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Effect of Pedagogy on Conceptual Change in an Introductory Materials Science Course*

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In this paper on research–to-practice we have addressed the question of what the effect of different pedagogies would be on conceptual change and repair of misconceptions or 'impediments' of different origin. This has been done by measuring conceptual change over a semester with a Materials Concept Inventory (MCI) for four introductory materials science courses taught by the same instructor who employed four different pedagogies in 2002, 2003, 2007, and 2009. Conceptual change theory was used to frame the overall study using results of gains from particular MCI questions. These questions were selected since they each represented a prototype that fit Taber's five categories of the types of impediments that underlie the origins of different types of misconceptions. The degree of conceptual change achieved for the four different types of pedagogies was analyzed using Chi's recently published schema for characterizing the effectiveness of different active learning activities based on hypothesized underlying cognitive processes. In applying Chi's framework to MCI results for conceptual gain for the four pedagogies, they were ranked as follows: interactive with hands-on activity (concept sketching) > interactive with sorting activity (concept-context sort with no hands-on) > interactive discussion only > passive (lecture). Thus, the results agree in general with Chi's predicted effectiveness of learning, except that hands-on activities produced the most conceptual change as measured by the selected MCI questions. Overall, in this research–to-practice practice paper we have addressed, with a limited set of results, the question of what effect different pedagogies have on conceptual change and repair of misconceptions or 'impediments' of different origin. The results indicate that it may be possible to use these principles to design and create classroom environments, instructional materials, and activities that are intended to elicit in students cognitive processes and learning mechanisms that result in different degrees of conceptual gain in materials science and other engineering disciplines.

Keywords: misconceptions; conceptual change; learning impediments; teaching effectiveness; pedagogy

1. INTRODUCTION

THE SCIENCE of learning is moving forward rapidly, as described in *How People Learn*: *Brain, Mind, Experience, and School* [1], which summarizes and highlights some of the most important findings in the field of cognition of teaching and learning. One major finding is that students bring their own experience to the classroom as prior knowledge about how the world works. This prior knowledge consists of preconceptions, often referred to as misconceptions, which may persist during instruction and act as a barrier to learning. In introductory materials science and engineering (MSE) courses students come from various engineering disciplines and have taken many physical science classes through their K-13 education, including one or two college level chemistry classes. The goal of the K-13 classes is for students to be able to understand and explain nature, including the characteristics and chemistry of materials. However, since the goal of engineering is to use science and mathematics to create new entities to benefit society, the focus of the introductory MSE class is to learn the approach that materials science and engineering uses for the processing and properties of materials for real world applications in the engineering design of components, devices, and systems. Thus, the conceptual framework of students must shift from an understanding of physical science and the chemistry of materials towards a framework of an understanding of the processing and properties of materials for engineering applications. As such, there may be limited exposure to important engineering materials, such as metals and poly-

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mers, in students' K-13 education. It is therefore particularly important to understand students' prior knowledge and personal experience at the beginning of the introductory MSE course. Additionally, the topic of MSE is for students a significant intellectual challenge because they need to relate a material's desired macroscale properties to its nanoscale structure. That is so because, in MSE, there is difficulty in learners constructing a useful conceptual framework to effectively link the concrete 'macroworld' of everyday objects and phenomena to the abstract 'nanoworld' of atoms, molecules and microstructure which actually control material's properties. The behavior of materials is often counterintuitive and, when 'novice' learners use everyday experience to create the *mental models* that comprise their conceptual framework [2], they may result in misconceptions. These are an individual's scientifically-inaccurate interpretations of the world that can neither explain nor predict phenomena. An example of a faulty *mental model* resulting in a misconception is 'the malleable copper atom' [3]. The question then arises as to how MSE instructors might more effectively deal with the challenge of delivering an effective learning experience so students can apply the principles to their own disciplinary needs.

For instructors to create an effective learning experience they must be aware of and acknowledge students' *conceptual framework* and the *mental models.* The framework and mental models that have been developed are from *prior knowledge* acquired from academic settings of earlier physical science and chemistry classes and from everyday *previous personal experience,* where information might be acquired from sources such as personal observation, the television, and the internet. The *mental models* that do not align with scientifically correct consensus models of the scientific community are *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. In order for an instructor to facilitate more effective student construction of new knowledge, the students' misconceptions need to be addressed. How this might be done is discussed next.

