. Legitimation Code Theory (LCT), a rapidly growing approach to education, offers a way of analyzing the organizing principles of knowledge practices and their effects on science education. This article focuses on one specific concept from LCT—semantic gravity—that conceptualizes differences in context dependence. The article uses this concept to qualitatively analyze tertiary student responses to a thermal physics question. One result, that legitimate answers must reside within a specific range of context dependence, illustrates how a focus on the organizing principles of knowledge offers a way forward for science education.

Résumé: La recherche en enseignement des sciences a produit de nombreuses études sur la compréhension des étudiants, mais a souvent ignoré la nature du savoir scientifique lui-même. La théorie de la légitimation du code (TLC), une approche de plus en plus importante en enseignement, propose une façon d'analyser les principes structurels des pratiques du savoir et leurs effets sur l'enseignement des sciences. Cet article est centré sur un concept en particulier tiré de la TLC—la gravité sémantique—qui conceptualise les différences comme étant dépendantes du contexte. L'article se sert de ce concept pour faire une analyse qualitative des réponses tertiaires des étudiants à une question de physique thermique. L'un des résultats, selon lequel les réponses légitimes doivent se situer dans un certain rayon de dépendance contextuelle, illustre comment le fait de mettre l'accent sur les principes structurels du savoir ouvre une avenue prometteuse pour l'enseignement des sciences.

INTRODUCTION

One of the most established research programs in science education is the study of students' conceptions and conceptual change (Chang, Chang, & Tseng, 2010; Tsai & Wen, 2005). Forty years of research into students' thinking has led to significant theoretical and practical advances; for

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example, explicating students difficulties as "alternative conceptions" has underpinned development of tools for identifying conceptions and determining learning outcomes of newly designed instructional approaches (Bektasli, 2013; Francek, 2013; Yalcin, Altun, Turgut, & Aggul, 2009). Several fundamental issues remain subject to considerable debate, including the nature of student conceptions (diSessa, 2006) and the value of notions of alternative conceptions (Clement, Brown, & Zietsman, 1989). Nonetheless, the centrality to research of this focus on students' understandings of specific ideas remains a fundamental orthodoxy of science education research. The current article begins from a different starting point. It highlights how this existing focus can obscure exploration of the nature of knowledge itself and its effects for science education, including for student conceptions themselves. To explore this issue, we introduce a complementary perspective based on the multidimensional conceptual framework of Legitimation Code Theory (LCT). This approach offers a means of exploring the forms taken by knowledge in ways that embrace a wide range of institutional, disciplinary, and social contexts and is rapidly growing as a basis for empirical research into knowledge practices in education and beyond. To illustrate its usefulness, we introduce one concept from this sophisticated approach—*semantic gravity*—which explores the context dependence of knowledge. We then apply this concept in a case study of student responses to a thermodynamics question. Highlighting the theoretical value and practical pedagogic implications enabled by this framework, we conclude by proposing that LCT offers a potentially fruitful approach for analyzing and shaping science education research programs into the future.

THEORETICAL BACKGROUND

Seeing Knowledge in Science Education Research

Joseph Schwab (1978) described a heuristic for the study of science education, which he called "commonplaces." Schwab's original four commonplaces included the teacher, student, subject matter, and milieu (environment), which he emphasized as equally important:

> None of these can be omitted without omitting a vital factor in educational thought and practice. No one of them may be allowed to dominate the deliberation unless that domination is conscious and capable of defense in terms of the circumstances. (Schwab, 1978, p. 371)

Helms and Carlone (1999) suggested that Schwab's heuristic "provides the opportunity to meld perspectives from metascience disciplines and science education to connect theory and practice" (p. 242) and could improve understanding of classroom practices. However, as yet not all four commonplaces have received equal attention in science education research. As mentioned above, "the student" and "the teacher" have been the focus of considerable and sustained research; student conceptions and instructional strategies have been dominant objects of study for the field. The "milieu" has come to increasing prominence since the 1970s with the rise of sociocultural theories. "Subject matter," however, remains relatively underexplored—it is a commonplace that is rarely discussed.

