

Interactive-Constructive-Active-Passive:  
The Relative Effectiveness of Differentiated Activities

on Students' Learning

by

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## ABSTRACT

From the instructional perspective, the scope of “active learning” in the literature is very broad and includes all sorts of classroom activities that engage students with the learning experience. However, classifying all classroom activities as a mode of “active learning” simply ignores the unique cognitive processes associated with the type of activity. The lack of an extensive framework and taxonomy regarding the relative effectiveness of these “active” activities makes it difficult to compare and contrast the value of conditions in different studies in terms of student learning. Recently, Chi (2009) proposed a framework of differentiated overt learning activities (DOLA) as *active*, *constructive*, and *interactive* based on their underlying cognitive principles and their effectiveness on students’ learning outcomes. The motivating question behind this framework is whether some types of engagement affect learning outcomes more than the others.

This work evaluated the effectiveness and applicability of the DOLA framework to learning activities for STEM classes. After classification of overt learning activities as being *active*, *constructive* or *interactive*, I then tested the ICAP hypothesis, which states that student learning is more effective in *interactive* activities than *constructive* activities, which are more effective than *active* activities, which are more effective than *passive* activities.

I conducted two studies (Study 1 and Study 2) to determine how and to what degree differentiated activities affected students’ learning outcomes. For both studies, I measured students’ knowledge of materials science and engineering concepts.

Results for Study 1 showed that students scored higher on all post-class quiz questions after participating in *interactive* and *constructive* activities than after the *active* activities. However, student scores on more difficult, inference questions suggested that *interactive* activities provided significantly deeper learning than either *constructive* or *active* activities. Results for Study 2 showed that students' learning, in terms of gain scores, increased systematically from *passive* to *active* to *constructive* to *interactive*, as predicted by ICAP. All the increases, from condition to condition, were significant.

Verbal analysis of the students' dialogue in *interactive* condition indicated a strong correlation between the co-construction of knowledge and learning gains. When the statements and responses of each student build upon those of the other, both students benefit from the collaboration. Also, the linear combination of discourse moves was significantly related to the adjusted gain scores with a very high correlation coefficient. Specifically, the *elaborate* type discourse moves were positively correlated with learning outcomes; whereas the *accept* type moves were negatively correlated with learning outcomes.

Analyses of authentic activities in a STEM classroom showed that they fit within the taxonomy of the DOLA framework. The results of the two studies provided evidence to support the predictions of the ICAP hypothesis.

This dissertation is dedicated to

My parents,

*Yaşare and Osman Menekşe*

And to my aunt,

*Neriman Köseoğlu Olus*

For their endless love and support

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## Chapter 1

### INTRODUCTION

#### Overview

Over the past decades considerable attention has been given to “active learning” methods in different domains including, including the learning sciences, educational psychology, science education, and recently, engineering education (e.g., Chen, Lattuca, & Hamilton, 2008; Heller, Beil, Dam, & Haerum, 2010; Lin & Tsai, 2009; Prince, 2004; Prince & Felder, 2006). “Active learning” has been implemented in the context of problem-based, inquiry-based, discovery, collaborative, cooperative, team-based and inductive learning methods in many studies (e.g., Johnson, Johnson & Smith, 1991; Prince, 2004; Schroeder, Scott, Tolson, Huang, & Lee, 2007). Examples of “active learning” from the Science, Technology, Engineering, and Mathematics (STEM) education literature include examination of student learning from inquiry-based real life problems (Higley & Marianno, 2001), use of multimedia to facilitate student interaction (Burleson, Ganz, & Harris, 2001), use of a teamwork-based approach to solve complex problems (Pendergrass, et al., 2002; Yasar, 2008), use of activity oriented instruction to increase active engagement (Shooter & McNeill, 2002; Starrett & Morcos, 2001), and comparing collaborative learning methods with traditional instruction (Terenzini, Cabrera, Colbeck, Parente, & Bjorklund, 2001). Taken as a whole, “active learning” methods in the current literature refer broadly to innovative *student-centered* instructional approaches that dynamically involve students in the learning process. The main constructs of “active learning” seem to

include the (a) participation and the engagement of students with concrete learning experiences, (b) with knowledge *construction* via meaningful learning activities, and (c) with some degree of student *interaction*.