To address misconceptions, they need to be first identified. Instruction then needs to be modified so that the students' misconceptions are repaired or replaced, so faulty mental models in the students' conceptual framework give way to scientifically correct mental models. Much research has been done in these areas. For example, Hestenes created the Force Concept Inventory to identify misconceptions students hold about Newtonian physics [4]. Many other concept inventories have been created for other science, math, and engineering disciplines, including the Materials Concept Inventory (MCI) for identifying students' misconceptions in MSE [5]. Likewise, various pedagogies that use active learning have been developed based on the finding of Hake [6] and many others that, in order to achieve significant conceptual gain in a given subject, students must be actively engaged in their own learning. In spite of significant advances achieved in student learning over the past two decades, troublesome problems still exist. Some concepts are still difficult to teach, even with active learning pedagogies there are misconceptions which are persistent and difficult to repair. These have been referred as 'robust' misconceptions by Chi [7], Streveler [8] and others. To better address such robust misconceptions with a more thorough approach it might be better to not only identify misconceptions, but also characterize their origin. Furthermore, the use of a given active learning pedagogy might be made more effective if the underlying cognitive processes of learning were understood. Two recent research papers that provide approaches to classifying origins of dislocations include one by Taber [9] and another to classify effectiveness of different active learning activities by hypothesizing the underlying cognitive processes is by Chi [10]. In this paper we report on applying these approaches to better explain and understand results of the MCI when used to assess conceptual gain for the classroom practice of an introductory MSE course which used four different pedagogies: lecturing, team discussion, team discussion with concept sketching and team discussion with concept-context sorting worksheets.

2. BACKGROUND

2.1 Academic theories of conceptual change

There are several conceptual change theories commonly used by science and engineering education researchers like Streveler, Litzinger, Miller, and Steif [8]. As previously described, Posner, Strike, and Gertzong's [1] 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. 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 [12] '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 [13] 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 [14] '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 theoretical framework to use to study a student's conceptual framework and associated conceptual change. Application of conceptual change theory may be facilitated by better understanding the origins of misconceptions for which Taber's schema [9] is used and for the understanding of the effectiveness of different active learning methods with respect to underlying cognitive processes we use Chi's schema [10].

2.2 Taber's classification scheme of the origin of different types of misconceptions

Taber [9] has created a schema that ascribes the origins of misconceptions to impediments which originate from personal experience, prior knowledge from previous classes, or inappropriate application of prior knowledge to new subject material. The two general types of impediments, null and substantive, are described in Table 3. All of these prior knowledge and experience impediments underlie misconceptions that impede learning. To achieve effective conceptual change in new material, different learning strategies may be necessary to repair or replace misconceptions of different origin. There are many learning strategies used today such as problem based learning, project based learning, modeling phenomena, Just in Time Teaching, and many others. A question arises as to which type of strategy and pedagogy might be most effective in addressing misconceptions of different origins as described in Taber's framework [9]. One approach to this is to apply a schema developed by Chi [10] to assess the effectiveness of different categories of learning strategies that bound different types of teaching approaches. This will be introduced below and discussed in more detail later.

2.3 A framework on classroom strategies to elicit effective learning activities

Over the past two decades a broad array of modes of active learning have been described, implemented and assessed. However, only recently has Chi [10] sorted and classified this array with an assessment of their learning effectiveness and hypothesized underlying cognitive processes and learning mechanisms. Chi's work provides a cognitive framework that differentiates different types of *student engagement modes—active, constructive, and interactive*—in terms of observable *differentiated overt learning activities* (DOLA) as hypothetically linked to underlying cognitive processes. While all three modes of student engagement are better than *passive* learning (e.g. lecture), a comparison of the literature indicates the following: *interactive activities* are more likely to be better than *constructive activities*, which in turn are better than *active activities*. These modes are described with a summary in Table 2.

