Paper presented at the Learning Progressions in Science (LeaPS) Conference, June 2009, Iowa City, IA

UNDERSTANDING LEARNING PROGRESSION IN STUDENT CONCEPTUALIZATION OF ATOMIC STRUCTURE BY VARIATION THEORY FOR LEARNING

Abstract: Teaching and learning about a big idea, "the structure of an atom" has been an important topic in science education. Nevertheless of the importance of the big idea, studies show student alternative conceptions and learning difficulties. Moreover, those alternative conceptions had been identified in textbooks, curriculum materials, and instructions provided by science teachers. In a study of student understanding of matter and atomic-molecular theory, the idea of "learning progressions" was proposed as a useful tool for developing science curriculum to teach these concepts and designing assessments to evaluate students understanding. The learning progression for the big idea assists in predicting student learning in a classroom context and aids in the preparation of "level appropriate" instruction. This study suggests a new interpretation of learning progression by employing variation theory. Learning progression in the current study is defined as a construct composed of varied students' conceptions in a hierarchical order and progression of learning is acquired through conceptual awareness along with increasing complexity and inclusivity.

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Introduction

Human beings have always wondered about the nature of reality. The history of science and philosophy is populated by a wide variety of theories for understanding the basic structure of the world. Atomic theory was developed early in Greek philosophy and later, the belief in the existence of fundamental and indivisible object was revived in modern science as a crucial theoretical premise for comprehending the nature of the world. As a result, teaching and learning about the structure of an atom has been an important topic in science education. In particular, the atomic-molecular theory has been also suggested as a 'big idea' which is a 'most accessible and fundamental idea 1) providing a framework for organizing children's learning of new facts, inquiry, and explanation, 2) empowering children to understand the distinctive value of science and, 3) preparing children for further learning science' (Chapter 8, NRC, 2006).

Although the particulate nature of matter and atomic theory have been emphasized as critical concepts in the secondary school science curriculum, student alternative conceptions (often regarded as misconceptions) and learning difficulties have been reported in many studies (Griffiths & Preston, 1992; Harrison & Treagust, 1996; Park & Light, 2009). Moreover, the analysis of the representation of these critical concepts in textbooks and curriculum materials shows similar alternative conceptions (Shiland, 1995 & 1997; Niaz, 1998; Harrison & Treagust, 2002). For example, in their analysis of the Australian science curriculum, Harrison and Treagust (2002) reported that alternative conceptions are often not only found in textbooks but also in the instruction provided by science teachers. Teachers' alternative conceptions indicate that some teachers hold a very limited degree of the intrinsic pedagogical content knowledge in their teaching of submicroscopic/symbolic level concepts, particularly as related to macroscopic level phenomena. In addition, Shiland (1995, 1997) pointed out that many textbooks include inappropriate curriculum content in terms of the treatment of quantum mechanics, hindering their ability to help student make the conceptual change from a Bohr model to the current quantum atomic models. Implementation of level-appropriate content with respect to student learning abilities is regarded as an important issue in curriculum development and instruction (Berry, 1986; Gillespie, 1991; Hawkes, 1992; NRC, 1996; Shiland, 1995; Tsaparlis, 1997; Johnson, 1998).

Several studies have conducted longitudinal research exploring how students conceive of the particulate nature of matter (including atomic structure) and how their conceptual learning of these concepts progresses in a school environment (Novak, 2005; Johnson, 1998, 2005; Liu & Lesniak, 2005, 2006; Smith, Wiser, Anderson & Krajcik, 2006; Stevens, Shin, Delgado, & Krajcik, 2007; Adbo & Taber, 2009; Talanquer, 2009). Indeed, in their study of student understanding of matter and atomic-molecular theory, Smith et al and Stevens et al proposed the idea of "learning progressions" as a useful tool for developing science curriculum to teach these concepts, and to evaluate students understanding. According to the NRC (2006) definition, learning progressions are "descriptions of the successively more sophisticates ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time (Chapter 8, p5) and in a simpler way, Alonzo and Steedle (2008, p2) define it as "ordered descriptions of student understanding." In order to improve assessments at national or state levels, Smith et al (2006) analyzed standards and previous research on students' understanding of matter and atomic/molecular theory. The latter study builds learning progressions of matter and atomic/molecular theory by connecting learning performance to progression. The learning progression for the big idea of matter and atomic/molecular theory, developed through longitudinal studies (Smith et al., 2006; Stevens, Shin, Delgado, Krajcik, & Pelligrino, 2008), can also assist in predicting student learning in a classroom context and aid in the preparation of "level appropriate" instruction (Stevens et al., 2006, p2).

