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A novel approach for investigating students' learning progression for the concept of phase transitions

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ABSTRACT
Learning fundamental concepts in science in order to develop deep understanding of complex scientific concepts is an essential task. However, research that uses rigorous methods to investigate how students' concepts develop over time is limited. In this article, we answer two key questions about learning progressions for the concept of phase transitions: (1) what mental models of matter and phase change do students possess across grades, and (2) what conceptual pathways do students follow for these concepts? We describe the results from a study involving fourth, fifth, and seventh through twelfth grade students (N = 832). Our work led to two main findings. First, students' mental models of the targeted concepts gradually shifted from direct and sensory to synthetic and then to scientific-like. Second, based on our cladistics analysis, we found that some crucial concepts developed before students possessed scientific models. Our results provide a novel perspective from which to revisit learning progressions associated with the development of core scientific knowledge.

KEYWORDS: learning progressions, cladistics, phase transitions, conceptual change

Resumen (Un método novedoso para investigar la progresión de aprendizaje sobre el concepto de transiciones de fase)
El aprendizaje de conceptos fundamentales en ciencia con el fin de facilitar la comprensión de conceptos más complejos es una tarea educativa esencial. Sin embargo, las investigaciones que se basan en el uso de métodos rigurosos para estudiar cómo se desarrollan los conceptos de los estudiantes a través tiempo son limitadas. En este artículo respondemos a dos preguntas claves sobre progresiones de aprendizaje del concepto de transiciones de fase: (1) ¿Qué modelos mentales sobre la materia y los cambios de fase poseen los estudiantes de diferentes grados escolares? y (2) ¿Qué trayectorias conceptuales siguen los estudiantes al aprender estos conceptos? Presentamos los resultados de un estudio que involucró estudiantes en los grados cuarto, quinto y de séptimo a doceavo (N= 832). Nuestro trabajo dio lugar a dos resultados principales. Primero, los modelos mentales de los estudiantes sobre los conceptos estudiados cambiaron gradualmente de directos y sensoriales a sintéticos, y después a de tipo científico. Segundo, con base en un análisis de cladística, encontramos conceptos cruciales que deben desarrollarse antes de que los estudiantes posean los conceptos científicos. Nuestros resultados proporcionan una perspectiva novedosa desde la cual abordar el estudio de progresiones de aprendizaje sobre conocimientos científicos fundamentales.

Palabras clave: Progresiones de aprendizaje, cladística, transiciones de fase, cambio conceptual

Introduction

Researchers in science education utilize various strategies to collect and analyze students' learning outcomes in order to capture trajectories of learning progression. Each method provides different results and serves different purposes in the work of improving student learning and science teacher instruction. Strategies for assessing students' alternative conceptions may begin by asking students to answer paper-and-pencil multiple-choice tests, draw a concept map, or build relational links that show the connections and consistency among concepts that they hold. Two-tier and three-tier test items are also commonly used to reveal underlying ideas behind students' conceptions of a phenomenon (Chandrasegaran, Treagust, & Mocerino, 2007; Chiu, 2007; Harika Ozge, Cigdemogiu, & Moseley, 2012; Liang, Chou, & Chiu, 2011).

No matter what research strategy is chosen, the intention of the researchers is to uncover students' knowledge representations (fragmented or coherent), types and sources of alternative conceptions, and students' mental models in order to design more effective teaching materials and strategies. Nevertheless, different research approaches often deliver different conclusions. For instance, in a series of studies by Vosniadou and colleagues (e.g., Ioannides & Vosniadou, 2002; Vosniadou, 1994; Vosniadou & Brewer, 1992), these

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researchers asked children to express and represent their thinking about certain scientific concepts (such as the shape of the Earth, or conceptions of force and motion). These investigators identified several types of mental models ranging from initial to synthetic to scientific models. They also claimed that young students held consistent models that they used to comprehend the physical world. A couple of years later, diSessa, Gillespie, and Esterly (2004) replicated Ioannides and Vosniadou's (2002) work on students' conceptions of force, and questioned the coherence and systematicity of students' ideas (p. 844). Siegal & Surian (2004) have argued that the use of drawings in research studies might lead to the misrepresentation of students' thinking because students lack the skill to draw three-dimensional objects, such as the shape of the Earth. When Nobes et al. (2003) interviewed children about the shape of the Earth using physical objects instead of drawings, they found that young children's underlying knowledge structure about the targeted topics was fragmented. These results indicate that when uncovering students' thinking about scientific phenomena, the methods we choose for assessment and data collection, as well as the way we analyze the associated data, influence our interpretations.

