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## **AC 2011-1299: ADDRESSING MISCONCEPTIONS AND KNOWLEDGE GAPS IN THE RESTRUCTURING OF ATOMIC BONDING COURSE CONTENT TO ENHANCE CONCEPTUAL CHANGE**

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# **Addressing Misconceptions and Knowledge Gaps in Restructuring of Atomic Bonding Content in a Materials Course to Enhance Student Conceptual Change**

## **Abstract**

It is generally acknowledged in science and engineering education research that students have prior knowledge about how the world works, such as preconceptions and misconceptions and in order create, develop, or restructure instructional materials and activities, they must be informed by that prior knowledge. In a sense, prior knowledge in a classroom setting consists of, in addition to preconceptions and misconceptions, knowledge gaps, limited language skills, and varying analytical, computational, and graphical skills. As found in science education, effective instructional materials and classroom practice are informed by and address information from broad formative assessment of foundational knowledge of students learning new content. In engineering education, instruction must build on this idea to teach students not only about scientific phenomena, but also application of scientific phenomena to engineering applications. In this research, teaching and learning materials and activities that do this have been informed by such assessment results.

In this paper we report on the research question, "How can instructional materials be modified to address and assess misconception and knowledge gap identification and repair from formative and summative assessments in an introductory materials class?" Information from a materials concept inventory, pre-post topic concept question sets, team activities, and classroom dialogue have been used to remodel class notes. Students learned concepts by connecting a real-world artifact's macroscopic properties to its internal atomic and microscopic structural characteristics with multiple representations of the linkages. Application of analogical reasoning and cognitive dissonance learning tools were incorporated in class notes and team activities to promote conceptual change. Incorporating hard data in "explain and predict activities" forces students to address anomalies in their mental models and revise and remodel their conceptual framework in a given topical area. Effective instructional materials can not only address student issues, but also inform instructor practice to enhance his/her pedagogical content knowledge. Two examples are given in this paper about a knowledge gap and a misconception. One is for an atomic bonding knowledge gap about van der Waals bonding and associated misconceptions related to polymer properties. The other is about metallic bonding and students' representation of image and function of bonding in metals. Approaches to addressing these issues are illustrated with implementation of informed instructional materials, activities, and tools in the classroom. These will be presented and discussed in detail in the paper with the goal of illustrating possible pathways to broader implementation of innovative pedagogy by more instructors and possibly other engineering disciplines.

## **Introduction**

In introductory materials science and engineering (MSE) courses, a major goal is to effectively teach learners from a variety of disciplines about engineering a material's macroscale properties based on the understanding of its atomic and microscopic scale structure. This goal is a

significant intellectual challenge because learners must develop a conceptual framework to understand and solve materials-related problems in their own discipline. To develop this conceptual framework, MSE principles about structure-processing-property relationships need to be used to understand and correlate the concrete "macroworld" of everyday objects, properties, and phenomena to the abstract "atomic world" of atoms, molecules, and microstructure, which actually control a material's properties. However, there may be difficulties in addressing materials' macro-micro relationships because some of students' prior knowledge may have knowledge gaps and misconceptions. The knowledge gaps may exist due particular concepts not covered in a previous course or students' inability to transfer already-covered concepts to the new classroom settings. Also, students may hold misconceptions, which are scientifically-inaccurate interpretations about materials that can neither explain nor predict materials' phenomena or properties. In order to deal with the issue of the effect of knowledge gaps and misconceptions on teaching and learning, they must first be identified, addressed through informed instruction, and then assessed to measure the effectiveness of remodeled instructional materials and practices on filling knowledge gaps and repairing misconceptions.

In this paper we will report on methods that: identify knowledge gaps and misconceptions about particular topics in an introductory MSE course; the effect of instructional approaches used to address knowledge gaps and misconceptions; and the assessment of the effectiveness of the approach on repairing the knowledge gaps and misconceptions. As such, the tools used to reveal them, the instructional changes incorporated to address them, and the instruments to assess repair will be described and discussed. Implications and suggestions for instruction based on this approach are then discussed. Overall, we report on the research question, "How can instructional materials be modified to address and assess misconception and knowledge gap identity and repair from formative and summative assessments in an introductory materials class?"

## **Background**

An important aspect of the approach used in developing innovative materials was to illustrate the relevance and significance of a concept by demonstrating its application in the context of a real-world item that would be familiar to students. An example would be to illustrate structure-property-processing relationships for components of an engineering system like a motorcycle. Such components being made of metals, polymers, and ceramics would have property and processing requirements linked to material internal structure. As such, the instructional materials and practices using this approach were referred to as Concept Learning In Context (CLIC) instruction. The goal was to tie concepts to real-world items and applications in order to bridge the familiar and concreteness of an everyday item to the unfamiliar and foreign abstract concept of the macroscopic property and microscopic structure relationship. Ideally, this approach has the potential to illustrate relevance and significance of a concept as well as to motivate students with a concept's importance to their future learning and courses as well as their careers.

