The Role of Prior Knowledge on the Origin and Repair of Misconceptions in an Introductory Class on Materials Science and Engineering

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***Abstract**: The book, How People Learn, states that all learning involves transfer from prior knowledge (e.g. from earlier classes) and previous experiences (e.g. observations) which can facilitate or impede learning. Taber classifies misconceptions according to their origin as a type of "impediment" to learning, for which there are two general types, each with subtypes. Null impediment refers to missing information (necessary for learning new material) due to students: 1) not having prior knowledge (deficiency) or; 2) not recognizing links between new material and their prior existing knowledge (transfer). Substantive impediment refers to faulty concept models of students from: 1) observations or personal experience or (experiential); 2) prior courses and teaching (pedagogic) and; 3) bending or misinterpreting of new concepts to fit prior knowledge (misinterpretive). In this paper on research–to-practice we address the question of what learning strategies are most effective in repairing misconceptions or "impediments" of different origin.*

Introduction

The context of this study is the teaching and learning of introductory courses in materials science and engineering (MSE) and what the role of prior knowledge is on misconceptions and conceptual change. Significant findings in cognition of teaching and learning have been summarized by the book, *How People Learn*: *Brain, Mind, Experience, and School* (Donovan, Bransford & Pellegrino, 1999). One important finding is that, students have prior knowledge about how the world works, consisting of preconceptions (if incorrect, misconceptions) and, if their initial understanding is not engaged, they may fail to grasp new concepts and information and revert to their preconceptions outside the classroom. A second finding is that novice learners are unlike expert learners in that experts have developed the learning skills to build a deep content understanding of their subject and have facts and ideas organized into a conceptual framework that facilitates their retrieval and transfer to new and different applications. A third finding is that experts are metacognitive learners who develop their own expertise by defining learning goals and monitoring their progress. In this study we are focused on the first finding. In particular, since all learning involves transfer from prior knowledge and previous experiences, an awareness and understanding of a learner's initial *conceptual framework* and/or topic can be used to formulate more effective teaching strategies. If this idea is taken a step further, it could be said that, since misconceptions comprise part of a conceptual framework, then understanding origins of misconceptions would further facilitate development of effective teaching strategies.

A student's conceptual framework may have various types of misconceptions with different origins and characteristics that may require different learning strategies. To facilitate misconception repair Taber (2004) created a classification system based on misconception origin as a type of "impediment" to learning. He specifies two general types, both with subtypes. *Null impediment* refers to missing information (necessary for learning new material) due to students: 1) not having prior knowledge (*deficiency*) or; 2) not recognizing links between new material and their prior existing knowledge (*transfer*). *Substantive impediment* refers to faulty concept models students hold from: 1) personal experience or observations (*experiential*); 2) prior courses and teaching (*pedagogic*) and; 3) bending or misinterpreting of new concepts to fit prior knowledge (*misinterpretive*). We are using Taber's classification method, in conjunction with results of the Materials Concept Inventory (MCI) (Krause, Decker, Niska, & Alford, 2002) to assess effectiveness of different pedagogies and associated learning strategies to repair misconceptions of different origins in MSE courses. Overall, the *research questions* we are investigating are: *what* is the origin of knowledge and experiences students bring to introductory MSE courses; *why* does this knowledge pose challenges for learning MSE concepts; and *how* can more effective learning strategies be implemented to enhance student understanding.

Background

MSE is an applied field which has, as a major goal of the discipline, educating students of other engineering disciplines on how to control a material's macroscale properties based on the understanding of its nanoscale structure. But, achieving this goal is a significant intellectual challenge to learners who must develop their own *mental models* (Boulter & Buckley, 2000) that effectively link the concrete "macroworld" of everyday objects and phenomena to the abstract "nanoworld" of atoms, molecules and microstructure. Students enter introductory MSE classes with a *conceptual framework* comprised of *mental models.* These arise from *prior knowledge* acquired in an academic setting of earlier chemistry classes or from everyday *previous experience* where information might be acquired from sources such as personal observation, the television, and the internet. When students' *mental models* fail to align with scientifically correct models, they are often referred to as *misconceptions*. These are scientifically inaccurate interpretations of the world that can neither explain nor predict the characteristics and behavior of the systems and phenomena of interest. Some examples of include the explanation that copper metal is malleable because "individual copper atoms are malleable (Ben-Zvi, Eylon & Silverstein, 1986) or that the metal nickel can only exist as a solid (Krause, Tasooji, & Griffin, 2004)." Such misconceptions inhibit or impede conceptual change.