The learning mode of *being active* involves doing something (often involving physical or kinesthetic movement) while learning. In a virtual environment students exploring by *steering* and *peddling* a stationary bike while traveling through a virtual environment would be considered an *active* activity. On the other hand, students *watching* a video recording without exploring or manipulating the environment are considered *passive* since they are not doing anything. Cognitive processes that may correspond to *active* activities include underlining, copying, and manipulating by the learner. Such a learner activates existing knowledge, searches for related knowledge, encodes, stores, or assimilates knowledge that is new to him or her. Thus, these processes are known as 'attending' processes. Such attending processes can foster learning because, if information is already known, then activating it can further strengthen existing knowledge and make it more salient, stable and retrievable, thereby enhancing learning. *How People Learn* [1] states that characteristics such as framed, stable, and retrievable knowledge are typical for expert learners. Assimilating information novel to the learner also means one is adding new knowledge, and perhaps filling gaps in one's knowledge base. These attending processes can enhance learning as they enrich knowledge and strengthen existing knowledge.

The learning mode of *constructive* differs from being *active* in that learners produce additional outputs. These often contain new content-relevant

Table 1. Taber's Classification Scheme Describing Impediment Types and Definitions [9]

Type of Impediment	Definition of Impediment
null deficiency impediment	missing information necessary for learning new material due to students not having prior knowledge
null transfer impediment	missing information necessary for learning new material due to students not recognizing the links between new material and their prior existing knowledge
substantive experiential impediment	faulty concept models students hold from personal experience or observations
substantive pedagogic impediment	faulty concept models students hold from prior courses and teaching
substantive misinterpretive impediment	faulty concept models students hold from bending or misinterpreting of new concepts to fit prior knowledge

Table 2. Explanation of Chi's differentiated overt learning activities [10]

	ACTIVE	CONSTRUCTIVE	INTERACTIVE
Main Features	• Doing something physically	• Producing outputs that contain ideas that go beyond the presented information	• Dialoguing substantively on the same topic, and not ignoring a partner's contributions
Overt Activities	*Engaging Activities* • Look, gaze, or fixate • Underline or highlight • Gesture or Point • Paraphrase • Manipulate objects or tapes • Select • Repeat	*Self-construction Activities* • Explain or elaborate • Justify or provide reasons • Connect or Link • Construct a concept map • Reflect or self-monitor • Plan and predict outcomes • Generate hypotheses	*Guided-construction Activities in Instructional Dialogue:* • Respond to scaffoldings • Revise errors from feedback *Sequential or Co-construction Activities in Joint Dialogue* • Build on partner's contribution, argue, defend, confront, or challenge
Cognitive Processes	*Attending Processes* • Activate existing knowledge • Assimilate, encode, or store new information • Search existing knowledge	*Creating Processes* • Infer new knowledge • Integrate new information with existing knowledge • Organize own knowledge for coherence • Repair own faulty knowledge • Restructure own knowledge	*Jointly Creating Processes* • That incorporate a partner's contributions

ideas that go beyond the information being studied. For example, in an *active* type of activity such as *underlining,* learners are not producing additional outputs because underlined sentences are a part of originally presented materials. In contrast, a *constructive* type of activity, such as self-explaining, in which learners articulate out loud what a text sentence or a physics solution step means, is producing utterances that have been referred to as self-explanations [15], which often contain elaborations and ideas not explicitly stated in the text, so they go beyond the provided information. *Constructive* activities generally have two characteristics. One is that learners produce overt outputs, such as explanations from self-explaining, notes from note-taking, hypotheses from inducing, questions from question-asking, predictions from generating, concept maps from drawing, and self-report assertions such as 'I don't understand' from monitoring. A second is that learners produce outputs not contained in learning materials such as comparing-and-contrasting two worked-out examples that requires the students to say explicitly what is the same or different between them. Processes that may underlie *being constructive* are those that generate new ideas (self-explaining, drawing a concept map, comparing and contrasting cases, inducing hypotheses) and allow learners to infer new insights or new conclusions. This may happen from making deductions and inductions, from reasoning analogically through comparisons, from integrating new knowledge with old knowledge, or by linking information from disparate sources. As such, these 'creating' processes of comparing, connecting, inducing, analogizing, generalizing, etc., allow the learners not only to infer new knowledge, but also repair and improve their existing knowledge. These 'creating' processes of *constructive* activities may engage 'attending' processes such as activate and assimilate. Thus, 'creating' processes include 'attending' processes. Creating processes enhance learning by inferring new relations, new conclusions, and new insights, all of which can make one's knowledge richer, repair one's knowledge, make it more coherent, more accurate, and better-informed. These changes can deepen one's understanding of new materials, and have been shown to improve learning, such as from explaining-to-self [16] and explaining-to-other [17].

