Students' Understanding of Density: A Cognitive Linguistics Perspective

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Abstract. Density is an important, multifaceted concept that occurs at many levels of physics education. Previous research has shown that a primary instantiation of the concept, mass density, is not well understood by high school or university students. This study seeks to determine how students understand the broad concept of density, and whether particular aspects of their understanding are helpful in structuring the concept of charge density. Qualitative data were gathered in the form of questionnaires distributed to 172 freshmen comprising three different academic groups. Broad, open ended questions prompted for responses involving free writing and drawn diagrams. The data were analysed by an approach suggested by Grounded Theory. Using the theoretical lens of Conceptual Metaphor Theory, six underlying (foothold) concepts were identified in terms of which density was conceptualised: 'filled container'; 'packing'; 'weight/heaviness'; 'intensive property'; 'floating/sinking'; 'impenetrability/solidity'. The foothold concept of 'packing' proved to be the most productive for conceptualising 'charge density'.

Keywords: Density, Conceptual Metaphor Theory, Foothold Concept
PACS: 01.40.Fk

INTRODUCTION

Research conducted in early childhood development [1], secondary school education [2] and tertiary education [3] demonstrate that the various aspects of the concept of density are not easily grasped.

Density is an important concept that is taught at various levels of education. In a standard university introductory level text book mass density is introduced when covering the topic of fluids and is defined as the ratio of mass to volume. At intermediate level, physics students are typically expected to have mastered the following concepts: mass density, charge density, surface charge density, volume current density, surface current density, energy density, flux density, density of field lines, density of states and probability density. Students could benefit from a foundational concept which can serve as a foothold for their understanding of some of these concepts.

The aim of this study is to determine whether particular underlying (foothold) concepts are used by students in understanding the broad concept of density, and whether these foothold concepts might be productive in understanding the concept of charge density.

THEORETICAL FRAMEWORK

Conceptual Metaphor Theory (CMT) has as a central premise the idea that many of our abstract concepts are understood in terms of concrete concepts which are ultimately grounded in our embodied experience. Foundational concepts are termed image schemas (e.g. 'container', 'up-down'): 'imagistic' in that they derive from external experience and 'schematic' in that they are pre-conceptual, flexible structures which provide the scaffolding for more detailed concepts. Image schemas are grounded in recurrent patterns of our experience. Some of the image schemas identified by Cognitive Linguists bear a resemblance to the p-prims identified by di Sessa [4]. For example, Johnson [5] distinguishes between the force-related image schemas of *compulsion* and *diversion* and di Sessa similarly distinguishes between the p-prims *force as mover* and *force as deflector*.

We interpreted our data as providing evidence for structures underlying students' understanding, and termed these structures 'foothold concepts'. While related to the notion of an underlying metaphor or image schema, foothold concepts (like p-prims) occur at a grain size useful for educational purposes and make no assumptions regarding broader reasoning and representational processes.

METHODOLOGY

Instrument

The basic instrument is a questionnaire comprising a number of questions that require both written and drawn responses as well as calculations. It was modified to suit the three different sample cohorts (see below), resulting in three separate questionnaires. The questions were designed in order to obtain general patterns of response for the broad concept of density and to observe the transfer of this concept to the concept of charge density. The sequence of questions was similar for each questionnaire: Students were asked to provide a written description of density, a drawn representation of density, and a calculation or written description of charge density.

Where explanations were requested, a specific audience was posited [6]. The audience was chosen in order to produce a decending gradient of knowledge, with the student positioned as the more knowledgeable party. For example, the questions posed to the BA English cohort were:

Question 1: Your younger brother is having trouble understanding the concept of density. Explain to him as clearly as possible whatever you know about density.

Question 2: Draw a diagram that will further help your brother understand the concept of density.

Question 3: Explain what *you* think charge density is.

Each question appeared at the top of a blank A4 sheet of paper giving the students ample 'answer space' without prompting for an answer of a particular length.

Sample

Data were collected from 172 freshmen comprising three cohorts: (i) 81 students in BSc. Physics Special Access Program; (ii) 47 students in a BA English Program; (iii) 44 students in BSc. Physics Mainstream Program.

The BSc. Special Access Program targets students from previously disadvantaged communities. These students typically have a workable albeit superficial knowledge of physics concepts, having emerged from classroom environments which often use rote or 'parrot fashion' instruction. This cohort had briefly been taught about the concept of mass density in their chemistry course two weeks prior to taking the questionnaire. The BA English students typically have no physics background. The findings reported in this paper reflect a subset of a larger project. Hence, the different sample groups were chosen for various reasons, some not congruent with the emergent findings included in this paper. For example, at the time of taking the questionnaire the BSc. Physics Mainstream students had already learned about charge density.