In contrast to “active learning”, “passive learning” is usually defined as involving *teacher-centered* methods that favor direct instruction in which students often learn through listening to and observing lectures presented by an instructor. “Active learning” methods and activities have been contrasted with “passive learning” methods by using pair-wise designs in which students in one condition engage in some kind of an “active” intervention whereas students in another condition “passively” receive information from an instructor, expert or a computer system. These contrasts include studies comparing inductive versus deductive reasoning (Lott, 1983; Prince & Felder, 2006), inquiry-based instruction versus direct instruction (Minner, Levy, & Century, 2010), discovery learning versus traditional methods (Klahr & Nigam, 2004), and collaborative learning versus learning from lecture (Terenzini, et al., 2001).

Although the literature has often shown that “active learning” methods led to superior student learning outcomes as compared to passive methods (Lambert & McCombs, 1998; National Research Council, 1996; Prince, 2004; Schroeder et al., 2007; Smith, Sheppard, Johnson, & Johnson, 2005), other studies found either the opposite effect (e.g., Kirschner, Sweller, & Clark, 2006; Klahr & Nigam, 2004; Mayer, 2004; Montpas, 2004) or “active” is not always better than “passive” (e.g., Colliver, 2000; Hundley, 2007, Martin, 2009; Osman, 2008a; Osman2008b; Sadler, 2002; Stull & Mayer, 2007; Sendag & Odabasi, 2009;

Strobel & van Barneveld, 2009; Rittle-Johnson, 2006; Wilson, 1999). These discrepant results make it difficult to reach definitive conclusions about the relative effectiveness of these methods (Lederman, Lederman, & Wickman, 2008; Blanchard, Southerland, Osborne, Sampson, Annetta, & Granger, 2010).

### Problem Statement

There are three general problems with the notion of “active learning” that may shed light on why discrepant results have been obtained. The first problem may have to do with how the effectiveness of “active learning” methods is measured (Prince, 2004), since evidence for content validity and difficulty level of individual test items is typically not reported in the literature. Evidence for content validity supports the premise that test items are accurate and cover a representative sample of content from a given domain (Messick, 1995). Knowledge about item difficulty is necessary to understand the depth of student learning as evidenced by their test scores. If test items are easy and measure lower levels of cognitive processing (e.g. recall), test results may not easily favor “active” methods of learning and the results may not even differ significantly from more “passive” forms of learning (Chi, 2009). However, “active learning” methods may have more significant effects on learning in an engineering curriculum in which higher levels of cognitive processing are needed to succeed.

A second problem that may precipitate the discrepant results in the literature is the lack of shared terminology or definition for “active learning” methods across various disciplines. For example, some studies use “active

learning” synonymously with “inquiry” and classify any “hands-on” activity as an inquiry intervention without stating the important aspects of inquiry, such as to what degree students will be responsible to generate research questions, or who is in charge (i.e., teacher or students) of deciding data collection methods. Another example of the lack of shared terminology appears in team-based learning. Teams and team-based learning are very popular in engineering schools as a way to foster “active learning.” However, some studies classify any group of students working together for any length of time as a team even though having a group does not guarantee that the members will necessarily collaborate in a productive way.

A third problem is that “active learning” methods include all sorts of classroom activities that engage students with the learning experience in some manner, and this broad scope may also account for the inconsistent findings. However, treating all classroom activities as engaging students in the same way ignores the unique cognitive processes associated with each type of activity. The lack of a comprehensive framework and taxonomy regarding the components and characteristics of “active learning” methods make it difficult to compare and contrast the value of “active” methods in different studies in terms of student learning.

The fourth problem is related to factors that influence the effectiveness of collaborative and interactive learning methods. Collaborative learning methods have been extensively studied in many different domains with many different tasks and research studies showed the value of learning collaboratively in terms of



cognitive and social learning benefits (e.g., Fischer & Mandl, 2005; Hausmann, Chi & Roy, 2004; Kaartinen & Kumpulainen, 2002; Kapur, 2008; Richmond & Striley, 1996; Rochelle, 1992; Sampson & Clark, 2009; Slavin, 1996; Summers, Beretvas, Svinicki, & Gorin, 2005; Vygotsky, 1978; Webb, 1989; White & Pea, 2011). However, it is still an open question why collaboration supports learning? And what are the potential mechanisms that improve learning while collaborating with a peer?