Typically, subject matter has been displaced by the student, such as exploring student conceptions of subject matter. Consider, for example, one of the more sophisticated theoretical approaches to science education research, the "resources framework" advanced by Redish and colleagues (e.g., Bing & Redish, 2009; Redish, 2003). Focusing on an aspect that resonates with our substantive focus further below, the resources framework terms *epistemological framing* as the "student's perception or judgement (unconscious or conscious) as to what class of tools and skills are appropriate in a given context" (Bing & Redish, 2009, p. 1). Bing and Redish showed that a student's ideas about the nature of scientific knowledge, such as it being "fixed and absolute or as being relative to one's point of view" (2009, p. 4), influence how a student approaches instructional tasks. This work valuably foregrounds differences in the forms taken by student conceptions of knowledge. However, were this to be equated with (rather than complemented by) conceptualization of the knowledge itself, an understanding of subject matter would be reduced to analyzing the student.

This knowledge-blindness is not confined to science education research—it reflects a wider subjectivist doxa in educational research (Maton, 2014). Since the late 1990s, a growing number of social realists (e.g., Maton & Moore, 2010; Moore, 2009; Wheelahan, 2010) have argued that knowledge has been largely neglected by educational research, thanks to a "widespread belief that 'knowledge' entirely comprises a state of mind, consciousness or a disposition to act, is wholly sensory in source, and must be inextricably associated with a knowing subject" (Maton, 2014, p. 4). They highlight that psychologically influenced approaches typically focus on students' learning processes, and sociologically influenced approaches typically foreground how students' experiences are shaped by power relations (whether with the teacher or within the milieu). Both thereby tend to foreground the knowing of knowers and background knowledge; both obscure the nature of what is being learned, treating knowledge itself as homogeneous and neutral. Knowledge as an object of study emergent from but irreducible to the ways and contexts in which individuals or groups know has been largely obscured. In contrast, social realists highlight a growing body of work (see further below) that reveals how different forms of knowledge have effects, including on the foci of other commonplaces. Student learning outcomes, for example, are formed through interactions not simply with a phenomenon but also (and often only) with existing knowledge of different kinds—commonsense knowledge, popular forms of scientific knowledge, educational knowledge—and the forms taken by these knowledges help shape students' understandings (Maton, 2013, 2014).

This is not to suggest that the potential for analyzing forms of knowledge is absent from science education research. Though focused on student conceptions, models such as the resources framework can be extended to explore the nature of the knowledges that students encounter. Similarly, studies of individual concepts abound, typically focusing on the development and change of students' understandings and involving, for example, identification of misconceptions (Chang et al., 2010; diSessa, 2006). Concepts have been the unit of interest because of their value in offering students a means for navigating disciplines (diSessa, 1993; Halloun & Hestenes, 1985; Hammer, 1994; Minstrell, 2001; Sabella & Redish, 2007). This body of work represents a valuable first step. Indeed, a number of explanatory models have emerged from this focus (e.g., novice expert and misconceptions), some leading to large-scale policy decisions (Beichner, 2009).

Nonetheless, even if extended to embrace knowledge as well as knowing, this first step requires developing further to overcome the tendency of existing models toward an undifferentiated and often atomistic image of science knowledge. For example, diSessa (1993) foregrounds pieces of knowledge in physics that students believe are an irreducible feature of reality (i.e., requiring no further explanation) or *phenomenological primitives* (p-prims). Leaving aside this focus on students' understanding, the p-prims themselves are homogeneous in form and science education reductively conceived as the sum of learning individual parts. Redish (2003) extends the model to

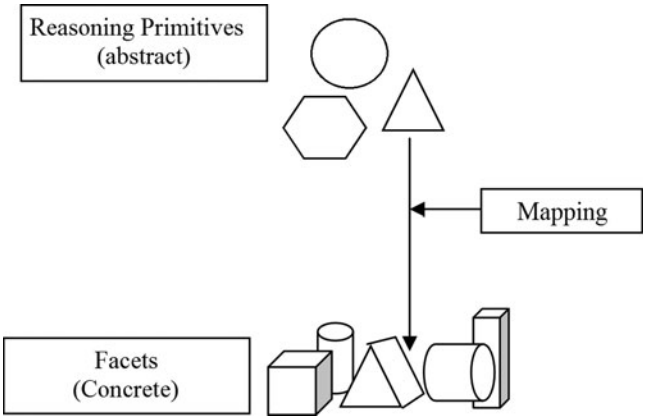

FIGURE 1 Abstract Reasoning Primitives Are Mapped Onto Facets for Specific Physical Situations (Amended From Redish, 2003, p. 17).

explore differences within science knowledge in terms of a further *abstract reasoning primitive*, which is a general rule or relationship that “maps” onto p-prims, now redefined as representations of concrete facets of real-world objects or quantities (see Figure 1). This begins to overcome the homogeneity of the form taken by p-prims by differentiating between a “general idea” and a “concrete observable description” where the former may map onto the latter and the two types of knowledge have distinct functions for explaining the natural world.

