Assessment as a tool to Understand Students' Conceptions of the Structure of Matter

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Assessment as a tool to Understand Students’ Conceptions of the Structure of Matter

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Abstract. Learning progressions built and based on empirical evidence provide a foundation for advancing the state of the art of teaching. This paper contributes to the advancement of the idea that assessment can provide empirical evidence to examine the underlying theory of cognition and provides a method for developing and verifying the theory. Using a construct within the science domain of Structure of Matter as a basis for discussion, issues of how to address theoretical ambiguities and practical dilemmas are explored.

1. Introduction

What is the nature of the learning progression in the content domain of Structure of Matter? To address this, we put forth a hypothesized progression, which is based on the literature of how students understand the structure of matter [1-7].

Six components or constructs were identified and articulated into the learning progression. There are four core constructs and two auxiliary ones. Macro Properties (MAC), Changes of State and Other Physical Changes (PHS), Particulate Explanations of Physical Change (EPC), and Particulate Explanations of Chemical Change (ECC) are the core constructs while Measurement and Data Handling (MDH), and Density and Mass & Volume (DMV) are auxiliary. Multiple links connect these six variables to form the learning progression. The focus of this paper is on one of the core constructs, ECC.

Student understanding of the Particulate Explanations of Chemical Changes (ECC) construct, was initially hypothesized to have six progressive levels (Levels 0-5). At Level 0 or the lowest level of understanding, students think that total mass may change in all types of substance change. At Level 1, students think that, the total volume of the substances involved may change yet the total mass remains the same in both chemical and physical changes. At Level 2, students understand that chemical changes can be distinguished from physical changes, i.e., from dissolving, or heating, or changes of state, by the appearance of new substances. These may have properties quite different from the properties of the original substances, and the changes are often irreversible. Also, at Level 2, students also understand that, in chemical changes, while mass is conserved, many other properties may change. At Level 3, students think that the smallest possible particles of a substance
may either be atoms, or combinations of different kinds of atoms. The latter are called molecules. Also, different substances can be made of the same types of atoms, but are composed of different combinations of these atoms, i.e., different molecules. At Level 4, students understand that, (a) in a chemical change the molecules/atoms of the products will be different from those of the reactants, but the total numbers of atoms will remain the same, and (b) in physical changes, the atoms/molecules remain the same, their numbers and their total mass remains the same, but they may be arranged in different ways. Finally, at Level 5, students understand that, in a chemical change the atoms will be unchanged, but may combine in new ways to form different molecules; the molecules of any substance may just break apart to give two new substances.

2. Methods and Data Sources
We approached this investigation using a construct modeling approach as recommended in Developing Assessments for the Next Generation Science Standards [8]. This approach allows for an integrated means of developing assessments that support and build on the goals for curriculum and intentions of instruction. Specifically, researchers used the BEAR Assessment System [9,10] to provide guiding principles for the development and revision of the assessment materials.

Researchers developed assessments to measure students’ understanding for each of the theorized levels of the ECC construct. Before administering the assessments on a large scale, all items went through a rigorous review, which included review panels by teams of teachers, scientists, and other content experts; cognitive interviews with middle school students; and small-scale administrations to ensure students were responding to items as intended.

The final test consisted of 56 items, which included 17 multiple-choice, 9 open-ended, 3 drawing, and 27 fill-in-blank items. Each item was hypothesized to correspond to the theoretical developmental levels described within the construct map. Figure 1 shows an example of a multiple-choice item. The correct choice is “A” and the targeted construct map level is Level 4 on the ECC construct map.

<table>
<thead>
<tr>
<th>SAMPLE ITEM: In a chemical reaction, the number of reactant atoms:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Is equal to the number of product atoms.</td>
</tr>
<tr>
<td>B. Is greater than the number of product atoms.</td>
</tr>
<tr>
<td>C. Cannot be determined.</td>
</tr>
<tr>
<td>D. Is less than the number of product atoms</td>
</tr>
</tbody>
</table>

Figure 1: Sample ECC item.

Student responses to the 56 items were scored and calibrated using the partial credit model. After calibration, the items were reviewed in light of the construct map. A total of 1,086 middle grade students participated in this research.

3. Results and Discussion
For the analysis each component including the construct map, items, scoring guides, student responses, and the analysis were examined. We focus on the construct levels and how the empirical evidence in this paper informs the levels. As the ordering of the construct levels is an important part of the empirical testing of the hypothesized construct map, we examined the relationship between the theoretical progression and the empirical results. We found that the a priori level assignments of items did not align as anticipated with the hypothesized levels in the construct map. Hence, we explored the possibility of an alternative structure within the item sequences in the construct. We started with a re-examination of the results from the psychometric analyses and also included a
qualitative examination of the items within the construct and considered whether they might be grouped in relation to similarities within the items of each group. This work was done through research meetings with content experts and teachers. Interpretation of the analysis led researchers to three progressive levels rather than six. And, the types of chemical changes were parsed into “strands” to capture their differences.

The ECC items can be categorized into three groups, which are labeled as strands, with each strand being a distinct component of the main ECC construct. These three strands are described as follows:

- **ECC-A**: Chemical and physical changes in the inter-atomic combinations and in the arrangements of atoms and molecules
- **ECC-B**: Changes in macroscopic properties, which accompany chemical and/or physical changes
- **ECC-C**: Representations of elements, compounds, and different phases, in terms of arrangements of atoms and molecules

In ECC-A, students can explain chemical and physical changes in terms of the inter-atomic combinations and the arrangements of atoms and molecules. At the first level, students can recognize and explain molecular and atomic representations of physical and chemical changes. In the second level, students understand that in a chemical change, the atoms or molecules change the way they combine and form new materials. Students also know that there are empty spaces or a vacuum between atoms and molecules. Lastly, in the third level, students can construct diagrams to give molecular and atomic representations of both physical and chemical changes. They know that in a chemical change, the atoms stay the same, but in different molecules. The numbers of atoms involved remain the same for both physical and chemical changes.