We are using a theoretical framework of constructivism, with learning as *conceptual change* with students learning most effectively by constructing their own knowledge through modification of their *conceptual framework*. The framework is comprised of *mental models*, which are simplified, conceptual representations that are personalized interpretations of *target systems or phenomena* in the world around us. Useful *mental models* allow a learner to understand, explain, and predict behavior of systems and phenomena, whereas faulty *mental models* that lead to misconceptions do not. Thus, characterizing a learner's initial *conceptual framework* is useful since prior knowledge and previous experiences may facilitate or impede learning. Learning can be facilitated by activating prior knowledge from an earlier class or with a familiar context for new material to provide a linkage to a learner's previous experiences. Conversely, learning can be impeded by misconceptions that originate from personal experience, previous classes, or misapplication of prior knowledge to new content.

Conceptual change is sometimes difficult and may be impeded by robust misconceptions resistant to change because of students' arguments, contradictions, and obstinacy (Niaz, 2005). Thus, the general strategies of assimilation or accommodation have been used to promote conceptual change (Dykstra, Boyle & Monarch, 1992). The strategy of assimilation is to build on existing *mental models* and associated concepts of a conceptual framework. In contrast is accommodation, in which change occurs by major revision or replacement of an existing misconception and associated *mental model* (Lakoff, 1993). Misconceptions must be identified before they can be analyzed and addressed. They may be revealed by various methods such as pre-class, in-class, or two-tiered questions (multiple choice plus open-ended explanation), student interviews, focus groups, classroom talking, writing, and sketching. Here, conceptual change and innovative teaching strategies were assessed with the MCI.

There are several conceptual change theories commonly used by science and engineering education researchers (Streveler, Litzinger, Miller, and Steif, 2008). Posner, Strike, and Gertzong's (1982) theory of conceptual change requires four conditions for conceptual change to occur: 1) there must be dissatisfaction with the students' existing concept, 2) the new concept must be intelligible, 3) the new concept must be plausible, and 4) the new concept should be fruitful. Discrepant events have been used in the light of this theory. An example that shows the buoyancy of a large and a heavy object, such as wood in water, forces students to reconsider the misconception that heavy objects always sink. More recently, new theories have emerged that focus more on understanding why some science concepts are so difficult to learn. For example, Vosniadou and Ioannides's (1998) "theory-theory" states that students form their own theories of science concepts which are sometimes in conflict with scientific theories. An example of such a misconception is the impetus theory that all moving objects have to have a force that acts in the direction the object is moving. diSessa (1988), on the other hand, argues that students have partial and fragmented understanding of concepts that he calls "knowledge in pieces." According to this conceptual change theory, a child can have a normative understanding of a concept such as thermal equilibrium in room temperature in one context (e.g., for wood) but not in another (e.g., for metals). Chi's (1992) "ontological theory of conceptual change" is a theory that sheds light on causes of robust misconceptions. Chi says concepts such as electric current and heat are difficult because they miscategorize these concepts as "things" rather than "processes." A challenge for engineering and science educators is to decide which framework to use to study conceptual change.

Methods and Results

This work examined the nature and origins of different types of misconceptions. Their robustness and the effectiveness of teaching strategies in repairing them were also considered. Qualitative and quantitative data were collected and analyzed from introductory MSE courses in three different years. For 2002 (n=51) content was delivered by lectures, for 2003 (n=43) by lectures and team-based discussions, and in 2007 ((n=33) by team-based hands-on activities, concept sketching and discussions. Results were from MCI pre-and post-class testing, student focus group discussions and individual student interviews.

I. Null-impediment Based Misconceptions

The first type of null impediment (missing information necessary for learning new material) is due to lack of prior knowledge or a null *deficiency* impediment, like diffusion of atoms in a solid.

1. Atoms in a solid:
a) Cannot move, only electrons can
b) May move through vacancies in a crystal lattice
c) May move in spaces between atoms in a crystal lattice
d) Can move through both vacancies and in the spaces between atoms in a crystal lattice
e) None of the above

In college chemistry students learn atoms in liquids and solids are in "motion" with 3-D translations. However, MCI pre-test scores, 2002 (29%), 2003 (24%), and 2007 (16%), show most students entering MSE classes unaware that solid state diffusion can occur at higher temperatures. Since there is "missing information", this is a *null impediment misconception* which students would not be expected to understand. However, MSE instructors assume students have some familiarity with diffusion and may fail to define or explain the concept of solid state diffusion, thus increasing the difficulty of understanding the topic. This is evident from post test scores, 2002 (65%; 50% gain), 2003 (68%; 58% gain), and 2007 (100%; 100% gain). The pedagogy of the three classes was; 2002 lecture, 2003 team discussions, and 2007 team discussions and concept sketching. Concept sketching was the most effective pedagogy for this null impediment misconception. Students who fail to understand diffusion will have their learning impeded for topics such as annealing and isothermal transformation of steels.