The learning mode of *being interactive* can refer to several types of overt activities, such as a learner talking with another person (a peer, a teacher, a tutor, a parent), responding to a system, such as an intelligent tutoring system, or interacting in some other physical way involving motor movements. Two children can be interacting physically when they jointly build a Lego model [18], or two students can be interacting physically when they coordinate their use of a mouse at a single computer monitor. However, even with two students working together at a single computer simulation model, the learning probably occurs in the verbal discussion rather than the kinesthetic interactions. This supports the assumption that discourse activities are related to cognitive processes of learning [19]. Because human dialogues are dense and rich in content, dynamics of interactions can be interpreted more accurately by analyzing discourse content compared to a sequence of interacting gestures. Processes underlying peer interaction can be more extensive than each peer constructing alone from reading text or worked-out examples. In peer interaction, underlying processes occur by peers building on each others contributions, reciprocally so, in what can be called sequential-construction. The partners' contributions interact reciprocally by sequentially building on, refining, and modifying the original concept in some way. This type of interaction can spiral and produce some novel ideas or products, resulting in innovations.

The impact of this cognitive framework just described is that, by specifying the distinctions between the *differentiated overt learning activities* (DOLA) for *active, constructive, and interactive* modes of student engagement, it may become possible to demonstrate how learning activities can be characterized and how each kind of activity might be elicited in a learning process. Thus, this framework could be used to customize learning strategies so that one could focus specifically on a misconception of a particular nature and origin. Chi's schema [10] could then be linked to Taber's [9] five categories of origins of misconceptions from the learner's prior knowledge and experience. A Chi and Taber linked approach could provide structure and direction for addressing robust misconceptions that a broader approach to active learning in engineering education has not yet resolved. This idea can be framed by the extensive review of active learning in engineering education by Prince [29] who cites a definition by Bonwell and Eison [21], 'Active learning is generally defined as any instructional method that engages students in the learning process. In short, active learning requires students to do meaningful learning activities and think about what they are doing.' Prince elaborates further in stating, 'While this definition could include traditional activities such as homework, in practice active learning refers to activities that are introduced into the classroom. The core elements of active learning are student activity and engagement in the learning process. Active learning is often contrasted to the traditional lecture where students *passively* receive information from the instructor.' Additionally, Streveler, et. al. [8] focused on the issue of how to address robust misconceptions by drawing heavily on fundamental research by cognitive psychologists and applied research by science educators to provide a background on fundamental issues on learning conceptual knowledge in the engineering sciences. They presented valuable insights on the issue of learning difficult concepts in engineering sciences, but finally concluded that, 'Although the literature on conceptual knowledge is extensive, a very practical research question remains largely unanswered—how can one construct learning experiences that help students learn difficult concepts in engineering science?'

In this work we want to address the issue of difficult concepts and associated robust misconceptions. As suggested earlier, this may be possible by first identifying their origin and then modifying instruction to elicit more effective learning activities. It might then be possible to repair or replace students' misconceptions so that specific faulty mental models in the students' conceptual framework give way to scientifically correct mental models that can both explain and predict a phenomenon in the content domain. A great deal of research has been done in these areas but there is still need for further progress. For example, the Force Concept Inventory was developed to identify misconceptions students hold about Newtonian physics [4]. Many other concept inventories have been created for other science, math, and engineering disciplines, including the Materials Concept Inventory (MCI) for identifying students' misconceptions in MSE [5, 22]. Likewise, a great variety of pedagogical approaches using active learning have been developed based on the finding of Hake and many others that, in order to achieve significant conceptual gain in a given subject, students must be actively engaged [6]. For example, Halloun and Hestenes have shown the effectiveness of achieving conceptual change with modeling instruction [23] as have Crouch and Mazur with peer instruction pedagogy [24]. In spite of significant advances achieved in student learning over the past two decades, troublesome problems still exist. Thus, in this work we want to first identify robust misconceptions using MCI data from four different pedagogies used by the same instructor for four semester long introductory MSE classes. We then will use Taber's schema [9] to select misconceptions that fit the five categories of origin. We will then examine the relative conceptual gain of the different pedagogies and use Chi's DOLA framework to postulate what underlying cognitive processes might account for differences in MCI results due to differing pedagogies. The pedagogies that were employed in this study were: lecturing, team discussion, team discussion with concept sketching and team based discussion with concept and context sorting activities. Also, we discuss in the results and discussion section possible strategies that might be used by instructors for achieving greater conceptual gain in the future.