Protocol

Questionnaires were answered under exam conditions. Students were not permitted to 'go back' and modify previous answers but were instructed to insert footnotes containing any modifications. Both cohorts of BSc. Physics students answered the question during 'physics class time' and recognised the researcher as a physics tutor in the Physics Department. They were thus likely to frame the activity as a 'physics activity'. The BA student cohort answered the question during their English Tutorial and were unaware of the purpose of the questionnaire. Many of the students were unfamiliar with the term 'charge density' and were thus asked to provide an intuitive guess as to its possible meaning.

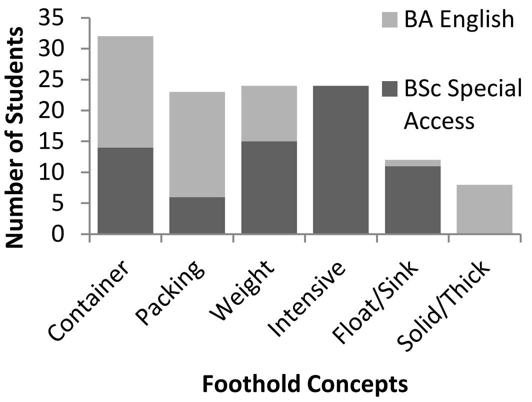
ANALYSIS

The data was analysed using an approach suggested by Grounded Theory. After looking for general patterns within the data, broad categories were identified. Microanalysis (or line by line analysis) was then used by introducing 'fine grained coding' within the broader coding scheme. Approximately 75 categories and fine grained categories were identified for each student cohort. A student's response could be coded as belonging to multiple categories.

FINDINGS

We shall list four interesting findings from the research.

First, the written and drawn responses from all the sample groups could be fairly neatly pigeonholed as using one or more of six foothold concepts: (i) container; (ii) packing; (iii) weight/heaviness; (iv) intensive/fixed property; (v) floating/sinking; (vi) solidity/impenetrability. The foothold concept 'container' was extended to include any representation of a definite, bounded region of space; 'Packing' included any representation of discrete entities (such as molecules) with emphasis on their spatial arrangement. e.g. A simple drawn representation of a container filled with discrete entities was *not* coded as using 'packing', but a side by side comparison of two containers with appropriately arranged discrete entities was. (See Figure 2). 'Intensive/fixed property' included any mention of the density of an object being unchanging with size or amount, and was also used to code the drawn representation of a straight line graph of mass vs. volume. Four of these six foothold concepts are mentioned in this written response from a BSc. Special Access Student: *"Density firstly is measured in g.cm^3 [sic]. It is calculated by the formula mass/volume. It is the amount of space or how heavy the amount of mass the substance takes up of a container. The less the density the lighter it weighs. e.g. if water and iodine are put in a container, water will be at the bottom. Density does not change due to the amount of a substance. It is a fixed property."* Here is an example of the use of the foothold concept 'packing': "*For something to be dense, its particles must be close to one another.*" A significant number of BA Students used some notion of solidity/impenetrability: *"A rock is dense and solid. While air is not dense and just floats around."* The distribution of these foothold concepts in students' written responses is given in Figure 1 below.



Foothold Concepts	BSc Special Access	BA English
Container	14	18
Packing	6	17
Weight	15	9
Intensive	24	0
Float/Sink	11	1
Solid/Thick	0	8

FIGURE 1. Foothold Concepts used in Written Responses

When students were asked to draw a representation of density a similar pattern of foothold concepts emerged. Examples are provided in the 4 figures below.