To address some of these problems, Chi (2009; Chi & Wylie, in preparation) proposed the Differentiated Overt Learning Activities (DOLA) framework that separated “active learning” methods into three modes, as being *active*, *constructive*, or *interactive* depending on what activities students overtly display. The framework differentiates and makes a claim only about overt engagement activities as these are the only behaviors that we (and teachers in classrooms) can observe. Moreover, according to Chi (2009), each mode of activities corresponds to a distinct set of cognitive processes.

The motivating question behind development of this framework was whether some modes of overt engagement activities are more effective than others. Based on the cognitive processes corresponding to each mode of overt engagement activity, the framework can be used to predict differential effectiveness of these activities on students’ learning outcomes. After a review and reinterpretation of experimental studies in the learning sciences literature, Chi (2009) found that all three *active*, *constructive* and *interactive* modes are better than the *passive* mode, in terms of students’ learning. Furthermore, there were

differences in the learning effectiveness of the three non-*passive* modes, such that pair-wise comparisons of the three non-*passive* modes indicated that *interactive* activities were more likely to be better than *constructive* activities, which in turn were better than *active* activities, resulting in the *Interactive>Constructive>Active>Passive* (ICAP) hypothesis (Chi & Wylie, in preparation). Details of this framework will be presented in the literature review section.

Chi's (2009) study provided an excellent review of the existing learning studies in order to make comparisons across conditions. However, Chi's analysis consisted only of pairwise comparisons since the reviewed studies typically used two conditions. Also, the studies reviewed in Chi's (2009) article used different variables such as different populations, interventions, concepts, or sample sizes. In addition, none of the studies reported in the Chi's paper were in an engineering context. Thus, another intended contribution of my dissertation study was to enrich the engineering education literature by adding experimental learning studies in the engineering context. Since, similar to other STEM related domains, the engineering schools are investigating new approaches to curricula and rethinking and developing innovative ways to replace traditional teaching methods, I believe this work will provide a substantive contribution to this effort and discussion.

The current study evaluated the effectiveness and applicability of the differentiated overt learning activities (DOLA) framework and tested ICAP hypothesis in an engineering context. I conducted two studies (Study 1 and Study

2) to find out how and to what degree differentiated activities affect students' learning outcomes. Whereas study 1 was conducted in an engineering classroom during the actual class sessions, study 2 was conducted in a more controlled environment. However, participants in both studies were undergraduate engineering students. In both studies, I measured students' cognitive learning outcomes rather than affective and psychomotor aspects of their learning. I used introductory materials science and engineering concepts as content to be taught, since these concepts are rich and difficult, with a fundamental tenet of bridging nano-scale structural features (i.e., electronic structure, atomic bonding, lattice parameters, and grain size) to macro-scale properties (i.e., stiffness, strength, deformation, and functional properties).

In addition, this study examined the verbal analysis of the interactive processes between pairs in order to investigate the potential mechanisms that enhance the learning outcomes in collaborative/interactive learning settings. I investigated how students' co-construction of knowledge influences students' learning outcomes in interactive conditions. I also differentiated discourse moves that have significant effects on students' knowledge construction while working collaboratively.

Overall, the contribution to the literature is twofold: First, this is the first work in which the DOLA framework was evaluated using data from a controlled experiment. Second, this is the first work in which the value and utility of this framework were explored in an engineering context. Engineering educators are investigating new approaches to curricula and rethinking and developing

innovative ways to replace traditional teaching methods, and thus I believe this work will provide a substantive contribution to this effort and discussion. Since there are not many controlled studies investigating classroom activities in engineering context, this work provides support for engineering educator's use of the DOLA framework when developing classroom activities as a means to increase student learning. It also supports researchers' use of the framework when designing future studies to advance our understanding of the relative effectiveness of "active learning" methods.