Nevertheless, in spite of the potential benefits of bridging learning studies and instruction/curriculum development, few studies on learning progressions have been conducted and these studies are mainly limited to building learning trajectories as levels of understanding or performance rather than explaining how they progress. To this end, this study suggests a new interpretation of learning progression by employing variation theory.

Variation Theory of Learning

Variation theory was developed from a research method, phenomenography, which is aimed at uncovering and describing the different ways in which people experiences or understand a particular phenomenon or concept in various contexts. (Marton 1994; Marton & Booth, 1997). The phenomenographic method usually describes these different experiences in terms of a hierarchical set of increasingly more sophisticated categories of conception or understanding. Where phenomenography is concerned with identifying this variation in understanding, variation theory is concerned with explaining how such variation occurs. It maintains that learning with respect to a particular phenomenon or concept consists of becoming aware of the variation—the aspects or dimensions of variation—in the ways in which people experience that phenomenon or concept (Bowden & Marton, 1998; Marton & Booth, 1997; Pang & Marton, 2005). It is these "aspects of variation," which distinguish student learning experiences, explaining learning as students' awareness of differences that they have not been able to discern previously (Marton & Booth, 1997; Marton & Pang, 2006). As such, it is important to unpack student conceptions and identify the aspects of variation differentiating their conceptual understanding (NRC, 1996; Shiland, 1995; Tsaparlis, 1997).

Unlike learning progression, variation theory, in general, does not describe a learning trajectory that a student follows but rather describes a hierarchical typology representing the spectrum of students' conceptions. Conceptions are distinguished by degree of inclusiveness of key aspects of variation. In addition, learning progressions are sequenced by "research-based conceptual and social analyses of the structure" (NRC, 2006, Chapter 8, p6) of learning performance composed of the disciplinary knowledge and practice skills that is to be learned, while conceptual variations are structured by research-based conceptual analyses of student understanding. Despite these differences, learning progression can be explained by "aspects of conceptual variation." Renstrom et al's study (1990) of secondary school student's understanding of the particulate nature of matter, suggests that conceptual variations structured by sophistication of understanding, describe a learning progression for that concept. In addition to delineating student understanding and potential learning difficulties associated with that understanding, aspects of conceptual variation also provide critical information for designing and developing curriculum, instruction and assessment; essentially focused on making the variation salient to students to enhance their learning. In addition to the studies describing conceptual variations (Akerlind, 2005; Renstrom, Andersson, & Marton, 1990), the relationship between the identification of variation in student conceptions and its influence on instruction, have been explored in several studies (Akerlind, 2005; Ingerman, Linder, & Marshall, 2007; Marton & Pang, 2006; Renstrom, Andersson, & Marton, 1990).

Student Conceptions of Atomic Structure

In order to better understand student learning of atomic structure and help teachers to guide students to make meaningful learning, the current study explored students' conceptions of atomic structure in terms of variation theory of learning. Aspects of conceptual variation have been disclosed to assess student mental models and how they progress in learning the concepts. With a focus on changes in student models over a term and students' ability to discern aspects of conceptual variation, progress in student learning toward a target level of understanding was analyzed. The study explains not only learning progression representing student experience/thinking but also limited to a term and an introductory college chemistry course, conceptual variations and changes in student conceptions of atomic structure over the term provide a way understanding learning progression by variation theory. As discussed in previous studies for learning progression, aspects of conceptual variation help us to better assess student learning and develop appropriate instruction. In addition, results of the study suggest that, together with building complexity and inclusivity, a key component leading students to describe more sophisticated ways of reasoning (Smith et al., 2006) can be acquired through meta-thinking as they become aware of aspects of conceptual variation.