3. METHODS

Previous analysis of the MCI has shown it to be a valid and reliable instrument, with factor analysis giving a Cronbach's alpha of 0.71 [5]. A reproduction of the full test is also available in the appendix of reference [5]. In this work the MCI has been used to measure conceptual change over a semester for four introductory MSE courses taught by the same instructor who employed four different pedagogies in the years 2002, 2003, 2007, and 2009. The student percentage gains over a semester have been calculated using the Hake method [6]. The calculation Hake used is given by the equation:

$$\%\text{ gain} = ((\text{post-score—pre-score})/(100\text{–pre-score})) \times 100.$$

The sections described here were one of three taught every fall and spring term. The course is required by some other engineering disciplines and was populated mainly by sophomore and junior

Table 3. Population enrolled in introductory materials science courses in 2002, 2003, 2007 and 2009

Participants (n)	2002		2003		2007		2009	
	enter n = 60 %	exit n = 54 %	enter n = 51 %	exit n = 48 %	enter n = 40 %	exit n = 33 %	enter n = 40 %	exit n = 38 %
Female	40	41	25	24	18	9	15	16
Male	60	59	75	76	83	91	85	84
	%	%	%	%	%	%	%	%
Aerospace	13	12	25	24	3	3	0	0
BioEngineering	28	29	22	22	13	12	0	0
Chemical	2	2	8	8	5	6	23	24
Industrial	7	7	7	6	5	3	5	5
Materials	2	2	1	1	3	3	8	8
Mechanical	37	37	27	29	70	70	60	58
Other	11	10	10	11	1	3	6	5

mechanical engineering undergraduates who comprise two-thirds of the class. The remaining one-third were students from other disciplines who were taking the course either as an elective or because it was required. These students included materials science and engineering (required), industrial engineering (required), chemical engineering (not required), aerospace engineering (not required) and bioengineering (not required). In 2002 and 2003 the course was required by aerospace engineering and bioengineering but the curriculum was changed and the course became an elective in those disciplines. This is the reason that class enrollments diminished after the 2003 course. This is shown in Table 3 where populations for all four years are listed. It is possible that the changing populations between 2002 and 2003 and 2007 and 2009 may have had some effect on the results since virtually all bioengineering and aerospace engineering students had dramatically diminished and the mechanical and chemical engineering populations increased significantly. Similarly, the female population also declined significantly in the same time frame, mainly due to the absence of bioengineers which have a population of close to 50% female. The setting also changed to promote team learning. In 2002 and in 2003 traditional classrooms were used with rows of movable chairs facing the front of the classroom. In 2007 and 2009 a laboratory room with round tables was used and students self organized themselves as teams. The lab was also outfitted with a projector and a floor-to-ceiling white board wall which students used to present and discuss team based results. This was part of the shift in pedagogy and may account for some of the increased conceptual gain that was reported. The textbook and content covered in the courses remained the same for all four pedagogies, although new problem sets were developed for 2009. In terms of pedagogy, the 2002 content was delivered by lectures, the 2003 content by lectures plus team-based discussions, the 2007 content by team-based discussions and concept sketching, and the 2009 content by team based discussions and concept in context sorting activities. In 2002 and 2003 students remained seated but in 2007 and 2009 team representatives reported their results via a wall screen at the front of the classroom. The MCI was administered during the first and last weeks of class in paper form in 2002 and 2003 and via computer outside class in 2007 and 2009. Students took the test voluntarily for all classes as handouts at the beginning and the end of the semester, except the entering and exiting 2009 MCI in which case they took the test via computer and received an incentive of a 2 point bonus in the 80 point maximum scale for the semester. Focus groups were held twice a semester during the 2002 and 2003 courses and were also held biweekly in the 2009 course. The questions selected from the MCI are shown in Fig. 1 and the MCI results for all years for those questions are shown in Table 4.