With this methodological concern in mind, in this contribution we discuss a novel approach (called cladistics) to investigate how cross-grade students' understanding of scientific phenomena develops. We also explore whether this new approach to data analysis provides a useful perspective for interpreting the development of cross-grade learners' knowledge in science.

Learning Progressions and Chemistry Education

The study of learning progressions in science is a relatively new area of research and there are actually various definitions for the concept of learning progression. The *Journal of Research in Science Teaching* (*JRST*) published a special issue in 2009 that discussed what learning progressions intend to achieve and what role they play in science education. Learning progressions aim to align curriculum, instruction, and assessment: the three pillars by which we evaluate learning outcomes within education.

Learning progressions have been defined as "descriptions of successively more sophisticated ways of reasoning within a content domain based on research syntheses and conceptual analyses" (Smith et al., 2006, p. 2). Learning progressions describe how students' understanding changes over time. Students' understanding changes as students come to develop sophisticated knowledge about big ideas in science and this knowledge in turn helps them learn about related concepts (Duschl, Schweingruber, & Shouse, 2007; Stevens, Delgado, & Krajcik, 2010). It is important to note that increasing sophistication of students' science knowledge is not a developmental inevitability (Duncan, Rogat, & Yarden, 2009). Learning progressions are descriptions of increasingly sophisticated ways of thinking about or understanding a topic, but necessitate carefully designed curricula in order to move learners' thinking forward since progressions are influenced by instruction (Duschl et al., 2007).

The methods chosen to assess learning progressions are important, in particular, if a researcher has to face a large-scale sample. Popham (2007) claimed that the analysis of learning progressions forms the framework for an optimally effective formative assessment process. Systematically collected evidence of student progress toward mastery of each key concept in a learning progression allows researchers to develop better understanding about teaching and learning. However, Smith et al. (2006) argued that learning progressions are associated with instruction and multiple pathways for achieving the targeted educational goals may exist. Students develop different mental representations when learning scientific concepts and go through different paths to form their understanding. While we have to take individual differences into account when designing curricula, we also have to understand at what stages most students develop core scientific concepts as well as the characteristics of the learning environments that foster such development (Chiu & Chung, 2013). In this paper, we look for the commonalities in student thinking about the core scientific concept of phase transitions, using a cladistic approach in the analysis of our data.

A Novel Approach to Analyze Students' Conceptions: A Cladistics Approach

Lin and Chiu (2006) introduced evolutionary principles to research in students' epistemic knowledge via the use of a "cladistics approach." In biology, cladistics is a method for classification in which organisms are grouped together based on whether or not they share one or more unique characteristics with a common ancestor. The group of organisms that includes the common ancestor and its descendants is called a clade, and the diagram that represents the relationships between organisms is known as a cladogram or evolutionary tree (see Figure 1). This method of classification allows biologists to build hypothesis about relationships between organisms and identify a species evolutionary history as represented in evolutionary trees. Lin and Chiu (2006, 2013) and Wu & Chiu (2011) have proposed that the development of students' conceptions is analogous to the evolutionary process. Therefore, identifying the key prior conceptions (ancestors) in a learning progression could help us understand relationships between different ideas and frame effective sequences in a curriculum. We believe that this evolutionary analogy provides a new and promising way of looking at students' science learning. The use of the cladistics approach (also called phylogenetic classification) allows us to understand the key conceptions that lead to the formation of students' mental models based on the analysis of a Conceptual Evolution Tree (CET).