Nonetheless, while pointing in the right direction, the model requires development to overcome the limits of the *kind of theorizing* such approaches embody. Typologies, including Bloom (1976) and Shulman (1986), and such widely used but ill-defined dichotomies as abstract/concrete, struggle to capture both empirical practices, which rarely fit within their lists of types and processes of change within and between types. They thus need developing to conceptualize the organizing principles that generate diverse types of knowledge practices. Moreover, to adapt Henri Poincaré (1895, as cited in Scribner, 1963), science is no more a collection of primitive parts than a house is a pile of bricks—scientific knowledge embodies an architecture based on organizing principles. It is apprenticeship into these organizing principles as much as, if not more than, learning specific atomic propositions that comprises the work of science education. We thus now turn to introduce a conceptual framework that explores the forms and organizing principles of knowledge practices across a wide range of phenomena, one that we suggest represents a valuable complement to existing approaches to science education research.

Legitimation Code Theory: Semantics

Legitimation Code Theory is an explanatory framework for analyzing and changing practice. It forms a core part of social realism, a broad coalition of approaches that reveal knowledge as both socially produced and real, in the sense of having effects, and that explore those effects (Maton, 2014; Maton & Moore, 2010). LCT extends and integrates ideas from a range of theories, most centrally the frameworks of Pierre Bourdieu and Basil Bernstein. This ongoing theoretical development is in close relation with empirical research. LCT is a practical approach and designed to be an open-ended endeavor that foresees its own repeated refinement, deepening, and extension through substantive studies (Maton, 2014). The framework is rapidly growing as a basis for empirical research into education at all institutional levels and across the disciplinary map—from primary schools to universities, from physics to jazz—in a widening range of national contexts, as well as beyond education (Maton, Hood, & Shay, 2014).[1] The framework of LCT includes a multidimensional conceptual toolkit, where each dimension offers concepts for analysing different organizing principles underlying practices (Maton, 2014).

In this article, to illustrate how LCT may offer a way of furthering the insights of existing approaches, we focus on one concept from the dimension of Semantics—*semantic gravity*—that addresses an issue already raised above (when discussing the work of Redish): the context dependence of knowledge. As Maton (2013, p. 11) defined 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.

Unlike typological conceptions of knowledge, the notion of semantic gravity is not a homogeneous box into which variegated and changing practices are to be reduced. Rather, all practices are characterized by semantic gravity, 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 toward generalizations and abstractions whose meanings are less dependent on that context, and strengthening semantic gravity, such as moving from abstract or generalized ideas toward concrete and delimited cases (Maton, 2013, p. 11). One can also describe the *semantic gravity range* of practices (the difference between their strongest and weakest strengths) and the gravity profile that changes in strengths trace over time (Maton, 2014, pp. 106–124).

It should be emphasized that semantic gravity is not the only concept in the dimension of Semantics, and Semantics is not the only dimension of LCT. Our illustrative focus on one small part of the framework is for the sake of brevity. Nonetheless, this concept is being widely adopted in studies of education, including biology and history (J. R. Martin & Maton, 2013), ethnographic methods (Hood, 2014), design (Shay & Steyn, 2014), engineering (Wolff & Luckett, 2013), environmental science (Tan, 2012), jazz (J. L. Martin, 2012), journalism (Kilpert & Shay, 2013), and teacher education (Shalem & 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. Within LCT, studies of science inform and are informed by studies of the arts and humanities, as well as informal learning contexts, such as museums (Maton, Carvalho, & Dong, 2014).

This flexibility is, however, not at the expense of empirical precision. LCT includes the notion of developing an external language of description or means for translating between concepts and empirical data that show how concepts are realized within the specific object of study being explored (Maton & Chen, 2014). For example, an external language of description for semantic gravity defines what is meant by *context* and how relative strengths are determined in the data under analysis. Having defined semantic gravity, we shall now describe the data, including the sample and educational context, and the external language of description developed to enact semantic gravity in this study.