The second type of null impediment transfer is missing information due to students not recognizing the links between new material and their prior existing knowledge and, as such, we have a null *transfer* impediment. An example of this is, effect of bond strength on relative melting points of 3 materials families (metals, polymers, and ceramics), is given by MCI question #5 below.

5. The melting points of most plastics are lower than most metals because:
a) covalent bonds are weaker than metallic bonds

b) ionic bonds are weaker than metallic bonds
c) Van der Waals bonds are weaker than metallic bonds
d) covalent and Van der Waals bonds are weaker than metallic bonds
e) ionic and Van der Waals bonds are weaker than metallic bonds

In college chemistry students learn about the three types of primary bonding, metallic, ionic, and covalent, as well as weaker secondary bonding. They also understand that, for two metals, the one with weaker bonding has a lower melting point (MCI question ~ 80% pre-test). However, MCI pre-test scores, 2002 (24%), 2003 (6%), and 2007 (32%), indicate less than a third of the students either never learned or did not transfer bonding concepts from earlier chemistry courses. Most MSE instructors assume students are familiar with the different bonding types, and associated melting points, for the three families of materials. Thus they may fail to define, explain, or review the concepts of bonding, likely increasing difficulty of understanding the topic. This is so from post test scores, 2002 (31%; 10% gain), 2003 (13%; 7% gain), and 2007 (30%; -3% gain). The pedagogy of the classes, 2002 lecture, 2003 team discussions, and 2007 team discussions plus concept sketching, made little difference in learning. It is uncertain how to address this robust misconception topic. Students who fail to understand bonding will have their learning impeded for a wide variety of topics.

II. Substantive-impediment Based Misconceptions

The first type of substantive impediment refers to faulty concept models students hold from personal experience or observations and is referred to as a substantive *experiential* impediment. An example of this is with respect to phases of a material is given by MCI question #4 below.

4. Nickel can exist as: a) solid only; b) liquid only; c) gas only; d) liquid or solid only; e) liquid or solid or gas

This example considers importance of materials phases, since they are processed from all phases. MCI results and focus group talk showed students believe metals exist only in the solid phase or only in the liquid and solid phases for this *experiential-based* misconception. Personal experience gave wrong answers: “I have never heard of Ni gas”, “I have never seen Ni gas”, and “I have only seen Ni as a solid”. MCI pre-test showed only half of the students understood that elements can exist in three phases; 2002 (45%), 2003 (47%), and 2007 (55%). The post-test MCI scores show an interesting result, 2002 (51%; 11% gain), 2003 (53%; 11% gain), and 2007 (93%; 84% gain). While the pedagogies of lecture (2002) and team discussion (2003) show modest gains, the team discussion and concept sketching (2007) show a significant gain which is most effective for conceptual change.

A second type of substantive impediment refers to faulty concept models students hold from prior courses and teaching and is referred to as a substantive *pedagogic* impediment. An example of this is with respect to solutions and solubility limits is given by MCI question #16 below.

16. When three tablespoons of salt are mixed into a glass of water and stirred, about a teaspoon of water-saturated salt remains on the bottom. If a small % of salt is slowly added to the glass while stirring the solution, the change in concentration of the salt in the solution is given by curve:

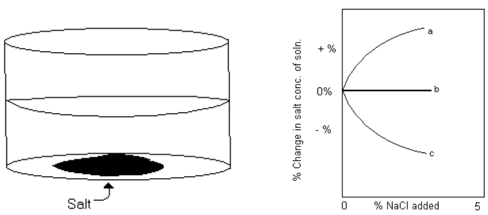

Figure 1. Salt solution and concentration change

Concepts of saturation and supersaturation are used in phase diagrams in MSE (e.g. precipitation hardening). Research shows that in chemistry, misconceptions on saturation and supersaturation are robust and persistent. The MCI pre-class results support this idea; 2002 (39%), 2003 (49%), and 2007 (42%). More than half of the students bring solution related issues with them to their MSE classes, making this a *substantive pedagogical misconception*. The post-class MCI scores are revealing; 2002 (65%; 42% gain), 2003 (82%; 64% gain), and 2007 (96%; 93% gain). The gains increase as pedagogy goes from lecturing (2002, 42%) to team discussions (2003, 64%) to team discussions with concept sketching (2007, 93%). Thus, when students engage in creating something, like a visual model of a phenomenon, their learning is the greatest. The topic of solutions and solubility play a critical role in many MSE topics related to phase diagrams, microstructures, and non-equilibrium thermal processing.

A third type of substantive impediment refers to faulty concept models students hold from bending or misinterpreting of new concepts to fit prior knowledge and is referred to as a substantive *misinterpretive* impediment. An example of this with respect to calculating properties from the macroscopic "rule of mixtures" is given below in MCI question #15.