In the following sections, we describe a study that demon-

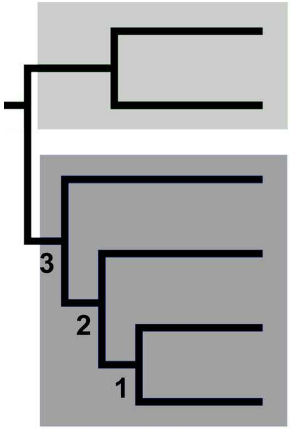


Figure 1. Schematic representation of a cladogram in which two clades are highlighted. The bottom clade is comprised of several sub-clades, so it is said to be nested. Ancestors in a clade are represented by the branch points or nodes (numbered in the image).

strates how the cladistics method can be used to represent and classify students' conceptions about phase transitions. This study was conducted with a large number of cross-grade participants who completed survey questionnaires designed to elicit fundamental conceptions about the targeted topic.

Main Study

A. Purpose

This study focused on students' understanding of phase transitions, which are common phenomena in our daily lives but students often struggle to understand (Coştu, Ayas, & Niaz, 2010). In this study, we investigated students' mental models of phase transitions, focusing our attention in the areas of "composition," "properties," "structure of three states," and "transition processes," which are all associated with common alternative conceptions in the research literature (e.g., Coştu et al., 2010; Stavy, 1990; Tsitsipis, Stamovlasis, & Papageorgiou, 2009). Based on the analysis of existing work in this field (Senocak, 2009; Johnson, 1998; Tatar, 2011), we identified seven mental models about phase changes commonly held by students (summarized in Table 1). To understand how these models develop across different school grades, we decided to use an approach that integrated a "Conceptual Evolutionary Tree" (CET) technique (Lin, 2006; Lin & Chiu, 2006, 2013; Wu & Chiu, 2011) and results from a cross-grade survey to show students' learning trajectory of the targeted concept.

The CET technique is intended to integrate cladistics with science education to enrich our understanding about student learning. This method assisted us in the construction of a hypothetical representation of the evolutionary pathway for the development of mental models of phase transitions. Then, a cross-grade survey was conducted to understand the percentage of students at different grade levels who possessed each mental model. Finally, the CET representation was used as a template to compare the results from the cross-grade survey, and to generate the validated evolutionary pathway of students' mental models. This validated pathway may serve as a framework for designing an appropriate learning progression for the concept of phase transitions.

Table 1. Categories and descriptions of different mental models about phase transformations.

Mental model	Brief descriptions of mental models		
	View of matter	Three states	Process of change
1 Sensory model (S)	continuous view	a. phases are different matter (no causal relationship) b. no temperature concept	a. mass change b. irreversible
2 Different composition model (D)	continuous view	a. phases are different matter b. no temperature concept	a. mass change b. irreversible
3 Properties change model (P)	mixed view	a. partial different matter	a. mass change b. irreversible
4 Particle Change model (C)	mixed view	a. partial different matter	a. mass change b. reversible c. changeable particles
5 Reorganization-between-particle model (O)	particulate view	a. identical matter	a. conservation of mass b. changed amount of particles c. attraction among particles d. change of structure
6 Particle rate change model (R)	particulate view	a. identical matter b. latent heat	a. conservation of mass and number b. unchanged particles c. change of movement
7 Dynamic equilibrium model (E)	particulate view	a. identical matter b. latent heat	a. Dynamic equilibrium

Research questions

Our research study was guided by the following research questions:

1. What are the fundamental conceptions about phase transitions of students in grades fourth through twelfth?
2. What is the hypothetical Conceptual Evolutionary Tree (CET) for students' mental models of phase transitions according to existing studies?
3. What is the empirical CET for students' mental models of phase transitions?

Methodology

Research Design: Two stages, namely hypothesis construction and hypothesis verification, were conducted to explore conceptual development processes in the area of phase transitions:

- In the hypothesis construction stage, every mental model was analyzed and coded as a unique set. The coding system used in this analysis is summarized in Table 2. For example, the Particle Change Model (C) described in Table 1 was linked to the cognitive states 1-1, 2-1, 3-1, 4-1, 5-1, 6-0, 7-0, 8-1, 9-0, 10-0, and 11-1. This coding system was built to highlight major differences in students' ideas about the composition, properties, structure, and transition processes for different phases of matter. Coding sets applied to characterize the different mental models in Table 1 served as input in the construction of the associated CET (the evolutionary tree for the development of mental models) using the PAUP* 4.0 software as described below.
- In the hypothesis verification stage, a survey of conceptions of phase transitions for cross-grade students was conducted and the results were aligned with relevant theories of conceptual change in science education.