METHOD, SAMPLE, AND EXTERNAL LANGUAGE OF DESCRIPTION

The data collection and analysis discussed here is part of a larger study that focuses on the subject area of thermodynamics. The rationale for this focus is nontrivial and explained in greater detail elsewhere (Georgiou, 2009; Georgiou & Sharma, 2010). Significantly, thermodynamics at the tertiary level has received much less attention than other content areas and has been reported as particularly difficult for students, and mastery of thermodynamics has been shown to have substantial benefits for a global scientific proficiency. Thermodynamics also underpins current and significant social and political issues such as climate change. The data discussed here primarily included student responses to the question below, which were analyzed with respect to their relative strengths of semantic gravity, and student interviews, conducted to triangulate this analysis.

> The frosty cylinder problem:
>
> 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 thermodynamic system involved in this situation is a typical cylinder used for barbecues, containing liquid fuel (propane or butane) and vapor fuel. The question asks why frost accumulates on the outside of the cylinder. The reason frost forms is due to heat exchange (heat transfer), from the air outside the cylinder (that contains the water molecules) to the cylinder. This heat exchange results in water condensing and freezing onto the cylinder. The heat transfer occurs from the air to the cylinder to the liquid fuel inside the cylinder as a result of evaporation occurring in the liquid fuel to maintain an equilibrium vapor pressure as the gas is released.

Many students did not realize that a gas cylinder contains both liquid and vapor fuel, though consistent answers could still be provided. One example of such a scientifically consistent response is that an expanding gas does work and therefore requires heat. The subsequent heat transfer from the cylinder and consequently the surrounding air results in the condensation of the water molecules in the air and their ultimate freezing.

That question assumed knowledge of the workings of a gas cylinder, combined with the requirement to explain at least one mechanism elicited an extensive range of physics content in student responses, which revealed both which concepts were deemed most relevant and an explanation of those concepts.

Sample

The study took place in 2011 with a sample of 133 first-year physics students at a large metropolitan university. The students were participating in a thermodynamics module, one of three modules in a first semester course. This particular question was one of four administered through the module and as part of the wider project tracking student conceptions during the evaluation of a new course structure.

The students in this sample were mainly bachelor of science, medical science, and engineering (approximately 63%) students, with very similar high school–leaving marks ($M = 91$, $SD = 5$), placing them in the top 10% of the state. The question was administered at the beginning of the lecture class and collected at the end. Lecture observations and evaluation forms show that the question was completed largely independently by the students, who reported serious effort in completing it, and took approximately 10–15 minutes to write their responses. The average length was three or four sentences with some use of equations and diagrams.

Data Analysis

Analysis of student responses to the *frosty cylinder problem* using the concept of semantic gravity was primarily conducted by the first author in consultation with the coauthors. This coding was validated through a formal meeting and e-mail discussions with two physics education researchers at the authors' university. These researchers were familiar with the data, having previously been asked to analyze the responses using the structure of learning outcomes (e.g., Biggs & Collis, 1982; Georgiou, 2009), which they found unsatisfactory and which led to contrasting and unreliable results. In contrast, using the LCT concept of semantic gravity led to agreement at an interrater reliability of at least 90%, with alterations to coding characterization occurring where necessary. This process of analysis enabled the external language of description shown in Table 1 to be developed.

Table 1 describes three levels representing relative strengths of semantic gravity. The weakest semantic gravity ("red" level) includes general principles used to justify the reasoning made in the response. The strongest semantic gravity ("yellow" level) includes descriptions of the objects in the question including repetition of the question in other words. The intermediate strength ("green" level) includes reasoning of the student and often linked knowledge claims with weaker semantic gravity to those with stronger semantic gravity. Having coded the responses, one can then analyze the success or otherwise of student responses in terms of the employment of knowledge characterized by these three strengths.

Although responses are grouped into categories of distinct strengths of semantic gravity, this is not to suggest that responses within categories are undifferentiated or the levels are homogeneous. For example, responses in the red level (discussed below) include abstract general principles but they are not equally abstract; for example, (iii) ($E = mc\Delta T$) compared to (viii) (the first law of thermodynamics). Though for our purposes it was unnecessary to make more finer-grained distinctions, this is a potential step for future analyses—the concept of semantic gravity enables unlimited differentiation.