Method

Subjects and Instruments

Data for this study were collected from a general chemistry class at a Midwestern university[1]. This course was an introductory college chemistry course that covered the first nine chapters of a general chemistry textbook (Brown, LeMay, & Bursten, 2000). Seven chapters were related to the main topic of this study, atomic structure: the nature of matter, electronic structure of atoms, introduction of quantum theory, properties of atoms, molecular geometry, and bonding theories. Students in the course responded to open-ended questionnaires. Four hundred-thirty-nine of the 633 students enrolled in the course responded to both pre- and post-questionnaires and fifteen students volunteered for the open-ended pre- and post-interviews designed to determine what the students knew about atomic structure prior to and after instruction. The questionnaires were designed to gather information related to student background and understanding of atomic structure. Students were asked to represent their understanding of atomic structure in written and diagrammatic/graphical forms. Three questions were mainly asked: the definition of an atom, the description of atomic structure, and what they knew about orbitals. Questionnaires for the pre-test were administered on the first day of recitation and the post-questionnaires were provided at the last laboratory session. Questions for the open-ended format interviews were prepared to map out student understanding of atomic structure. Students were asked to represent their understanding of atomic structure in verbal, gestural, concrete, and/or diagrammatic/graphical forms (verbal and diagrammatic forms only for the questionnaires).

Analysis of Aspects of Conceptual Variation: Questionnaire Analysis

Questionnaire responses were explored in detail to identify, categorize, and characterize types of conceptions of atomic structure (bottom-up approach based on student experience). Analysis of the questionnaire responses was conducted with respect to an analytic scheme based on the curriculum guides for the course and the instructor's notes to categorize the students' models. Different student understandings of atomic structure were ranked in terms of their scientific sophistication and complexity. The preliminary hierarchical order of varied student understanding and descriptive content of them were further determined through discussion with experts in the field of science and science education (top-down approach based on expert's experience). Sixty five initial categories

[1] For a full description of the study, its methods, analysis and findings, see Park (2006). Park et al (under review)

of atomic structure descriptions were identified and variations in student descriptions were then reduced to thirteen conceptions of atomic structure. These distinctively differentiated 13 conceptions of atomic structure were then used to assess students' mental models represented in interview responses.

In order to identify student conceptions and to construct a typology structured by conceptual inclusiveness, fifty sets of student questionnaire responses ─ pre- and post-questionnaire, one hundred responses in all ─ were randomly selected and reviewed by a researcher of this study and an expert in physics. The preliminary 13 types were used to code student conceptions of atomic structure as represented in questionnaires and the agreement between two raters were over 91%. For the student responses where the researcher and the expert differed, discussion was followed and agreement was reached.

Analysis of Student Mental Models: Interview Analysis

Analysis of the interview data was initially conducted with respect to the hierarchical structure developed through the analysis of the questionnaires. In addition to the 13 initial levels of understanding, the interviews were also categorized with respect to four historically linked scientific models: Particle model (P), the Nuclear model (N), Bohr's model (B), and the Quantum model (Q). Although quantum atomic models are currently accepted in the scientific community, the other three prominent models used to explain and support scientific observations and the understanding of the nature of an atom over the history of science, are still often used in school science curricula today. The 13 levels, arranged by conceptual inclusiveness and linked to these scientific models, provides codes for conducting a holistic analysis based on a combination of student diagrammatic/graphic, gestural, concrete, and verbal representations. Table 1 (below) provides details of 13 student models categorized and named by the two criteria. Aspects of variation show how student conception of atomic structure can be distinguished between levels. In order to assess "progress in learning," changes in student models (pre- and post-interview responses) were explored in detail.

To ensure inter-rater reliability, five sets of student interview responses ─ pre- and post-interview transcripts, ten interviews in all ─ were randomly selected and reviewed by the researcher and the expert. For the ten student mental models coded for scientific models, the researcher and the expert showed 100% agreement. For the mental models of the ten students coded by levels of understanding, the results were in 80 % agreement. For the two students where the researcher and the expert differed, the instructor of the course was consulted and agreement was reached.

Research Findings

Learning Progression: Conceptual Variations of Atomic Structure

This study found 13 student models of atomic structure which were related to 10 levels of conceptual understanding of atomic structure and four historical scientific models. The typology of student models of atomic structure is presented in Table 1 (below). It is hierarchically ordered and suggests a learning progression characterized by conceptual sophistication. Key aspects of conceptual variation listed in Table 1 (i) distinguish student levels of understanding of atomic structure from each other, and (ii) show the inclusivity of previous understandings into increasingly more complex understandings. Indeed, it is this increasing complexity which describes the hierarchical nature of the typology as learning progression of concepts. In the next section we provide examples of three of the different student models or conceptions of atomic structure described in the typology.