### Relationship of Students' Mental Models to Expressed Models, and Conceptual Frameworks

Constructivism espouses the belief that students learn most effectively by constructing their own knowledge and refer to learning as conceptual change<sup>1-3</sup>. *How People Learn*<sup>4</sup> discusses how cognitive processes act to achieve conceptual change, which occurs through modification of a student's conceptual framework. The framework is comprised of *mental models*, which are

transformed representations of real-world systems or phenomena called *modeled target systems or phenomena*<sup>5</sup>. As such, *mental models* are defined as simplified, conceptual representations that are personalized interpretations of *modeled target systems or phenomena* in the world around us. Thus, the transformed *modeled target systems or phenomena* turn into the *mental models* which become more visible or comprehensible to the individual<sup>6</sup>. Useful *mental models* allow us to understand, explain, and predict behavior of systems and phenomena, whereas faulty *mental models*, which lead to misconceptions, cannot. Use of *CLIC* in the materials course can uncover misconceptions which a teacher can use to adjust instruction. In order to understand how students think about a particular concept within a topic, that concept must be translated into a meaningful representation. As such, an individual communicates his/her *mental models* with some form of external representation, which are called *expressed models*. They might be verbal or written descriptions, equations, sketches, diagrams, physical models, computer models, or other forms of representation<sup>7</sup>. Thus, the *expressed models* reveal students' "ways of thinking" when elicited by appropriate questions, activities, and assessments. In fact, when students use a *mental model* in their conceptual framework and express it in various forms, they are, in effect, explaining their ideas or "modeling a concept". These *expressed mental models*, or modeled concepts, can be used as indicators to track conceptual change as measured by techniques such as the concept inventories, pre-post topic concept quizzes, interviews, drawn sketches, journaling, etc. As such, assessments that inquire about "multimodal" representation of concepts are better able to triangulate students' conceptual understanding of a topic.

### Assessing Student Knowledge Gaps and Misconceptions

Pre-Post Topic Concept Quizzes are formative assessments that were created to assess prior knowledge. They were given prior to instruction on a topic to reveal knowledge gaps and misconceptions<sup>8,9</sup>. If the same tool is administered as a Post-Topic Concept Quiz it informs instructors if knowledge gaps and misconceptions have been repaired, or, if still present, can be classified as robust misconceptions. Thus, the Pre-Post Topic Concept Quizzes are tools that have been used to measure effectiveness of instruction and conceptual change. Additionally, the Materials Concept Inventory (MCI) measures pre- and post-course concept knowledge and thus conceptual gain. Eliciting such information is critical in informing modification and continuous improvement of innovative and misconception-informed teaching materials. In effect, students are involved in designing their own instruction, which is an important strategic point for creating more effective instructional materials.

### Reconfiguring Instructional Materials to Address Knowledge Gaps and Misconceptions

The instructional materials were developed by restructuring an already-existing set of book publisher chapter slide set materials by using the principles described in the book, *How People Learn*. The *modified* already-existing publisher's materials were used to promote easy adoption of the teaching innovations by other instructors since the *modified materials* were reasonably well-aligned with their own *unmodified* already-existing publisher's materials. This addresses the important factor of *ease of implementation*. The results from the formative and summative assessments were collected and analyzed in order to reveal issues in student prior knowledge which included the knowledge gaps and misconceptions. The materials were then reconfigured in order to address the major impediments and barriers to student learning previously described.

## Facilitating Ease of Implementation of Innovative Instructional Materials

Henderson and Dancy made some suggestions to address issues cited above to inform curriculum materials developers of possible ways to improve implementation of innovative STEM teaching and learning strategies and materials<sup>10</sup>. They include the following. Provide easily modifiable materials to help engage faculty in modifying or redesigning their instruction so innovative materials are easy to use. Another suggestion is in fidelity of implementation of an innovation. For example, effective learning should not just elicit simple answers to contextualized questions, but also engage students in social construction of knowledge by peer discussion of underlying conceptual justification of responses. The last suggestion is to facilitate the implementation of innovative materials and practice by working with peers through workshops and colloquia. This needs to be done to provide personal support and build self-efficacy for instructors who want to implement innovative materials and practices in their classrooms. These concepts and ideas about implementation were used to inform development of materials described in this paper.

## Methods

Throughout instruction on all topics, students were asked to frequently express their mental models in multiple modes. This revealed student thoughts about and understandings of the content. Student expressions and explanations of thinking were expressed in different ways, or representations, including written, verbal, diagrammatical, mathematical, graphical, and kinesthetic. Writings were recorded from thoughts, solutions, or recommendations generated in class. Verbal expressions were made through team-based interactions and problem solving in response activity scenarios. The instructor accessed these verbal representations by moving from team to team and interacting verbally with each of them. Additionally, students were asked to express their thinking diagrammatically by sketching pictures. They gave a less ambiguous understanding of how students were thinking about phenomena. Students were given scenarios with specific numerical data and asked to predict or explain thoughts using models to justify their thinking. Graphical representations give students the opportunity to express ideas through graphical relationships. Students were sometimes asked to produce graphs in order to explain the relationships between two different ideas or concepts. The last mode of expression that students were asked to engage in was a kinesthetic representation of their understanding. To do this, students created and used physical models to aid in explaining their understanding of bonding topics. By having students explain their ideas in each of these modes at various times during instruction, frequent multimodal expressions of student mental models were elicited. These models and understandings were used to remodel instructional materials as described below.