15. If a small amount of Cu is added to Fe the electrical conductivity will change as shown (a is highest, b is middle, c is the lowest):
Incorrect prediction of macroscale properties can occur by use of the macroscopic "rule of mixtures". This means properties of a mixture of two or more materials are proportional to the volume fraction of the individual component materials' properties. Thus, if 1% Cu (which has three times the electrical conductivity of Zn) is alloyed with Zn, "rule-of-mixtures" reasoning predicts a 3% increase in conductivity (3X conductivity x 1%). Actually, there is a 6% *decrease* in conductivity. The reason is that, at the nanoscale, there are many more atomic level sites for impurity scattering of electrons that reduce conductivity. This shows the counterintuitive nature of materials' properties and how students create substantive impediment misconceptions when using an already existing model of *rule of mixtures* to predict the effect on electrical conductivity of one element added to another. For a similar question on the MCI, less than 20% of students were correct: 2002 (20%), 2003 (12%), and 2007 (13%). The post test results show good gains for all three pedagogies on the post-test; 2002 (75%; 68% gain), 2003 (61%; 55% gain), and 2007 (70%; 66% gain). Pedagogy has little effect here and students using the macroscopic model still persist at a level of 61% to 75% with room for improvement.

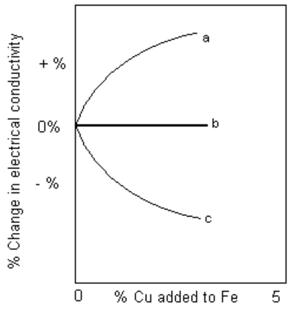

Figure 2. Change in electrical conductivity as a function of % Cu added to Fe.

Discussion and Conclusions

This paper shows the importance of the origin of misconceptions as impediments and the effectiveness of different teaching strategies on conceptual change. We will suggest possible suitable conceptual change theories that seem to fit the various categories of impediments.

The first, *null impediment based misconception*, *deficiency*, regarding lack of knowledge of solid state diffusion, fits diSessa's (1988) knowledge in pieces. There is a conceptual underpinning to the three phases in terms of thermal energy with solids having the lowest, liquids the next highest and gases which have the most energy for a given element. A hot solid with a temperature > T melting/2 will have sufficient energy to jump about a crystal lattice (usually in conjunction with vacancy motion) which would be a precursor to melting. Evidently the topic of diffusion in solids is not addressed in college chemistry although diffusion in gases and liquids is. So there is a hole in the conceptual framework that needs to be addressed when students enter MSE classes. Using knowledge in pieces theory it should be possible to create a teaching activity to address the topic of diffusion in solids.

The second, *null impediment transfer*, regarding bonding characteristics for different materials, may also fit diSessa's knowledge in pieces (1988). This may be because a coherent understanding about the role of bonding is often memorized by students and functional details and relationships of bonding to properties are not taught in a coherent fashion to create an integrated conceptual framework. As with the previous example, a teaching strategy is needed to present the concept of bonding effects on solids in a coherent fashion and not just memorizing pieces of information about their behavior.

The first *substantive impediment* is *experiential* since students' knowledge is fragmented and is based on observation which would fit diSessa's knowledge in pieces (1988). It appears that the topic of phases and thermal energy needs to be presented in a coherent fashion to restructure students' conceptual framework. A teaching strategy is needed to present the concept of thermal energy effects on solids in a coherent fashion and not just memorizing pieces of information about phase behavior.

The second type of *substantive impediment*, *pedagogic*, fits Voisniadou's (1998) theory-theory conceptual change misconception. From focus groups and concept questions it appears that saturation is misunderstood by students who do not understand the concept of solubility and solubility limit. Thus they have a framework which does not incorporate equilibrium in solution based processes.

The third type of *substantive impediment, misinterpretive*, fits Chi's (1992) ontological shift theory with miscategorization of a concept. Whereas calculating properties of an object by proportion or "rule of mixtures" reflects a combination of static "things", the concept of resistivity of a conductor is based on the mechanism of impurity scattering of electrons, which is an atomic processes category.

Overall, results show importance of understanding not only misconceptions that students hold, but the nature of their origin, as well as effectiveness of teaching strategy in repairing them. MSE classes could be more effective if instructors and textbooks were informed of student prior knowledge and experience, the effect of misconceptions on learning, and strategies for addressing them. Similarly, if prior classes, especially chemistry, were informed of prior knowledge and misconception issues, more effective learning might be possible in MSE courses. We have demonstrated a general classification scheme for origin of misconceptions based upon the underlying type of impediment. This classification scheme has potential for broader application in other disciplines. Thus, it may be possible to choose a teaching strategy from the diagnosis of type and origin of misconception.

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