Participants: A total 832 students in Taipei (Taiwan) participated in our study. Participants included students from grades fourth to twelfth (4^{th} grade, n = 86; 5^{th} grade, n = 84; 6^{th} grade, n = 95; 7^{th} grade, n = 109; 8^{th} grade, n = 80; 9^{th} grade, n = 92; 10^{th} grade, n = 97; 11^{th} grade, n = 96; 12^{th} grade, n = 93) (Wu, Chiu, & Liaw, 2013). All of the participants answered the questions on the survey in about thirty minutes and all of the data were collected in schools.

Instruments: Two main instruments were used in this study:

1. *Questionnaire of Particle Nature and Phase Transitions* (QPP): The QPP consists of three parts. The first part is the "Questionnaire on the View of Matter" in which students view virtual pictures of microscopic particles and then choose which one is the correct structure to represent ice, water, and vapor. The second part is the "Questionnaire on the View of Particles" in which students choose the proper behaviors of H_2O in different states. The third part is the "Questionnaire of Phase Transitions" in which students answer two-tier multiple-choice questions. The reliability of the QPP using Cronbach's α is .848 for primary school students, .896 for junior high school students, and .909 for high school students.
2. *Phylogenetic Analysis Using Parsimony* (PAUP* 4.0): This computer application (website: http://paup.csit.fsu.edu/) was used to compute and reconstruct the hypothesis of conceptual development. Different mental

Table 2. Coding system used in the analysis of different mental models about phase transitions.

Category	Cognitive characters	Cognitive states
Microscopic particle	1. View of matter	1-0 Continuous view, 1-1 Mixed view, 1-2 Particulate view
Change of matter	2. Change of element	2-0 Total change, 2-1 Partial change 2-2 No change
	3. Identical matte	3-0 Different matter, 3-1 Partial different matter 3-2 Identical matter
	4. Change of temperature	4-0 No influence, 4-1 consistent change, 4-2 Change at a constant specific temperature (latent heat)
Processes of change	5. Reversible	5-0 Irreversible, 5-1 Reversible
	6. Conservation of mass	6-0 Mass change, 6-1 Conservation
	7. Amount of particles	7-0 Changed amount, 7-1 Constant amount
	8. Unchangeable particles	8-0 No particulate view, 8-1 Changeable particles, 8-2 Unchangeable particles
	9. Attraction between particles	9-0 Constant attraction, 9-1 Altering attraction
	10. Movement and structure of change	10-0 No change, 10-1 Change of structure, 10-2 Change of movement
	11. Dynamic equilibrium	11-0 Consistent change in one way 11-1 No change, 11-2 Dynamic equilibrium

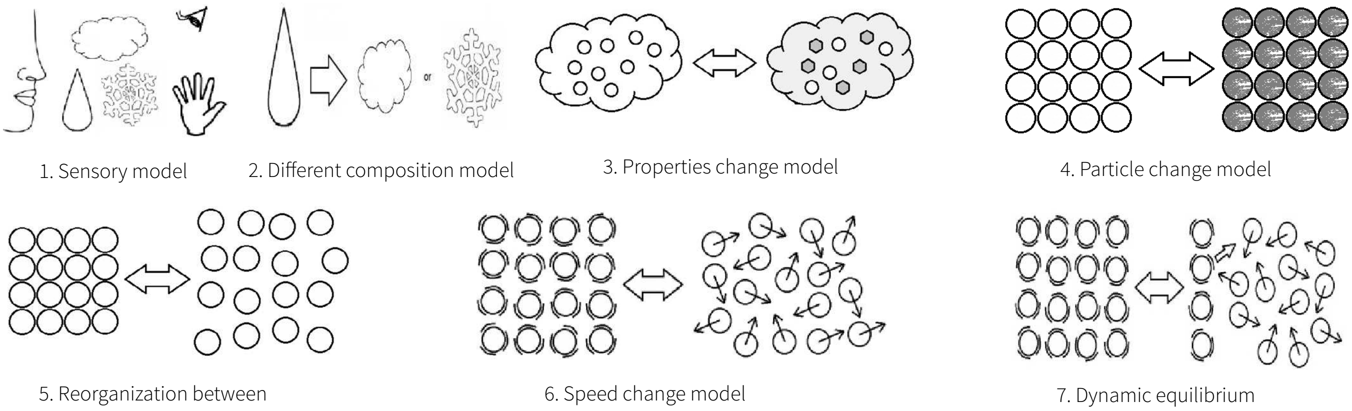


Figure 2. Different mental models about phase transitions. See Table 1 for more details about the different models.