## Results and Discussion

### Knowledge Gap About van der Waals Bonding In Polymers

Mini-lecture class notes were projected on a writing wall during instruction. All activity worksheets and instructions were incorporated within class notes. Students could print out a copy prior to attending class so that they were able to follow class instruction and activities. Class notes were contextualized and utilized multiple representations including visual, written,

graphical, and mathematical modes of explanations of content. They acted as a framework for the class. The contextualization allowed for the instructor to interact with students and to create connections between student prior experiences and the new information and concepts presented. This interaction, and the conversation that resulted, verbally elicited student mental models.

Pre-Post Topic Concept Quizzes were given before and after instruction of two classes on atomic bonding. This assessment asked students to briefly describe and sketch a diagram to represent each of the four types of atomic bonding: covalent, ionic, metallic, and van der Waals. These bonding types were chosen because they are the most central to the materials and processes examined in materials engineering. In another assessment, students were given three different materials: a paper clip, a glass bottle, and a PVC pipe. For each material, students were asked to identify bonding type(s) present and properties of the material important to its function. Examples of pre and post written descriptions and sketched models for five different students are shown below in Figure 1 for van der Waals bonding.

### Bonding Pre-Post Data Summary

In the space below, briefly describe and sketch each of the different types of bonding listed below.

#### Van Der Waals Bonding



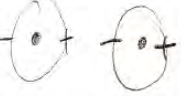
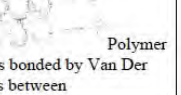
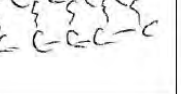
A0000- Van Der Waals Describe Pre / Post	Sketch Pre	Sketch Post
Weak bond, each element brings electrons		
weaker bonds, often between polymer chains		
A1117- Van Der Waals Describe Pre / Post	Sketch Pre	Sketch Post
A weak secondary bond		
A3743- Van Der Waals Describe Pre / Post	Sketch Pre	Sketch Post
A flexible bond		
weaker bonds that are flexible		
B5151- Van Der Waals Describe Pre / Post	Sketch Pre	Sketch Post
?	?	 <p>Polymer chains bonded by Van Der Waals between</p>
secondary bonds that are weak usually involve dipoles		
B8963 - Van Der Waals Describe Pre / Post	Sketch Pre	Sketch Post
weak attraction between all atoms		

Figure 1. Pre and Post Instruction Written and Sketched Descriptions of van der Waals Bonding. The data in Figure 1 show that for the pre-topic concept quiz, only 2 of 5 students provided a written response, and 1 of 5 provided a sketched model of van der Waals bonding. The description for student A0000 was only partially correct in describing the van der Waals bond in stating that it was a "weak bond" while student A3743 stated it was a "flexible bond". These results were representative of most of the class of 38 students.

Two classes of instruction were conducted on metallic, ionic, covalent, and van der Waals bonding. The first covered relationships of bonding to the periodic table and the second was on relationships of bonding to material properties for metals, ceramics and polymers. Bonding type was described for metals, ceramics, and polymers and related to the materials' properties of melting point, stiffness (or elastic modulus) and coefficient of thermal expansion. The instructional materials used will be described below and then discussed in conjunction with the post-instruction concept quiz results.

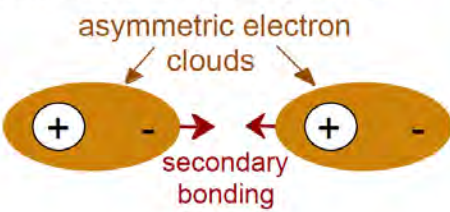
### Mini-Lecture Class Notes on van der Waals Bonding

Class note slide related to van der Waals bonds is shown below in Figure 2.


## Secondary Bonding

Arises from interaction between dipoles

- Fluctuating or temporary dipoles



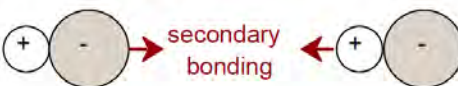
Example: Polymers




secondary bonding


- Permanent dipoles-molecule induced

-general case:





-ex: liquid HCl



Chapter 2 - 17




Figure 2. Schematic Model and Definition and Context of van der Waals Bonding

The slide was modified from the well-conceived original from the slide set of Chapter 2 – Atomic Bonding, from Callister's 8th edition of Materials Science and Engineering, an Introduction. Basically, it *defines and illustrates the symbolic model for van der Waals bonding*

and the relationship to the structure of a polymer. The slide has been modified and streamlined to emphasize the importance of how properties are affected by the van der Waals bonding between long, covalently bonded 1-D polymer chains. A feature recently added to the slide is the concept-in-context of a ultrahigh molecular weight polyethylene hip joints and body armor which illustrates the relevance of the role of van der Waals bonding in real world artifacts.