In ECC-B, students can distinguish between chemical and physical changes through the observations of macroscopic properties. For the first level, students can distinguish between these changes for obvious, familiar cases, such as when a chunk of wood burns or when an ice cube melts. In the second level, students can do this for less obvious cases, such as when a candle is burned or when sugar is dissolved into tea. Students also understand that mass is conserved throughout these changes. In the last stage, students can recognize that the properties differ after a chemical change. They can also distinguish chemical from physical changes in unfamiliar cases, such as when solid iodine turns into a gas.

In ECC-C, students are able to represent elements, compounds, and different phases, in terms of the arrangements of atoms and molecules. At the first level, students can recognize representations of monatomic molecules. They are aware that atoms and molecules are not usually visible and may also have different sizes. In the second level, students can recognize representations of diatomic molecules. They also know that atoms and molecules have weight. At the topmost level, students can recognize and distinguish between diagrams of different polyatomic elements and compounds.

Within each of these three strands, the items could be divided into three levels, with the type of demand similar within each group, but different, both qualitatively and in expected level of demand, between the groups.

Figure 2 shows the initial ECC construct map (on the left) and how it changed based on the empirical results (on the right side).
Initiate ECC construct map

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 5: Chemical Changes Produce different molecules</td>
<td>In a chemical change, the atoms will be unchanged, but may combine in new ways to form different molecules. The molecules of any substance may just break apart to give two new substances.</td>
</tr>
<tr>
<td>Level 4: Chemical &amp; Physical Change - Particulate Explanations of Differences</td>
<td>In a chemical change, the molecules/atoms of the products will be different from those of the reactants, but the total numbers of atoms will remain the same. In physical changes, the atoms/molecules remain the same, their numbers and their total mass remains the same, but they may be arranged in different ways.</td>
</tr>
<tr>
<td>Level 3: Atoms and Molecules</td>
<td>The smallest possible particle of a substance may either be atoms, or combinations of different kinds of atoms; the latter are called molecules. Different substances can be made of the same types of atoms, but are composed of different combinations of these atoms – i.e. different molecules.</td>
</tr>
<tr>
<td>Level 2: Chemical &amp; Physical Change - Observable Differences</td>
<td>Chemical changes can be distinguished from physical changes (i.e. from dissolving heating, changes of state) by the appearance of new substances. These may have properties quite different from the properties of the original substances, and the changes are often irreversible. In chemical changes, whilst mass is conserved, many other properties may change; in those involving solids and liquids, products may be solid or liquid or both.</td>
</tr>
<tr>
<td>Level 1: Conservation of Matter</td>
<td>In both chemical and physical changes, the total volume of the substances involved may change but the total mass remains the same.</td>
</tr>
<tr>
<td>Level 0: Matter not conserved</td>
<td>In all types of substance change, the total mass may change.</td>
</tr>
</tbody>
</table>

Empirically-Informed ECC construct map

<table>
<thead>
<tr>
<th>Strand A: Properties of Atoms &amp; Molecules</th>
<th>Strand B: Macroscopic properties</th>
<th>Strand C: Molecular representations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Showing that a chemical change the atoms stay the same but in different molecules, whilst a physical change the atoms stay in the same molecules, but that it helps change the number of atoms involved stay the same.</td>
<td>Can recognize that properties all differ after a chemical change.</td>
<td>Can recognize and distinguish between representations of one or two elements or compounds, or of a state of between these.</td>
</tr>
<tr>
<td>Understands that a chemical change the atoms or molecules change the way they combine and so form new materials.</td>
<td>Can distinguish chemical from physical change in ordinary cases.</td>
<td></td>
</tr>
<tr>
<td>Understands that two different materials will be made of the different molecules, but that there can be made of the same atoms or of different atoms.</td>
<td>Can distinguish chemical from physical change where it is clear whether or not a new material has been produced.</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Initial ECC construct map (left) with empirically informed ECC construct map (right).

As mentioned above, the outcome of this regrouping is shown as a Wright map in Figure 3. The Wright map shows the student ability distribution and item thresholds on the same logit scale. Here the three strands are shown separately and with respect to the same overall student score scale for ECC. The other feature shown here is that the three groups with each strand are represented by the colors – blue, green and yellow, representing the three levels from the lowest to the highest, respectively. Figure 3 shows evidence of a progression sequence with each strand, but also shows that the overlaps between the three produced the apparent lack of order when they are represented all together. The color-coded items also indicate a progression sequence, in a clear way for ECC-C but not for ECC-A. These possible inconsistencies will have to be explored by more a detailed examination of the ways in which the demands of individual questions are perceived by students.
Figure 3: Wright Map of ECC construct separated into three strands (ECC-A, ECC-B and ECC-C).

4. Significance
This research contributes to the current literature on understanding how assessment can illuminate and inform theories of student understanding. This research illustrates how assessments can provide empirical evidence to examine the underlying theory of learning and reveals issues that arise from investigating learning progressions. The issue of how to handle the strand-structure within a larger context and, indeed, putting the pieces together coherently to advance our knowledge of how students come to understand complex science ideas is presented here.

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