We now turn to discuss illustrative findings arising from this study. We begin with a dominant preoccupation of science education research: the content of student conceptions of scientific knowledge. Secondly, we explore how complementing this focus with exploration of the form and organizing principles of students' knowledge claims, employing the concept of semantic gravity, sheds further light on the basis of achievement in science education.

TABLE 1
An External Language of Description for Semantic Gravity (Description of Coding With Examples)

Semantic gravity	Coding categories	Description of coded content	Examples of student responses (including original grammatical and spelling errors)	
Weaker	Red (R)	Student is describing a physical principle, law, theory, or concept in a general enough way that it means something without reference to a specific concept.	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
	Green (G)	Student is describing the object(s) but making reference to a physical process(es)—either explicitly or embedding some cause. Often, the intermediate level "links" the red and yellow 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
			vii	And so the expanding gas removes heat from the nozzle of the cylinder
			viii	Work is done by the system—it loses energy in the form of heat
			ix	In this situation, heat leaves the tank as the gas is released
	Yellow (Y)	Student makes a reference to the object or its characteristics or rephrases or extends upon the question (or the language in 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
Stronger			viii	As gas is released the volume of gas decreases
			ix	The pressure in the tank decreases, however, the volume remains constant

RESULTS AND DISCUSSION

Emergent Conceptions

The reasoning displayed in students' responses included what can be termed their emergent conceptions, whether implicit or stated explicitly, of the mechanism leading to the frost formation, including:

- A 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.

Most of these emergent conceptions, when taken in the context of the students' full responses, are also alternative conceptions or misconceptions. The identification of alternative conceptions in diverse subject areas and student age groups is voluminous. For the subject area of thermodynamics, there has been less research, especially at the university level. However, even this small body of work is suggestive. Meltzer (2004, 2006), for example, has shown that misunderstanding of basic assumptions covered in first year carry on to advanced third-year subjects. He also presented evidence that many thermodynamical principles, including entropy, work and pressure–volume diagrams, are difficult to master. More troubling is the failure of university students to grasp very basic concepts that were introduced in high school and therefore represent assumed knowledge for first-year courses: basic mechanisms underlying real, thermodynamic phenomena, such as those evident in the frosty cylinder problem.

We also find parallels with our emergent conceptions in several recent studies in chemistry education. Specifically, we draw attention to two emergent conceptions, "A decrease in pressure leads to decrease in temperature" and "decreased temperature leads to frost forming." The former has been associated with an overreliance on algorithmic thinking or using formulae (Boudreaux & Campbell, 2012; Lin, Cheng, & Lawrenz, 2000), whereas the latter has been associated with lack of attention to microscopic processes. In other words, students have little understanding of the processes involved and are relying on the inappropriate selection and use of equations or principles.

So far, so familiar, at least in terms of the overall focus: identifying (alternative /mis)conceptions of students has been a central concern of the wider science education field. The point we are illustrating in this article, however, is that not only the content but also the form taken by students' knowledge claims offers insight into achievement. This is to foreground the organising principles realized by knowledge practices, such as semantic gravity.

Semantic Gravity Range of Student Responses

Table 2 presents the ways in which students' responses included knowledge claims of similar or differing strengths of semantic gravity. As Table 2 highlights, most of the responses (85%) were characterized by at least two of the levels we identified for this analysis. In short, the overwhelming majority of responses included a greater semantic gravity range than solely concrete description or solely abstract principles. In attempting (in differing ways, to which we shall return) to explain a concrete physical phenomenon in terms of general principles or physics mechanisms, their responses thereby embodied a greater semantic gravity range than those of novices to physics. For example, when asked to explain a physics phenomenon, junior high school students have

TABLE 2
Employment of Different Strengths of Semantic Gravity

Levels present	Coding present	No. of coding references
Single levels	Green only	15
	Yellow only	1
	Red only	4
Two levels	Green/Red	26
	Green/Yellow	37
	Red/Yellow	1
Totals	All three	49
	At least two	113
	Total	133

been found to be more likely to offer concrete or opinion responses embodying stronger semantic gravity (Georgiou & Sharma, 2010). Moving beyond context-dependent meanings may also be a defining characteristic of science: a similarly limited range of semantic gravity can be found among students in humanities degrees at university (Georgiou & Sharma, 2010).