**Team-Based Activity for Structure-Processing-Properties Relationships of Material Families**

The Chapter 2 slide set was separated into two classes. This was done in order to link the first class, Bonding and the Periodic Table, to students' prior knowledge from chemistry. The second class, Bonding and Material Properties emphasized the relationship of atomic bonding to properties of the families of materials. Additionally, the importance and significance of the relationship of bonding to processing of the different materials families was also introduced. This is not generally done in materials texts, but the nature of bonding for different materials families is critical to materials processing. In particular, most ceramics, with ionic and/or covalent bonding, require a high temperature processing step, usually greater than 600°C to 1000°C. For metals, with metallic bonding, their ductility makes shaping is possible by deformation processing at room temperature or at moderately elevated temperatures of 300°C to 800°C. For polymers, with weak van der Waals bonding between chains, processing is done in the molten state above Tg or Tm at relatively low temperatures of 150°C to 300°C. Polymers may also be formed at temperatures just below Tg or Tm by processes such as vacuum forming. Figure 3 illustrates the principle of connecting abstract concepts of the different bonding types to the real-world components of a motorcycle. It ties bonding to properties as well as processing methods.

1. Choose the most likely property, material, bonding, and process for these motorcycle items (20 pts)


	property	material	bonding	processing	
i) motorcycle fender	_____	_____	_____	_____	
ii) headlight lens	_____	_____	_____	_____	
iii) motorcycle seat	_____	_____	_____	_____	
iv) headlight filament	_____	_____	_____	_____	
v) spark plug insulator	_____	_____	_____	_____	
					
<b>PROPERTIES</b>	<b>MATERIAL</b>			<b>BONDING</b>	<b>PROCESSING</b>
I. transparent and impact resistant	1. tungsten - W			A. covalent	a. vacuum warm forming
II. stiff and ductile	2. polyvinylchloride			B. ionic	b. calendaring
III. flexible and tough	3. polycarbonate			C. metallic	c. wire drawing
IV thermal & electrical resistance	4. aluminum oxide (Al2O3)			D. van der Waals	d. metal stamping
V. thermally stable electrical conductor	5. steel - Fe + .2%C			E. covalent & van der Waals	e. sintering

Figure 3. Concept-in-Context Team Activity on Materials Selection that Connects Bonding-Property-Processing Relationships to Motorcycle Components for Different Materials Families



Students found the processing-bonding relationships quite interesting. In fact, about one third of the students found the materials processing aspect of bonding to be the most interesting part of the class, as elicited by the class-end Most Interesting Point reflection. While students found the processing techniques interesting, they were unfamiliar with them and wanted more information. As such, an informational sheet was developed which illustrated and defined the different processing techniques associated with the different component motorcycle parts. This is shown in Figure 4 below.

### Activity Information

#### Learning Objectives and Outcomes

**Learning Objective:** Demonstrate the relationships between properties of a material and its atomic bonding and its processing method and its performance application. These are some of the most important factors that come into play in the materials selection activity of the design process.

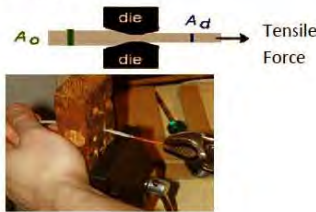
**Learning Outcome:** After completing this worksheet you will be able to look at an object and its important properties and identify the type of material, atomic bonding, and processing method used to make that object.

#### Directions:

1. Use all the answers from the Properties, Material, Bonding, and Processing boxes to fill in each column with one answer from the corresponding answers from each box should be used at least once, except for the Bonding Box where each choice which may be used more than once or not at all.
2. Household Item -

#### Materials Processing Methods

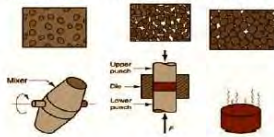
**Drawing-** Pulling a material through a reducing die with a tensile strength force applied to the emerging material.



**vacuum thermoforming-** softened thermoplastic sheet is placed on top of a mold and a vacuum pulls the sheet tightly over the mold allowing it to harden into the shape of the mold.



**Sintering-** Pressing diffused powdered aggregate into shape and then firing it at an elevated temperature.



**metal sheet stamping-** cold working a metal sheet where a stamping press pushes a die into the metal creating a complex shape.



**calendar rolling-** molten plastic is fed through a set of rollers that flatten the plastic into sheets

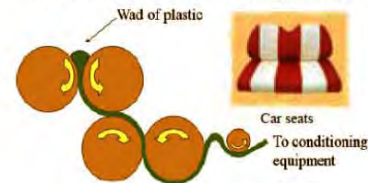


Figure 4. Activity Instruction and Processing Definition Learning Aid.

### Team Activity on Interpreting Meaning of Table of Structure-Processing-Properties Relationships of Material Families

In the second class on atomic bonding, the general trends of bond strength and type for the material families were related to property characteristics of material stiffness (elastic modulus), melting point ( $T_m$ ), and coefficient of thermal expansion. One of the trends for the families of materials is nicely shown in the Callister slide set for stiffness ranges for the different families as shown in Figure 5 below. It can be seen that the range of stiffnesses for polymers is roughly two

orders of magnitude less than for metals, ceramics, or composites. Students are queried about this using an approach of cognitive dissonance in that if a material has covalent bonding (albeit one-dimensional), why is stiffness so much less than for metal or ceramic materials? Students are encouraged to discuss this with team members with the hope that they resolve this issue by realizing the role that van der Waals bonding plays in stiffness. Another concept discussed is why polymers have melting points hundreds of degrees less than that for metals or polymers.