4. RESULTS AND DISCUSSION

4.1 Null-impediment based misconceptions

The first type of null impediment (missing information necessary for learning new material), a *null deficiency impediment,* refers to a lack of prior knowledge. An example of this is the diffusion of atoms in a solid, as shown from Question #1 located in Fig. 1. In K-12 and college chemistry students learn atoms in liquids and solids are in 'motion' but oscillate about a point in a solid and have 3-D translations in a liquid. However, MCI pretest scores shown in Table 3, which range between 0% and 29%, 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 deficiency impediment* 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, which range from 50% to 63%, except for 2007 when there was 100% gain. Of the

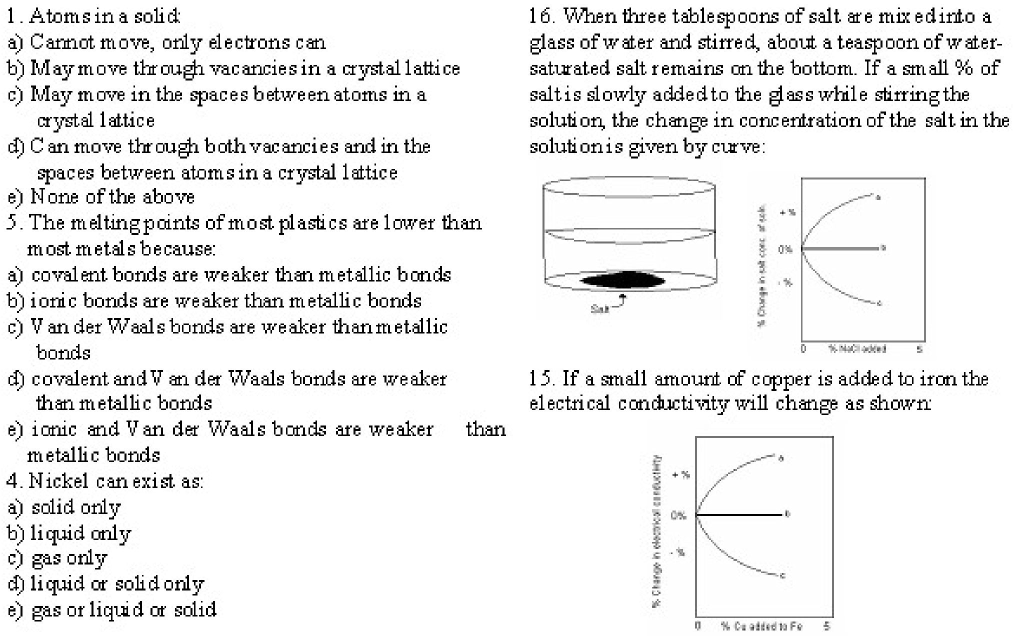

Fig. 1. Materials Concept Inventory Questions Numbers 1, 5, 4, 16, and 15.

Table 4. Materials Concept Inventory Pre-Class, Post-Class & Gain Scores for 2002, 2003, 2007 and 2009

	2002			2003			2007			2009		
MCI Abbreviated Question	pre	post	gain	pre	post	gain	pre	post	gain	pre	post	gain
Participation: n = number of participants	n = 51	n = 49	–	n = 43	n = 38	–	n = 33	n = 31	–	n = 34	n = 34	–
% = 100 (n / total enrollment at time of MCI)	85%	91%		84%	79%		83%	94%		85%	84%	
1. Can atoms move in a solid?	29%	65%	51%	24%	68%	58%	16%	100%	100%	0%	63%	63%
5. Why is Tmelt of polymers lower than metals?	24%	31%	9%	6%	13%	7%	32%	30%	–3%	0%	5%	5%
4. Can Ni exist in solid, liquid and gas phases?	45%	51%	11%	47%	53%	11%	55%	93%	84%	50%	73%	46%
16. What is effect of NaCl added to saturated solution?	39%	65%	43%	49%	82%	65%	42%	96%	93%	27%	81%	74%
15. What is effect of Cu added to Fe on conductivity?	20%	75%	69%	12%	61%	56%	13%	75%	71%	14%	45%	36%

four pedagogies, team discussion with concept sketching in 2007 was the most effective. In Chi's schema [10] this is both a *constructive* and an *interactive* activity with students discussing ideas while also creating new material. It is better than other 'interactive activities' with discussion alone (2003) or discussions with matching of concepts and contexts in 2009 where no new output was constructed beyond the given content. It may be possible for instructors to extend these positive results with other constructive activities such as a tabletop simulation of diffusion by moving coins around. The content in this question is important because students who fail to understand diffusion will have their learning impeded for topics such as annealing and isothermal transformation of steels. Thus it is suggested that instructors need to devise team based creative learning activities, for example by using coins to trace diffusion of an atom and a complementary vacancy.