Table 1. Conceptual Variation of Atomic Structure

Level	Description of mental model	Student model	Aspect of variation	Scientific model
1	Student understands atom as an indivisible particle.	P1a	Indivisible entity	Particle model (P)
	Student understands atom as an indivisible particle but also differentiates atoms and molecules.	P1b		
2	In addition to understanding an atom as a particle, the student understands that atoms are composed of protons, neutrons, and electrons.	N1	Subatomic components	Nuclear model (N)
3	In addition to level 2, the student understands the compositional relationship between protons and neutrons in a central nucleus, and electrons circling the nucleus)	N2	Circular orbit	
4	In addition to level 3, the student understands orbits with some reference to natural forces (gravity, strong, weak, and electromagnetic forces) holding them together.	N3	Circular orbit held by forces	
5	In addition to level 4, the student understands multiple different levels of orbitals as set paths of electrons in circular shape	B1a	Multiple orbits (paths)	Bohr's model (B)
	A student describes the Nuclear model (with ref to forces) and multiple different levels of orbitals as set paths of electrons in different shape.	B1b		
6	A student describes the Bohr's model and distinguishes orbital levels/shapes by energy quantization in quantum theory.	B2	Energy quantization	
7	A student arranges electrons not on a set path but within a certain area/space (or electrons within orbitals).	Q1	Orbital as space	Quantum model (Q)
8	A student describes electrons in terms of a space consistent with the meaning of probability based on the "uncertainty principle."	Q2	Probable space	
9	In addition to level 8, the student understands the different shapes of orbitals (but the different shapes are not representationally connected).	Q3a	Different space shapes	
	In addition to level 8, the student understands the different shapes of orbitals (and the different shapes are representationally integrated).	Q3b		
10	A student understands the basic idea of quantum theory (probability, wave function, energy quantization, etc.) and the modern picture of the atom and explains the atom in	Q4	Space shapes by mathematical wave function	

	terms of particles or waves. A student explains the concept of probability and orbitals in terms of quantum theory and integrates both concepts into atomic structure.		(basic idea of quantum theory)	

Student Models of Atomic Structure: Three Examples

Conception B1a (a Bohr model)

Students having this conception understand atomic structure as containing multiple levels of orbit or orbital as set paths of electrons in circular shape. This feature of *multiple orbits* differentiates student conceptions from a N3 (Nuclear) model (just before it in the typology) in which atomic structure is understood as simply having a *single circular orbit*. It is also distinguished from both the next model in the typology B1b, which describes orbits as having different *shapes*, and the model following that, which demonstrates an awareness of the different levels/shapes of electron orbits in terms of *energy quantization*. Figure 1a (below) represents a student's (KC) post-interview model of atomic structure. The student explained atomic structure with a central nucleus and orbiting electrons at different orbital levels: "they spin (rotate) around the nucleus" and "electrons orbit around nucleus."

a b

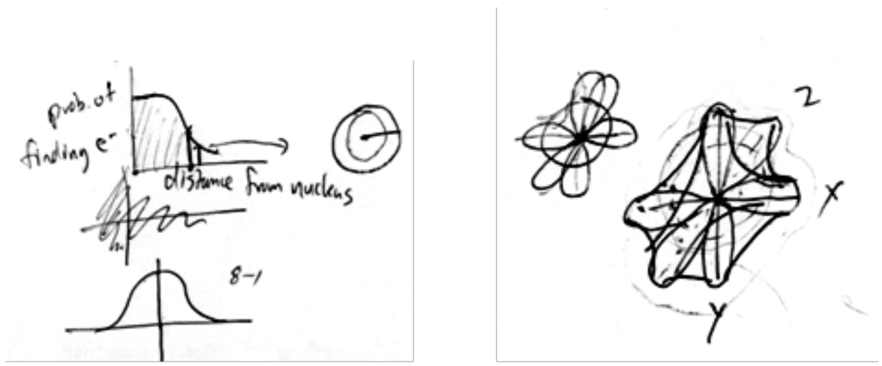
Figure 1. Example of students (KC and TK) diagrammatic descriptions of atomic structure: B1a model and Q2 model

Conception Q2 (a Quantum M odel)

Students at this level understand that an electron doesn't *orbit on a set path* but rather recognize (are aware of) orbitals as an orbital *space* defined in terms of *probability*. The Q2 model of atomic structure differs with less sophisticated conceptions in terms of student understanding of orbitals in terms of the *probability* for finding electrons. The atom in TK's atomic structure (Figure 1b above), for example, was described as "a marble in the middle and then, just like, just kind of a field around it" and the student explained the field as orbitals, "areas where randomly moving electrons can most likely be found." Randomly moving electrons in orbitals are displayed as arrows in Figure 1b.