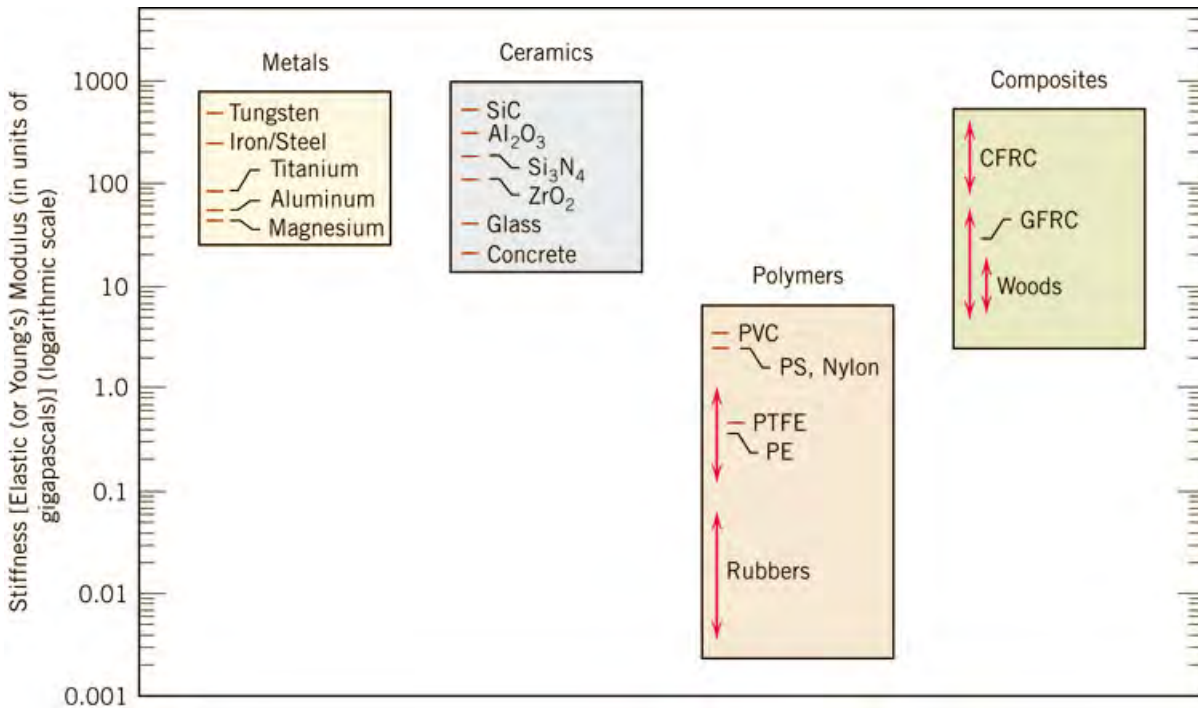


Figure 5. Stiffness (Elastic Modulus) Ranges for Metals, Ceramics, Polymers, and Composites

A Concept-Context Map Quiz, as shown below in Figure 6, was also created to show the big-picture conceptual framework of relationships between different families of materials, their types of atomic bonding, the Periodic Table, and the properties of material stiffness (elastic modulus), melting point  $T_m$ , and coefficient of thermal expansion. Students had to select the appropriate word from the Word Selection Bank to fill in empty bubbles in the CCmap quiz which promoted building of vocabulary and concepts. Supplementary team report-out sheets are being created so students can document discussions and reasoning for selections that they make. This approach seems to produce the most effective learning according to Chi's active-constructive-interactive model for effectiveness of different activities on student conceptual change and learning<sup>11</sup>.

In general, Concept-in-Context Maps (CCmaps) can be described as multimodal visual outlines, class topic guides, and hierarchical subject maps. The structure of Concept-in-Context maps places less emphasis on including linking words and the characteristic web structure of concept maps. Instead, it places more emphasis on establishing the hierarchy and interrelatedness of the information on any given concept, then connecting relevant supporting details and visual representations for topics and sub-topics. CCmaps show linkages between abstract concepts and concrete real world manifestations of those concepts. Any given concept on the map may be

connected to related macroscopic and microscopic images, equations, graphs, charts, and historical facts. This allows the student to see at a glance the important connections displayed in a visual manner that aims to encourage understanding and retention of information. The CCmap quiz shown in Figure 6 illustrates the potential for better engaging students in learning.