The second type of null impediment is missing information, or a *null transfer impediment* which is due to students not recognizing the links between new material and their prior existing knowledge. An example of this is, the effect of bond strength on relative melting points of 3 materials families (metals, polymers, and ceramics) and is given by MCI question #5 in Fig. 1. In K-12 and college chemistry students learn about the three types of primary bonding, metallic, ionic, and covalent, as well as weaker secondary bonding, but the types of interatomic bonding may not be explored much. Although the bonding along the polymer chain is covalent, there may not be discussion about van der Waals bonds between chains. So it is not a surprise that MCI pretest scores in Table 3 range between 0% and 32% which indicates less than a third of the students may not have transferred bonding concepts from earlier 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 may be so, as seen from gain scores, which are quite low, ranging from –3% to 10%. For all years and pedagogies there is little difference in learning. This is clearly a robust misconception that has proved immune to different pedagogies. It may be that this misconception fits Chi's ontological misclassification category of misconception [14] since students may be thinking of static bonds in solids as opposed to dynamic dissociation of molecules from one another with breaking of van der Waals bonds, which is a process [10]. It might be that a DOLA activity to address this would have to be both interactive and constructive, say with a plate of spaghetti representing polymers chains or possibly a creative activity where intermolecular chain interactions are represented. Students who fail to effectively understand polymer bonding will have learning impeded for a wide variety of subsequent topics related to processing and properties of polymers.

4.2 Substantive-impediment based misconceptions

The first type of substantive impediment, a *substantive experiential impediment,* refers to faulty concept models students hold from personal experience or observations. An example of this is with respect to phases of a material is given by MCI question #4 in Fig. 1. This example considers importance of materials phases, since metals, ceramics and polymers can be 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 misconception. Personal experience from focus groups gave wrong answers like: 'I have never heard of Ni gas', 'I have never seen Ni gas', and 'I have only seen Ni as a solid'. MCI pretest showed only half of the students understood that elements can exist in three phases with scores ranging from 45% to 55%. The post-test MCI scores show an interesting result. While the pedagogies of lecture (2002) and team discussion (2003) showed minimal gains of 11%, and the 2009 team discussion/concept-context sorting showed a moderate gain of 46%, team discussion and concept sketching (2007) showed the largest gain of 84% and was most effective for conceptual change. This may be a situation where knowledge is in pieces [13] since students are not connecting this question to other materials such as water as ice, liquid, or gas. Thus, discussion and concept sketching achieves higher conceptual gains in the MCI indicating that, from Chi's schema [10]; a combination of interactive mode with constructive activities is more effective for conceptual change and learning.

A second type of substantive impediment, a *substantive pedagogic impediment,* refers to faulty concept models students hold from prior courses and teaching. An example of this is with respect to solutions and solubility limits is given by MCI question #16 in Fig. 1. Concepts of saturation and supersaturation are used in phase diagrams in MSE (e.g. precipitation hardening). Research shows that in K-13, misconceptions on saturation and supersaturation are robust and persistent [25, 26]. The MCI pre-class results support this idea with scores of 27% to 49%. More than half of the students bring solution-related misconceptions with them to their MSE classes, making this a *substantive pedagogical misconception*. The post-class MCI scores are revealing, with gains of 42% in 2002, 64% in 2003, 93% in 2007, and 74% in 2009. The gains increase as pedagogy goes from lecturing, to team discussions, to team discussion and concept-context problem solving, but the highest again is team discussions with concept sketching. Thus, when students engage in discussion while constructing something, like a visual model of a phenomenon, their learning is greatest. This may fit Voisniadou and Ioannides' [12] theory-theory for conceptual change of misconceptions. 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. While Chi's [10] modes of constructive and interactive activities might seem suited to effective learning, the nature of the constructive activity may influence learning effectiveness. The topics of solutions and solubility play a critical role in many MSE topics related to phase diagrams, microstructures, and non-equilibrium thermal processing and it will be important for instructors to utilize the most effective pedagogy.