Conception Q4 (a Quantum M odel)

A student with a Q4 Quantum model understands the basic idea of quantum theory (including key features such as energy quantization, probability, wave function), and is able to explain the atom in terms of particles and waves. As an example of the Q4 level model, LJ (Figure 2a) explained electron distribution or electron density in terms of *probability* for finding electrons within certain areas. Moreover, he added detailed explanations about the mathematical representation of *wave function* (describing the probability of finding an electron at a point vs distance from the nucleus) and the shapes of orbitals or an atom. Figure 2a is the graphical representation of his reasoning process for constructing the shapes of s orbitals from a wave function. The concept of Pauli's exclusion principle, wave/particle duality, and the concept of energy quantization related to orbitals were also addressed. This model is distinguished from a Q3 model by an awareness of the orbital shape (Figure 2b) being determined by a mathematical wave function.



a b

Figure 2. Example of a student (LJ) diagrammatic descriptions of atomic structure: Q4 model

Conceptual Development

Conceptual development in student understanding - as identified in this study through the students' pre and post interview responses - can be represented by the typology described in this study (see Figure 3 below). While there were no student models of atomic structure (from the sample of 15 students who participated in both the pre- and post-interviews) coded at the P1a, N1, N2, N3, and B2 levels, all other models were found. Analysis of the student interview transcripts revealed that 12 students' models of atomic structure prior to the 10 week chemistry course were at the level Q2 or below, levels at which student models do not reflect an understanding of *orbital shape* in the structure of the atom. One model was at the P1 level (reflecting no understanding of orbit at all), while there were 4 B1a models, (in which there was no understanding of *orbitals as space* nor of the key ideas of *energy quantization* and *probability* for finding electrons, and 7 Q1 and Q2 models, in which there was a limited understanding of *energy quantization* and *probability*. Only three student models prior to the course were at the level Q3 and above. The number of student models of atomic structure post the course, on the other hand, consisted of 7 student models at the advanced levels of Q3 and Q4 (demonstrating an understanding of *orbital shape, energy quantization* and *probability*) and 8 at the Q2 level or below. Indeed, post the course, two students held Q4 models or conceptions of atomic structure in which they were able to demonstrate an understanding of *orbital shape* in terms of mathematical representation of *wave function*. Overall, seven students changed their understanding to a higher levels, 7 students kept the same models, and 1 student appears to have changed to a lower level of conception. In general, changes suggest that the typology was able to map the key aspects of change (or lack of change) in student models or conceptions of atomic structure over the 10 week period.

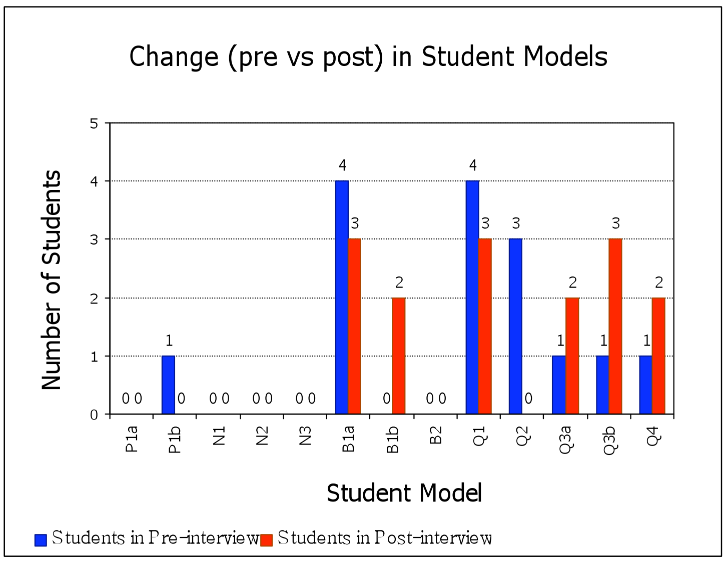


Figure 3. Number of student mental models of atomic structure from the pre- and post-interview responses