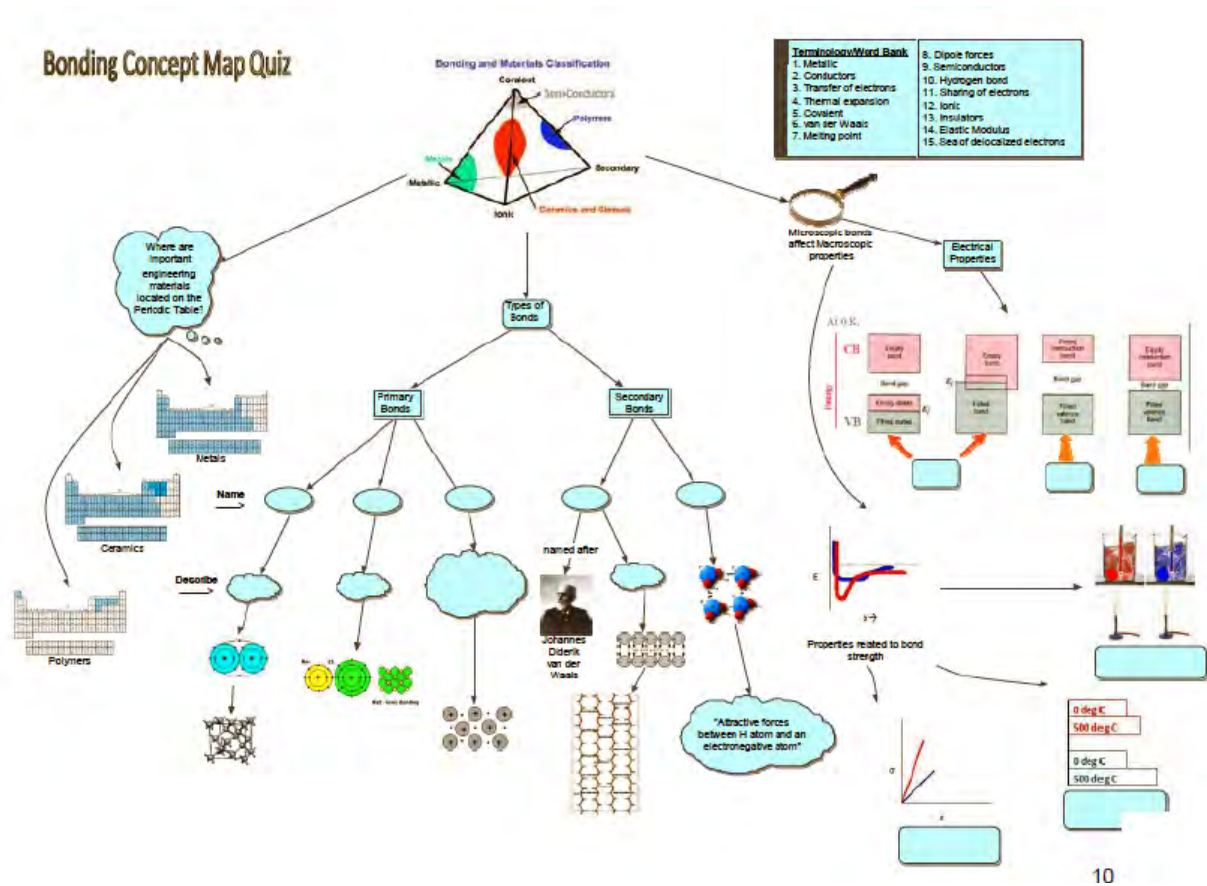


Figure 6. Concept-in-Context Quiz for Atomic Bonding

### Hands-on Kinesthetic Activities

In addition to the teaching and learning resources described above, hands-on activities were used throughout the bonding module to promote kinesthetic learning. Students were able to hold items made of materials with the representative bonding type(s). The item thus contextualized information about bonding. The activity was done in teams where students were encouraged to discuss observations and explain relevance to bonding. To further demonstrate and provide analogies for bonding in polymers, students were given polyethylene lunch bags to model van der Waals bonding and were able to see the difference in difficulty of pulling it apart under different orientations. To observe the anisotropic behavior of polymers as a result of their bonding, students applied tension to plastic bags along various axes by pulling them apart by hand and observing the differences. Each of these demonstrations was done in teams and students were asked to visually represent what was occurring at the molecular level. These activities elicited student written, verbal, and diagrammatic mental models.

## Concept-in-Context Contextualized Homework

Finally, contextualized homework, shown in Figure 7, required students to explain phenomena in multiple modes including written, visual, graphical, and mathematical representations. By requiring this, the instructor was able to elicit student mental models in each of these ways. Homework, once turned in and graded, was then reviewed in class. Student participation in this process gave the instructor an additional opportunity to observe students express their mental models in written and visual form.

3. A polyethylene container has the same composition as a candle long chain paraffins  $[n(\text{CH}_2) + 2\text{H}]$  where  $n$  equals the number of C atoms. Suggest a reason that describes why the melting point,  $T_m$ , increases as the number of C atoms increases as shown in the graph below.

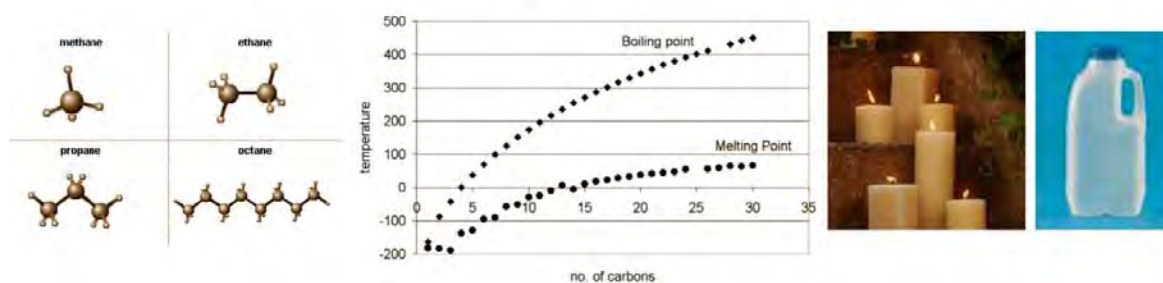


Figure 7. Concept-in-Context Homework Problem Using van der Waals Concept

### Assessment of Conceptual Change and Student Learning

The students experienced multiple methods of demonstrating the exact nature of van der Waals bonding and its significance with respect to properties of polymers including their stiffness and melting point compared to metals and ceramics. This occurred through classroom mini-lectures, hands-on demonstrations, concept-in-context sorting worksheets, concept-in-context maps, and homework problems. The effect of the changes to instructional materials and classroom practice is demonstrated both for the post-instruction concept quiz results as well as the MCI results.