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 is with respect to calculating properties from the macroscopic 'rule of mixtures' as given in MCI question #15 in Fig. 1. 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

Table 5. Summary of results relating relected MCI questions to Taber's impediment type [9], the misconception type, and Chi's learning effectiveness categories [10]

MCI Abbreviated Question	Impediment Type	Misconception Type	Highest % Gain
1. Can atoms move in a solid?	null deficiency	—	IC, I2, I1, P
5. Why is Tmelt of polymers lower than metals?	null transfer	ontological [14]	P, I1, I2, IC
4. Can Ni exist in solid, liquid & gas phases?	substantive experiential	knowledge in pieces [13]	IC, I2, I1, P
16. What is effect of NaCl added to saturated solution?	substantive pedagogic	theory-theory [12]	IC, I2, I1, P
15. What is effect of Cu added to Fe on conductivity?	substantive misinterpretive	ontological [14]	IC, P, I1, I2

Legend: P = passive (lecture) 2002; I1 = interactive (discussion alone) 2003.
IC = interactive + constructive (discussion + sketching) 2007; I2 = interactive (discussion + sorting) 2009.

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 with pre-MCI scores ranging from 12% to 20%. The post test results show good gains for all four pedagogies on the posttest but the best again was for the 2007 discussion with concept sketching. Again, this may be an issue of ontological miscategorization due to the fact that electron conduction is a nanoscale process whereas students may interpret it incorrectly because they may employ macroscopic view of the process. One possible macroscopic view could be an inappropriate analogy like electrons flowing through a wire like water flowing through a hose.

The results are summarized in Table 5 which relates, for the set of selected MCI questions, the impediment type (as categorized by Taber [9]) to the misconception type to Chi's learning effectiveness categories [10]. It can be seen that for four out of the five questions the modes of interactive plus constructive achieved higher gain. The higher gains were particularly dramatic for the first and third selected questions about atomic motion in solids and existence of three phases of materials. It may be possible that discussion and concept sketching can provide a pathway to link macroscopic and microscopic behavior with more concrete expressed models than discussion can alone. On the other hand, the second and fifth questions, which may be ontologically related misconceptions, concept sketching only has limited or little impact on repairing misconceptions. These appear to be more robust and may require better strategies, possibly those suggested in Chi's framework. The information in the table suggests that there are tools or approaches that now available to develop strategies to address misconceptions once they have been identified.

5. CONCLUSIONS

Overall, we have used conceptual change theory to frame the study to suggest possible effectiveness of different pedagogies in achieving conceptual gain (as measured by the MCI) and repairing misconceptions. This was done by using results of particular MCI questions as prototypes that fit Taber's five categories of impediments that underlie the origins of different types of misconceptions [9]. The effectiveness of the four different types of pedagogies on conceptual change was analyzed using Chi's DOLA schema [10] for characterizing effectiveness of different active learning activities based on hypothesized underlying cognitive processes. In this work the four pedagogies differed somewhat from the ones specifically described by Chi [10]. In particular, the pedagogy of team discussion plus concept sketching was kind of a hybrid between constructive (for an individual) that was hybridized with interactive for the team based discussions that also occurred. It also turns out that this pedagogy had the highest MCI scores for four out of the five questions that were selected based on Taber's five categories of impediments for misconception origins [9]. Of course this is a small data set, but these early findings are worthwhile pursuing by incorporating more concept sketching or other activities where students put a concept model to use in a new situation by incorporating a sketch or 3-D model which demonstrates the application of a concept to a particular situation. This might correspond to a situation of far transfer according to How People Learn [1] where the concept is understood at a deeper level. This will be explored further in the upcoming fall 2009 semester. To summarize the results for higher conceptual gain and possible effectiveness of the four pedagogies, they were ranked as follows: interactive with hands-on activity (concept sketching) > interactive with sorting activity (concept-context sort with no hands-on) > interactive discussion only > passive (lecture). Thus, the results agree generally with Chi's predicted effectiveness of learning [10], except that hands-on activities produced the most conceptual change as measured by selected MCI questions. The results indicate that it might be possible to use these principles to design and create classroom environments, instructional materials, and activities that are intended to elicit in students desired cognitive processes and learning mechanisms that result in repairing misconceptions and fostering conceptual change for greater conceptual gain in materials science and engineering and possibly also other engineering disciplines.

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