The novice–expert literature suggests that students begin to develop distinct characteristics as they become more expert learners: they are able to see past surface features of questions (such as the specific empirical example), successfully link theory to examples, and use the correct terminology. In this research, we suggest that the implicit sense of what makes a good answer can be made explicit by looking at the strengths and ranges of semantic gravity. Figure 2 offers a heuristic comparison of different ranges represented by student work from this and other studies (e.g., Georgiou & Sharma, 2010; cf. Maton, 2014, pp. 106–124). Students lacking experience in science present a very limited semantic gravity range in explanations—their knowledge claims

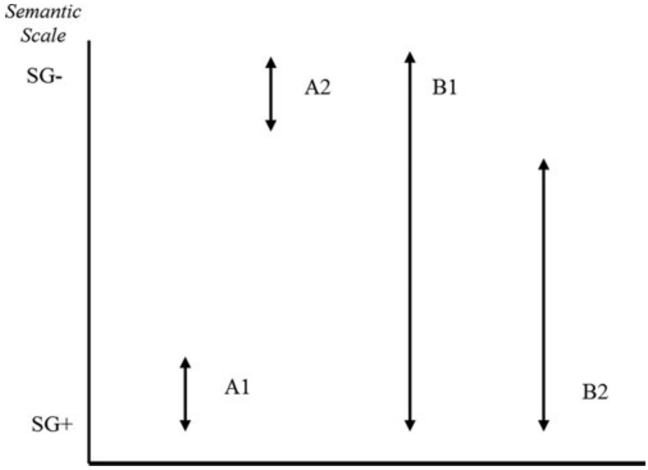

FIGURE 2 Examples of Different Ranges of Semantic Gravity in Student Responses (SG+ Refers to Relatively Stronger Gravity and More Context Dependent While SG- Is Relatively Weaker and More Abstract).

TABLE 3
Responses Explicitly or Implicitly Employing the Use of the Ideal Gas Equation

	Coded	No. of responses	Examples (including original grammatical and spelling errors)
Ideal gas equation/law	Red	38	Due to ideal gas law; $PV = nRT$
Implied references	Green	40	The decrease in pressure within the tank causes a decrease in temperature Since the volume of the gas increased, the temperature decreased However the amount of gas particles in the cylinder decreases causing a decrease in temperature as well

often remain at high levels of context dependence (A1). A similar limited range at a high level of abstraction (A2) is found much less frequently (e.g., see "Single levels—Red only" in Table 2). Students with more background in physics, although not necessarily successful in the *content* of their explanations, typically appreciate that a greater semantic gravity range is necessary for success (B1 and B2).

The "Icarus Effect"

Crucially, the emergent conceptions discussed above are found in the middle level of semantic gravity. They represent links between concrete description and generalizing principles. The significance of getting these right (what is termed in LCT as reaching the "semantic threshold"), and thus the continuing importance of research into conceptions, is obvious in enabling students' understandings to reach higher toward scientific principles. However, analysis using the concept of semantic gravity further reveals that it is not necessarily a case of "the higher the better": abstractions and generalizations are not themselves the goal. Moreover, it is also not merely a question of whether students' knowledge claims are scientifically accurate. Rather, our study suggests that assessments also require a particular semantic gravity range in the knowledge—the form taken by the knowledge claims is significant. Both of these points are illustrated by what we here term "the Icarus effect": students may reach too high, expressing knowledge whose semantic gravity is inappropriately weak for addressing the question at hand. By overreaching, students may fail to make the appropriate connections in explanations. In Figure 2, these responses are represented by B1.

For example, 39 of the 133 explanations in the sample explicitly mentioned the ideal gas law/equation (see Table 3). There were also 40 additional implied responses that made reference to the equation without explicitly mentioning it. Responses based on explanations formulated out of the ideal gas law were essentially unsuccessful. This means that a majority of students endorsed a mechanism for which they were unable to provide a coherent explanation.

The ideal gas law (equation 1) is a general law that applies to an ideal gas, a hypothetical substance that is associated with a group of assumptions. Most real gases can be considered as ideal gases and therefore the ideal gas law can be applied to determine characteristics of interest, usually due to a change in some conditions.

$$PV = nRT \tag{1}$$

where P is pressure, V is volume, n is the number of moles of gas, R is the gas constant (8.314 $\text{J}\cdot\text{K}^{-1}\ \text{mol}^{-1}$), and T is temperature.