The post-instruction data from Figure 1 shows all 5 students have described acceptable models for van der Waals bonding, although student B5151 has stated, "secondary bonds that are weak that usually involve dipoles." This not only describes the fact that van der Waals bonds are weaker than the primary bonds, but articulates the underlying reason. For this student instruction has proven quite effective. For the post-instruction sketch, 3 of the 5 students drew models which replicate the scientific consensus model for polymers as seen in Fig. 2. Another student, A1117, has shown two dipole molecules attracted to one another as the representation for van der Waals bonding. Although this is correct, it has not been applied to a polymer, which would have been a better interpretation of the model. One student did not draw any model at all, possibly indicating either disinterest or lack of conceptual change for repairing this knowledge gap. Overall, innovative instruction was moderately effective in achieving conceptual change as indicated by the Atomic Bonding Pre-Post Concept Quiz. There is still room for further improvement which

will be considered for future classes. The MCI results from the end-of-semester verify that learning is much more effective for the CLIC technique than for lecture. This is discussed below.

The MCI questions related to bonding and properties in polymers, as shown below in Figure 8, showed significantly higher Hake gain scores for CLIC instruction in Fall 2010 compared to lecture based instruction in 2002. In particular Hake gains for the two questions shown below were 45% gain for CLIC versus 5% gain for lecture and 49% gain for CLIC compared to 41% gain for lecture, respectively. Overall, the CLIC instruction is much more effective than the lecture-based learning mode, but improvements are needed to further enhance student learning. Student interviews and focus groups may be employed to better understand learning issues associated with van der Waals bonding and polymer property relationships.

Figure 8. Questions on the Materials Concept Inventory related to the relationship between bonding and properties in polymers.

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

A polymer rubber band can stretch more than a metal paper clip because: \_\_\_\_\_

- a) Covalent bonds along polymer chains can stretch and rotate
- b) Covalent bonds along polymer chains can rotate and the van der Waals bonds between chains allow chain slippage
- c) Covalent bonds along polymer chains can break and the van der Waals bonds between chains allow chain slippage
- d) Covalent bonds along polymer chains can stretch and the van der Waals bonds between chains allow chain slippage
- e) Covalent bonds along polymer chains can rotate and break

#### A Misconception About Metallic Bonding

Many engineering undergraduates complete their science prerequisites in courses structured for natural science students with limited treatment of metallic bonding. However, engineering faculty often assume that their students entering their courses are well prepared with respect to knowledge of all bonding types that might apply to materials for their design, selection, and fabrication. If we consider the types of atomic bonding addressed in materials science courses, it is quite possible that this may not be the case. Following a natural science course, it was found that metallic bonding was often not discussed. So when presented with concepts about the bonding behavior and properties of metals, many students had conceptual barriers to learning. An important challenge for introductory engineering science courses is to build on student understanding of scientific phenomena and help students shift their lens from one of natural science explanation to one of design in engineering with investigation, application, and innovation with materials as a key factor. Shown in Figure 8 below are the results for pre and post testing about metallic bonding and its presence in a metal item, a paper clip. Activities

similar to the ones described above for enhancing conceptual understanding of van der Waals bonding were also used for metallic bonding.





<p>Metallic</p> 	<p>Many atoms share and switch charges to have an overall neutral charge</p>	<p><math>Al^+</math> <math>Al^+</math> <math>Al^+</math></p>
<p>Metallic</p> 	<p>"sea" of electrons (metals) which share charges</p>	<p><math>+</math> <math>+</math> <math>Al</math> <math>+</math> <math>+</math></p>
<p>Metal Paper Clip</p> 	<p><del>malleable</del> <del>stiff enough to keep in place</del></p>	<p>Ionic</p>
<p>Metal Paper Clip</p> 	<p>- ductile - can hold shape</p>	<p>metallic</p>

Figure 9. Pre and Post Concept Quiz Results on Metallic Bonding Describe & Sketch Model and also Metal Paper Clip Property and Bonding Descriptions for a Single Student

The written description of the model of metallic bonding was quite colloquial in the pre-test, "many atoms share and switch charges to have an overall neutral charge." The description has the elements of a correct model for atomic bonding, but they are expressed in everyday language. In the post-test the description is representative of scientific consensus as "sea of electrons." The sketched models are flawed both before and after instruction. In the pre-test,  $Al^+$  ions are shown but the electrons are omitted. In the post-test a neutral aluminum is shown with pluses or positive charges floating around. Neither model is correct, and the written descriptions do not correlate with the sketched models. Clearly, future instruction will have to address these shortcomings for more effective learning.