In should also be mentioned that, as reported in similar studies (Alonzo & Steedle, 2008; Finegold & Gorsky, 1991; Justi & Gilbert, 1999; Renstrom, Andersson, & Marton, 1990), the current study also identified student models containing aspects of multiple scientific theories in their description of an atom (6 students in the pre- and 3 students in the post-interview). In contrast to Justi and Gilbert's (1999) hybrid models, defined as "models constituted of elements of different historical models treated as if they constituted a coherent whole" (p173), the analysis of student models of the current study shows that students appear to hold a dominant model or conception of atomic structure, but adopt a feature from a different model (in particular, Bohr's model - B1a) to explain certain characteristics of the atom (e.g., reaction, stability, quantum number, etc). These conceptions are not regarded as consistent models but rather are represented in terms of the multiple models (from the typology), used in the given situation.

Conclusion and Discussion

In order to understand a learning progression of a particular concept(s), we need to understand how student learning of that concept(s) progresses. This paper describes a typology of conceptions of atomic structure based on how learning occurs or progresses from one model to another through student awareness of key or critical aspects of variation distinguishing the successive models. It was derived from the ground up – i.e. from an empirical study of the variation in students own models – and, as such, provides an evidence based structure for the construction of a learning progression.

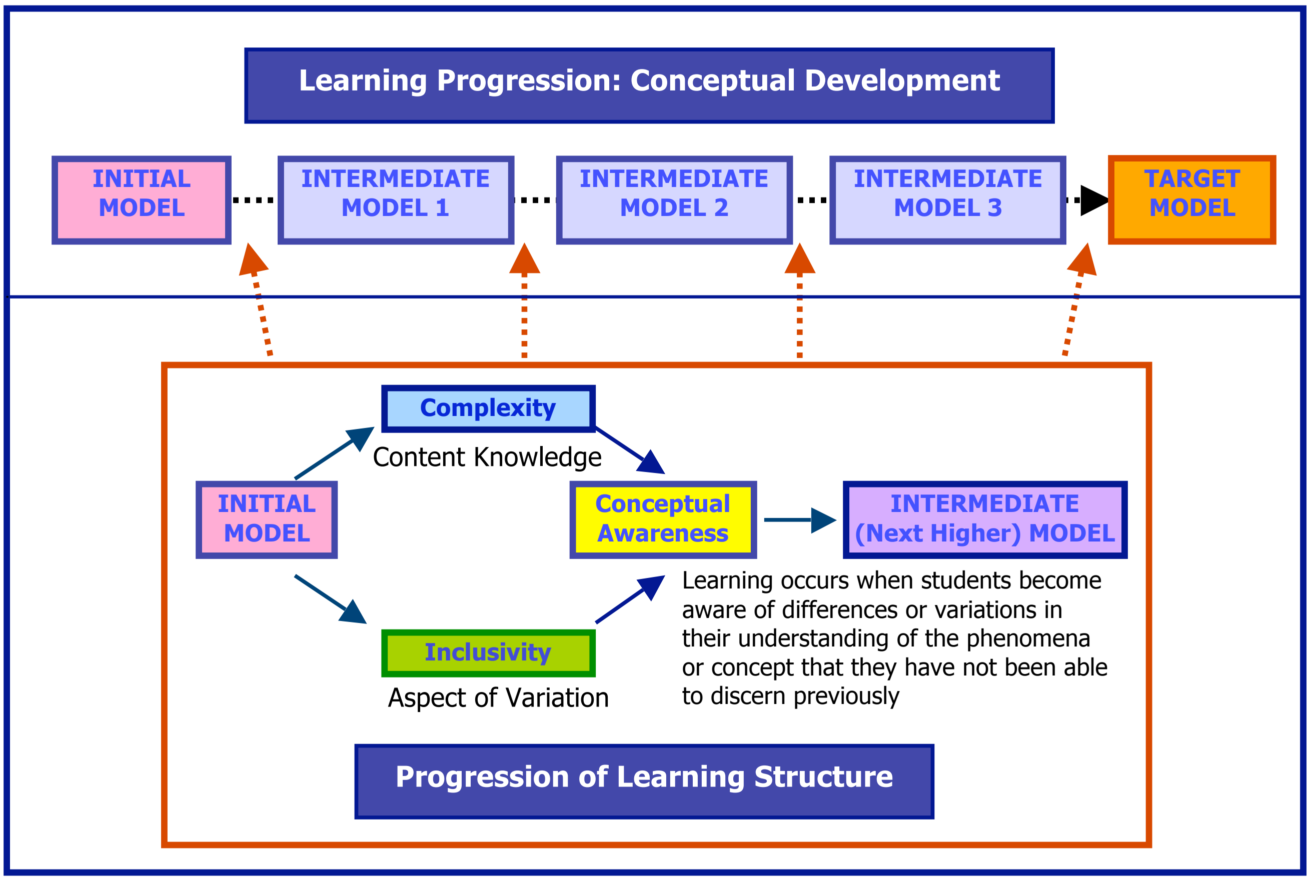


Figure 4. Learning progressions in terms of progression of Learning

The figure 4 (above) illustrates how a learning progression is defined and determined in terms of a progression of learning structure. Learning progression in the current study is a construct composed of varied students' conceptions in a hierarchical order and the construct represents a potential path for building conceptual development of a particular concept. How students' conceptions of learning a key concept (big idea) progress from an initial alternative model through intermediate models to the target model of a course (Clement, 2000) can be explained by the progression of learning structure based on variation theory of learning (Figure 4). Variation theory claims that learning occurs when students become aware of key differences or variations in their understanding of the phenomena or concept that they have not been able to discern previously. The lower portion of the Figure 4 describes the essential elements in the process of conceptual development in terms of this conceptual awareness with respect to both (i) complexity – awareness of the relevance of additional content knowledge; and (ii) inclusivity - awareness of the increasing inclusion of new aspects of variation differentiating conceptual models. The current study of student's direct experiences of phenomena provides qualitative, empirical evidence for progression in student models that occur through this conceptual awareness.