This law can tell you, 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 a powerful scientific principle, students often find the interpretation of this law difficult and are not successful in its application to different circumstances. Most commonly, the equation is misunderstood as a two-variable rather than three-variable problem, because two-variable problems are more common in physics; that is, $V = IR$. Only *one* variable can change when another has been altered, regardless of how many other variables are present in the mathematical equation. All uses of the ideal gas equation in response to the question in our data, implicit or explicit, were scientifically inaccurate either by contradiction or by failing to account for variables. For example, a common explanation for how the ideal gas equation can be used to explain the frost formation was as follows:

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

Many responses stated that the number of molecules remained constant, which contradicted the statement that pressure decreased because the gas was let out. This explanation not only assumes that the contents of the cylinder are the gas only but fails to account for the loss of molecules and therefore the decrease in n. If both the number of molecules and the pressure decrease, it is necessary to explain that one does so more than the other, to account for the drop in temperature. There was only one student that attempted to do so:

> pV = nRT T = PV/nr. As the gas is released from the cylinder, the pressure and number of molecules decrease. From the modified equation, the numerator decreases faster than the denominator, causing a decrease in temperature.

In this case, even if we accept that the student had no resources to understand that the cylinder contains a liquid as well as the gas, there is no reason provided for why one variable should change more than the other. Furthermore, mathematically, the statement is inaccurate. An additional decrease in the numerator would actually lead to a higher temperature.

There was also another option involving volume increase:

> pV = nRT therefore pressure decrease will cause both volume expansion and temperature decrease.

The typical oversight in regards to the three-variable problem resurfaces here; students are failing to recognize that they cannot describe all three variables changing at the same time. The pressure decrease cannot result in both volume increasing *and* temperature decreasing.

The difficulty students experienced in attempting to link changes in pressure, volume, and number of molecules to a change in temperature raises the question of why they chose to use the three-variable equation. Students were not required to employ the ideal gas equation in their reasoning but did so, making spurious or sometimes unreasonable assertions to reach the desired outcome. Interview data suggest that students suppressed their "intuition" to apply the equation to the situation. Six students 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.

> Because we saw it a lot.

> Equations are easier and more convenient to use compared to a conceptual understanding.
>
> 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: "Can you think of another way to explain this?" This response from a student was not untypical:

> 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 equation to explain what is happening with the frosty cylinder, it is not necessary or appropriate in this case. Nonetheless, students were enticed by the equation and thus reached up to a higher level of abstraction than the problem required. Our results thereby suggest there exists an appropriate semantic gravity range associated with success in solving the frosty cylinder problem (B2 in Figure 2), one in which higher is not necessarily better. Students who did not recognize the upper limit reached too high, to principles weaker than the strength of semantic gravity required to answer the specific question (B1 in Figure 2). It was not simply that students had problems understanding that three-variable equations could not be manipulated like two-variable problems; it was also that they felt compelled to reach up to a more general equation than was necessary.

IMPLICATIONS

The albeit illustrative analysis presented here suggests that the form taken by knowledge claims may be a significant factor in student achievement in science education. Specifically, it highlights the potential importance of apprenticeship into appreciating the degree of context dependence of meaning appropriate at different stages of the curriculum and for different kind of problems. This in turn has implications for research into issues such as student conceptions. For example, if mastering different ranges of strengths of semantic gravity is appropriate at different stages of learning, it puts in question whether tertiary students hold the same misconceptions as high school students and even primary school students by virtue of uttering the same words in a phrase. Put another way, to fully understand "conceptions" requires understanding the forms taken by the knowledge students are supposed to master through their educational career. In terms of semantic gravity, the tendency of science education to valorize abstraction and generalization, as suggested by the students themselves, might tempt us and them into believing "the higher the better" on the semantic scale. However, the Icarus effect highlights that the range of semantic gravity may have upper limits: one may fly too high too early. In the case study here, students employing