Note 1: No causal relationships among the phase transitions.

Note 2: Matter is changed after the phases are changed. Change is irreversible.

Note 3: Components stay the same after phase transitions but their characteristics are changed.

Note 4: Matter stays the same after phase transitions but the characteristic properties of the particles of matter are changed.

Note 5: Properties of matter do not change but the distribution of particles changes during the phase transitions.

Note 6: Speed of the particles of matter changes during the transition.

Note 7: Dynamic equilibrium during the phase transitions.

models of phase transition were coded based on the cognitive characters and states listed in Table 2. The data matrix, composed of cognitive characters and states for each mental model, was then entered into PAUP* 4.0 and a list of possible evolutionary trees (CETs) was obtained. CETs with higher Consistency Index (CI), representing their degree of conformity, were chosen.

Major Findings

Students' concepts of phase transition from fourth through twelfth grades: Our results showed that students acquired partial or incorrect particulate concepts before formal education. The results from the QPP indicated that over 50% of fifth graders held a mixed view about matter. This mixed view declined sharply at eighth grade while a particulate view reached a peak at 90%, and then remained steady at about 80%.

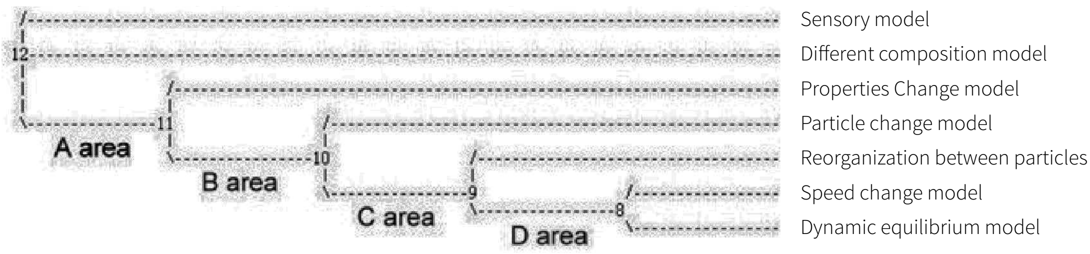
The analysis of a wider set of concepts elicited early, middle, and late development trends. First, over half of the students held correct macroscopic concepts and the idea of "identical matter in condensation processes" in the early stage. Second, the percentage of students' correct conceptions (such as reversible, conservation of mass, no change in number of particles, and identical matter in all phase transitions) stayed constant during the middle stages and then climbed substantially after junior high school. Finally, more complete and correct comprehension of the nature of particles was developed during the period of senior high school, which included appropriate conceptions about the size of particles, weight of particles, attractive forces between particles, and motion of particles.

Verifying the hypothetical evolutionary tree of students' mental models: The seven common types of mental models about phase transitions summarized in Table 1, and also represented in Figure 2, were categorized based on the 11 cognitive characters listed in Table 2. After the PAUP* 4.0 analysis, CET 22 was chosen as the best representation for our data with the highest CI value (Tree length = 18, CI = 1).

For analysis purposes, CET 22 was divided into four areas, A through D, as shown in Figure 3. The "Mixed View" of matter defined as viewing at least one of the three states as composed of particles, accompanied by some related conceptions was identified in Area A. The "Particulate View" of matter defined as viewing all three states of matter as made of particles, appears in Area C along with other scientific concepts. The "Unchangeable Particle" view was left in Area D. This suggested that a mixed view of matter was easy to develop but correct particulate concepts were delayed.

The key concept in area C of the CET in Figure 3 was the microscopic view of particles. When students reached Area C, they understood that matter in all of the three states was composed of particles and that the weight of matter would remain the same even after a phase transition. They also understood that phase transitions were related to the structure and attraction between particles.