The paper clip written descriptions of properties and bonding types have improved markedly from pre to post instruction concept quizzes. The pre-quiz terms were "malleable" and "stiff enough to keep in place" while the post-quiz terms were "ductile" and "can hold shape". The bonding type shifted from the incorrect "ionic" to the correct "metallic" going from the pre to the post instruction quizzes. The descriptions for properties and bonding have improved with some shift from colloquial to engineering speak, but instructional materials will need to focus more on language usage. The shift in bonding type from ionic to metallic was representative for many students having a similar issue in the class. It may be that more opportunities need to be given to

students to express the bonding-property relationships to promote more frequent use of macroscopic-property to microscopic-structure thinking. It may be possible to embed this concept in future classroom instructional materials as well as homework assignments.

## Summary and Conclusions

Since students prior knowledge affects their views about how the world works, such as knowledge gaps and misconceptions, instructional materials and activities for an introductory materials class were remodeled as informed by that prior knowledge and the principles of *How People Learn*. In particular, two examples were used in this paper, a knowledge gap and a misconception. One was for an atomic bonding knowledge gap about van der Waals bonding and associated misconceptions related to polymer properties. The other was about metallic bonding and students' representation of image and function of bonding in metals and associated metal properties. Instructional materials were modified in a variety of ways to address these issues in student prior knowledge. First a publisher's set of chapter slide sets were modified to address issues of student prior knowledge. Specifically, a single chapter slide set on atomic bonding was separated into two sets for two classes. The first set focused on Atomic Bonding and the Periodic Table. This was done to link students' prior knowledge on bonding and the periodic table to the use of bonding concepts for engineering materials. The second class set focused on Atomic Bonding and Properties for different families of materials. Thus, the focus was shifted from knowledge and understanding of scientific models, in this case atomic bonding, to using that knowledge of science to understand real-world engineering materials and their applications. The effects of bonding on materials properties and processing was emphasized, especially so for van der Waals intermolecular bonding in polymers.

Another change in the approach to instructional materials was to use familiar contexts, such as the families of materials associated with components of an engineering system, a motorcycle. Additionally, the importance and significance of the relationship of bonding to processing of the different materials families was introduced immediately with the topic of bonding. The linkage of bonding to both properties and processing was embedded in a team activity for materials selection with the motorcycle components as the contexts for metals, polymers, and ceramics. To illustrate differences in bonding types and the effects on properties a chart with trends of stiffnesses for the different families of materials was used as a catalyst to promote students to explain the differences based on differences in bonding. Additionally, a team activity with a concept context map quiz was used to provide a conceptual framework for relationships between the periodic table and bonding and properties utilizing multiple representations with models, words and labels. The difficult concept of van der Waals bonding in polymers was again addressed in a homework assignment with a data explanation activity. The multiple modes of presenting and representing concepts was intended to have students develop a multimodal understanding of atomic bonding concepts applied to engineering materials. Pre-post concept quiz results and MCI results showed moderate improvements in student understanding of atomic bonding concepts using the CLIC instructional approach compared to earlier lecture based results for the MCI. Overall, use of CLIC instructional strategies and materials has the potential for application in other engineering disciplines but would need application and testing with similar types of tools applied in different course contexts.

## Acknowledgements

The authors are grateful for support of this work by the National Science Foundation from NSF CCLI Grant #0737146 and NSF IEECI Grant #0836041.

## References

1. Von Glaserfeld, E. (1987). *The Construction of Knowledge: Contributions of Conceptual Semantics* (Seaside, CA: Intersystems Publications, Inc.).
2. Von Glaserfeld, E. (1995). *Radical Constructivism: A Way of Knowing and Learning* (Washington, DC: The Falmer Press).
3. Vygotsky, L. (1962) *Thought and Language*, T. E. Hanfmann & G. Vaka (Eds.), Cambridge, MA: MIT Press.
4. Donovan, M. S., Bransford, J. D. & Pellegrino, J. W. (Eds.) (1999). *How people learn: Bridging research and practice*. National Academy Press, Washington, DC.
5. Norman, D. (1983) Some observations on mental models. In *Mental Models*, D. Gentner and A. Stevens (Eds.), Hillsdale, NJ, Erlbaum.
6. Gilbert, J. (1995) The role of models and modeling in some narratives in science learning. *1995 Annual Meeting of the American Educational Research Association*, San Francisco, CA.
7. Boulter, C. J., & Buckley, B. C. (2000). Constructing a typology of models in science education, in Gilbert, J. K., & Boulter, C. J. (Eds.), *Developing models in science education*. Dordrecht, Netherlands, Kluwer Academic Publishers.
8. Kelly, J., Krause, S., and Baker, S. (2010). A Pre-Post Topic Assessment Tool for Uncovering Misconceptions and Assessing Their Repair and Conceptual Change. 2010 Frontiers in Education Annual Conference.
9. Krause, S., Kelly, J., Triplett, J., Eller, A., and Baker, D. (2010). Uncovering and Addressing Some Common Types of Misconceptions in Introductory Materials Science and Engineering Courses. *Journal of Materials Education*, 32(5- 6), 255-272.
10. Henderson, C. and Dancy, M. (2007) Barriers to the Use of Research-Based Instructional Strategies: The Influence of Both Individual and Situational Characteristics. *Physical Review Special Topics: Physics Education Research*, 3 (2), 020102-1 - 020102-14.
11. Chi, M. (2009). Active-constructive-interactive: A conceptual framework for differentiating learning activities. *Topics in Cognitive Science*, 1(1), 73-105.