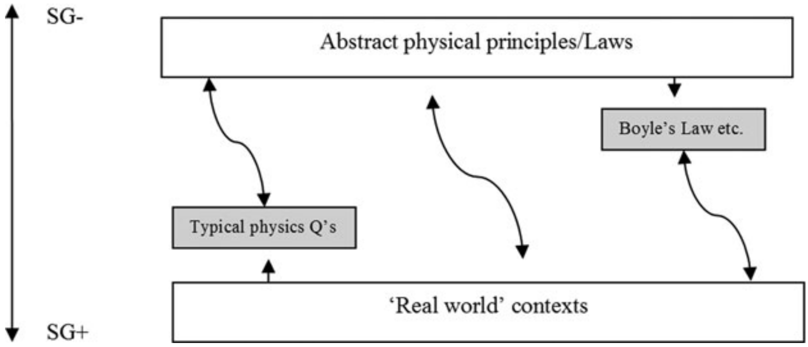

FIGURE 3 Implications for Teaching. The Question May Be Made Less Context Dependent or the Principle Applied Can Be Further Simplified; Both Reduce the Semantic Gravity Range.

knowledge with relatively weaker levels of semantic gravity—signaled by use of the ideal gas law—were more likely to be unsuccessful.

This approach also has implications for instruction. It is known, for example, that most physics problems are highly specialized (Teodorescu, Bennhold, Feldman, & Medsker, 2013). In thermodynamics courses students are often asked to "consider an ideal gas in a cylinder with a frictionless piston . . ." or "using Charles's Law, predict . . ." However, the type of question analyzed in this article requires explanation of a real-world phenomenon. Students are expected to reach up the semantic scale from the context-dependent problem to select which (less context-dependent) concept is appropriate and then move down the semantic scale to enact this concept in an explanation of the given scenario. Students find the frosty cylinder problem difficult because, while establishing the strongest semantic gravity setting required (the concrete example), the question does not indicate its weakest setting; unlike questions that remain in a relatively abstract realm ("consider an ideal gas . . ."), the sky could be the limit in terms of how abstract the knowledge that students are required to demonstrate. The question involves a potentially large semantic gravity range of knowledge.

To illustrate this issue, Figure 3 represents how typical physics questions weaken semantic gravity by avoiding real or familiar physical situations and drawing on idealizations (e.g., frictionless, massless, no air resistance, ideal gas etc.). This brings them close in semantic gravity to the abstract principle of scientific knowledge required in a successful answer. Although in a typical undergraduate course students are trained to approach these questions to succeed in their physics study, students' success or otherwise in this type of task might or might not transfer into other unfamiliar contexts (Atkinson, Renkl, & Merrill, 2003). Thus, questions like the frosty cylinder problem may require additional instruction to establish the semantic gravity range appropriate to their solution, either through extensive modeling by teachers or through making the range explicit using concepts like semantic gravity as a metalanguage in teaching.

As Bing and Redish (2009, p. 4) emphasized, how students approach a question is influenced by, among other things, their ideas about "what kind of knowledge is at play here." Central to the approach offered by LCT is a relational understanding of practice: student outcomes result from the meeting of their dispositions and the context. In terms of science education research, this is to emphasize that student conceptions are student conceptions of something and that something requires analysis. LCT offers a means of analyzing not only knowing and knowers but also knowledge, not only teacher, student, and milieu but also subject matter. Its concepts can be used to analyze both student conceptions and the knowledge they are expected to learn (as realized in model answers, curriculum, textbooks, etc.), showing the degrees to which they match or clash (see Maton, 2014). This is less a focus on right and wrong, alternative conception or misconception of content and more a relational understanding of achievement in terms of the organizing principles of student understanding and science knowledge. It thus emphasizes that science is more than just its content: it has an architecture, including what *form* of knowledge is appropriate, such as the semantic gravity range required to adequately explain a particular problem. LCT also has direct and practical implications for teaching and learning, as evidenced by a growing number of pedagogic interventions drawing on the framework. Macnaught et al. (2013), for example, reported on a study in which teachers were trained to model "semantic waves" (recurrent movements in the context dependency and degree of condensation of meaning) in classroom practice.

Studies in many disciplines are turning their focus to knowledge practices. We have but briefly illustrated one concept from a multidimensional framework that is rapidly growing as the basis for empirical studies across the disciplinary map. Nonetheless, this example shows that Schwab's (1978) commonplace of subject matter does indeed matter, in terms of not only content but also form. LCT offers one way in which we can not only recover knowledge for research into science education but also develop a more sophisticated understanding of its role in science education itself.

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NOTE

1. Numerous examples of this body of work can be found at the LCT website: http://www.legitimationcodetheory.com

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