This approach to learning progressions differs from existing frameworks for learning progression in that it provides a structure of levels of understanding which are internally defined. Rather than providing a progression of performances (concepts and/or process skills) that are defined externally as "higher" or "better" by experts, these levels (and models) are described as "better" in terms of the nature of student awareness of the increasing complexity and inclusivity describing a particular model. The successive models include an awareness of the previous aspects of variation as well as those distinguishing a student's best model. This study identified nine hierarchical aspects of variation for atomic structure: *divisibility, circular orbits, force, multiple orbits, energy quantization, probability, orbital shape, and wave function*. Descriptions of student conception and the analysis of changes provide information about how students understand atomic structure and the potential conceptual barriers relating to learning difficulties.

Making these critical aspects salient to students and facilitating them to figure out the aspects of variation characterizing each concept will enhance student learning about atomic structure. This suggests such a learning progression can be a useful tool for 1) curriculum design, 2) pedagogical instruction, and 3) assessment development. For instance, assessments can be constructed which are specifically focused on determining whether or not students are aware of a particular aspect of variation. Awareness of the role of *energy quantization* in the determination of *multiple orbits/orbitals* of atomic structure, for example, would provide evidence of a B2 conception of atomic structure. Similarly, recognition of *sub-atomic components* would provide evidence of a N1 understanding. Recognition of an inclusive range of these aspects of variations would provide evidence for conceptions of atomic structure associated with the highest level of aspect of variation of which a student displayed awareness. Likewise, instructional interventions could be specifically designed to facilitate student awareness of the critical aspects of variation in the order in which they are hierarchically structured. For example, assisting students to recognize the role of *energy quantization* would need to follow a previous *awareness of multiple orbits*. Providing these concepts at the same time may not allow students to discern the key variation in the model. (Marton & Booth 1997; Marton & Booth 2006).

Finally, existing learning progression frameworks as levels of understanding are limited in their ability to represent inconsistent use of multiple conceptions in a given situation, insofar as the conceptual variation framework describes a collective map of conceptions, it is relatively flexible in labeling student thinking of a phenomena in terms of multiple conceptions.[2]

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[2] For an in depth discussion of student's use of multiple conceptions and the relationship to aspects of variation, see Park et al (under review).

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