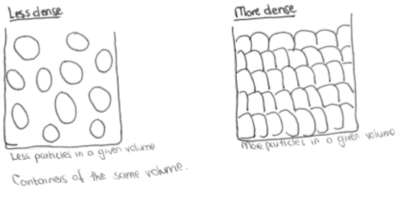


FIGURE 2. Packing

FIGURE 3. Weight/Heaviness

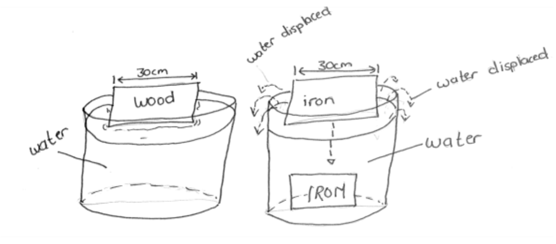


FIGURE 4. Floating/Sinking

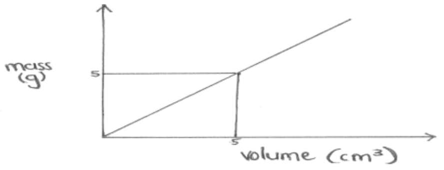
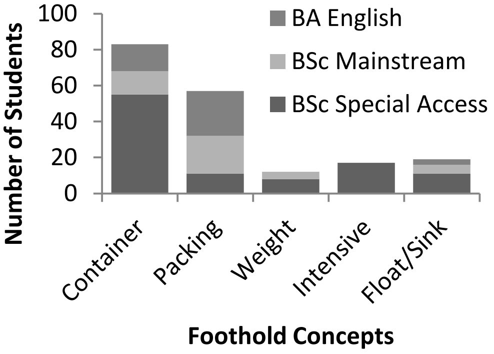


FIGURE 5. Graph (Intensive Property)

The distribution of the foothold concepts from the drawn responses is shown in Figure 6 below.



Foothold Concepts	BSc Special Access	BSc Mainstream	BA English
Container	55	13	15
Packing	11	21	25
Weight	8	4	0
Intensive	17	0	0
Float/Sink	11	5	3

FIGURE 6. Foothold Concepts in Drawn Responses

Second, written and drawn tasks triggered different responses. For example: Of the eleven BSc. Special Access students who drew 'floating/sinking' in their drawn response, only six mentioned the idea of 'floating/sinking' in their written response.

Third, 'packing' seemed to be the most productive foothold concept for structuring the concept of charge density. The BSc. Special Access Students were presented with the diagram of a charged metal rod and given the parameters of length, radius, volume, surface area, mass and charge, and asked to calculate the charge density of the rod. All students indicated that they did not know what charge density was. The length and radius were provided as distracters to decrease the possibility of a student taking a 'lucky guess' of the ratio of two quantities. A chart representing the various foothold concepts drawn by the BSc. Special Access Students is given in Figure 7 below. The number of students to correctly answer the question on charge density is overlaid in light grey. Of the twelve students who drew packing, eight went on to calculate charge density correctly.

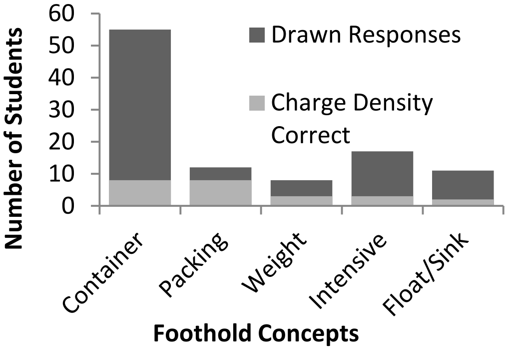


FIGURE 7. Productivity of Foothold Concepts

A similar finding emerged from the BA students' responses. The BA students were asked to describe what they thought charge density was. All of the students indicated that they did not know what the concept meant, and were thus instructed to give an intuitive guess. Eleven students correctly described charge density as the amount of charge packed into a particular volume. Of these eleven students, nine had drawn a representation of packing.

Lastly, it was found that a significant proportion of BSc. Special Access students had an entrenched quantitative understanding of the word 'density': approximately one third of these students used the ratio m/V in their calculation of charge density. A common example being: charge density = charge × m/V. This suggests that students who predominantly rely on the rote learning of formulas, graphs or stock phrases such as "density is an intensive property" (see Fig. 1) do not access productive foothold concepts which may be used in creative transfer of a concept.

DISCUSSION

Most of the previous research conducted on students understanding of density makes use of 'closed questions' or particular tasks. If density is indeed understood via six underlying foothold concepts, then a particular task, such as predicting the buoyancy of an object, may only assess a student's familiarity with a particular foothold concept, and not her understanding of the broad, transferable concept of density.

Bloom [7] modelled students' discussions of density and found that the notion of 'packing particles' was a salient feature of their discussion.

Smith, et al. [2] interviewed and distributed questionnaires to thirty 8th grade students in order to assess their ability to differentiate between the concepts of weight and density. After requesting drawn responses from students, they found that "the use of 'dot crowdedness' models for density was significantly associated with making a clear differentiation between weight and density". 'Dot crowdedness' models are synonomous with the drawn images we categorized as 'packing'.

Thus the notion of 'packing of particles' seems to be an important foothold concept in understanding the broad concept of density: it is associated with the differentiation of weight and density and also with the accurate conceptualisation of charge density.

ACKNOWLEDGEMENTS

The authors thank the SASOL Inzalo Foundation and the staff and students of the University of Cape Town's Physics, English, Linguistics and Philosophy departments.

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