To sum up our major findings, our results from the cross-year survey closely matched cognitive characters in the CET 22: (1) Areas A and B in Figure 3 both represent the early development stage characteristic of younger children, (2) Area C represents the middle trend for junior high school students, and (3) part of Area C and Area D represent the late trend for high school students. Incremental trends in



Area	Node number	Cognitive characters and states
	No. 12 ~ S model	4-0 No influence by temperature
A	No. 12 ~ No. 11	1-1 **Mixed view** 3-1 Partial different matter 11-1 No change after equilibrium
B	No. 11 ~ No. 10	2-1 Partial different matter 5-1 Reversiblee 8-1 Changeable particles
C	No. 10 ~ No. 9	1-2 **Particulate view** 2-2 No change of element 3-2 Identical matter 6-1 Conservation of mass 9-1 Altering attraction 10-1 Change of structure
D	No.9 ~ No.8	4-2 Change at a constant specific temperature 7-1 Constant amount 8-2 Unchangeable particles 10-2 Change of movement
	No.8 ~ E model	11-2 Dynamic equilibrium

Figure 3. Conceptual Evolutionary Tree 22 (CET 22). The image shows major conceptual areas ("clades") linked to a specific node (numbered 8 through 12).

constructing the concepts of particles and phase transitions were found.

Discussion

Misconceptions related to microscopic particles might originate from misplacement of ontological categories (Chi, 2005). In this study, high percentages of fifth graders held mental models of phases of matter involving continuous and particulate views. Beliefs and presuppositions can be expected to restrict students' mental models and the knowledge acquisition process (Vosniadou, 2002). For this study, students' microscopic views of matter led to different mental models along with many specific misconceptions (e.g., students with C model used "change of particle" to explain phase transitions). The analysis of cognitive characters indicated that conceptions of matter interacted with each other and produced various mental models.

Students developed partial or incorrect concepts of microscopic particles before formal education. Our investigations revealed that in the process of learning, prior concepts and new concepts interacted with each other. Specifically, the pre-existing concept of particle nature of matter helped students acquire a better understanding of phase transitions. The validity and reliability of our findings were enhanced by being based on various kinds of data generated by different research methods that compensated for the inadequacies of one another. Our study relied on multiple methods to improve teaching and learning sequences and produce a comprehensive conceptual development framework.

Concluding Remarks and Implications

Based upon the methods and results of our studies, we propose a novel taxonomical approach to analyze learning trajactories of scientific concepts across different grades. Taking into consideration students' evolving conceptual structures, researchers and curriculum designers can better formulate effective learning and teaching materials from an epistemological approach. This novel approach displays an evidence-based representation of conceptual and evolutionary pathways that can pinpoint what concepts should be taught before others and support the development of scientific-like mental models of science concepts. Our intent is not to offer a specific curricular sequence for teaching concepts, but rather to suggest an analytical framework that takes into consideration students' prior knowledge about a particular concept while designing curriculum. With the goal of enriching the intended pathway, we suggest taking Johnstone's (1993, 2000) triangle approach (e.g., macroscopic, microscopic, and symbols) into consideration and making good use of models of science that incorporate the components of scientific theory and practice to structure chemistry teaching and education research. In addition to Johnstone's perspectives, we should take into consideration cultural and language perspectives (Chiu, 2012) that contribute to our understanding of science. Cultural and language factors can facilitate or hinder deep learning yet rarely gain attention in many places of the globe. We argue that learning is a complex process that requires a degree of cognitive effort in order to achieve the desired educational goals. We thus advocate the use of systematic methods to uncover teaching and learning sequences, diagnose students' learning progression, and further empower students to appreciate science.

Researchers can use traditional cross-grade studies to examine the development of different science concepts. However, our novel approach creates an explicit representation from which to describe the evolution of students' mental models. The evolutionary pathway of students' mental models not only reveals the incremental growth of the concepts that students hold, but it also shows when alternative conceptions are re-structured to match scientific models. Understanding the evolutionary pathways of students' mental models allows science educators and teachers to better understand how complex scientific concepts develop. We suggest that researchers explore the relationship between the evolutionary pathways of students' mental models and the development of curriculum in order to provide the most effective instruction. They should also consider the interaction of concepts and alternative conceptions when designing teaching strategies and sequences in order to optimize students' conceptual change.

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