### Research Questions

This work had two main purposes: 1) to investigate how and to what degree differentiated activities affect students' learning outcomes and 2) to investigate the potential mechanism that promotes collaborative learning in interactive settings. Five specific research questions were analyzed:

1. Do students participating *interactive* activities perform better on learning measures than the students participating *constructive* activities?
2. Do students participating *constructive* activities perform better on learning measures than the students participating *active* activities?
3. Do students participating *active* activities perform better on learning measures than the students participating *passive* activities?
4. How do students' co-construction of knowledge influence students' learning outcomes in *interactive* conditions?

5. What kinds of discourse moves have significant effects on students' knowledge construction while working collaboratively?

## Chapter 2

### LITERATURE REVIEW

#### Active Learning

Literature shows “active learning” methods have been frequently studied in many domains including the science and engineering education over the past decades (e.g., Chen, Lattuca, & Hamilton, 2008; Prince, 2004; Prince & Felder, 2006; Wise & Okey, 1983). “Active learning” refers to innovative *student-centered* instructional approaches that actively involve students in the learning process. The main constructs of active learning include the participation and the engagement of students with the concrete learning experience, knowledge construction of students via meaningful learning activities, and the degree of student interaction. A broad array of modes of active learning have been described, implemented and assessed in different domains. For example, problem-based, inquiry-based, case-based, project-based, discovery, collaborative, cooperative, team-based and inductive learning methods have been classified as the modes of “active learning” in many studies (e.g., Edelson, Gordin, & Pea, 1999; Hmelo-Silver, 2006; Johnson, Johnson & Smith, 1991; Prince, 2004; Schroeder, Scott, Tolson, Huang, & Lee, 2007; Shulman & Keisler, 1966).

Constructivism, as a learning theory, is the basis for the “active learning” methods. Constructivism simply depicts learning as constructing knowledge and meaning rather than receiving directly. The main implications of the constructivism suggest an active role for students in their own learning. The philosophical base of constructivism was rooted in the early 20<sup>th</sup> century based on

the work of John Dewey. Dewey argued and supported the notion of: (1) Students begin learning via experience and, therefore, they should have the opportunity to take part in their own learning, (2) learning primarily shaped by social and interactive processes, (3) students are part of a social group and these social relations influence their learning, and (4) students need to be challenged to use their creativity to arrive at individual solutions to problems (Dewey, 1933, 1938; Harms & DePencier, 1996). Consequently, Dewey's ideas provided a significant source for the fundamentals of design principles of "active learning" methods.

In addition to Dewey, Lev Semenovich Vygotsky contributed most to fundamentals of constructivism. Especially, social constructivist approaches which emphasize the importance of social context in the learning process have been mainly shaped by the Vygotsky's work of the Zone of Proximal Development (ZPD). The Zone of Proximal Development basically states the distance between what a learner can do without help and what she/he can accomplish with the guidance of an expert/teacher/tutor and/or collaboration of a peer (Vygotsky, 1978). This idea supports that social interaction plays a fundamental role in the process of cognitive development and learning. Overall, Vygotsky's thoughts set a conceptual foundation for collaborative learning as an instructional approach (Roschelle & Goldman, 1992).

The implications of constructivist view of learning shaped most of the "active learning" methods and applications that we use today. For example, cognitive apprenticeship in which a learner works with an expert or more advanced peer and acquire knowledge to accomplish complex tasks involves the

similar social proposes in knowledge construction as proposed by Vygotsky (Slavin, 2003). Likewise, the reciprocal teaching is a well-known strategy in educational sciences and its effectiveness to promote learning has been shown in many studies (e.g., King, 1990; Palinscar & Brown, 1984; Rosenshine & Meister, 1994). The reciprocal teaching is effective because it promotes powerful cognitive strategies such as summarizing, feedback from expert and/or peers, questioning, clarifying and predicting. Similarly, teaching/learning models like scaffolding, collaborative learning, cooperative learning, peer tutoring, argumentation, self-regulated learning, problem-based learning, case-based learning, and inquiry-based learning share the common fundamental principles of constructivism and they all promote meaningful learning to a certain degree.

#### Effectiveness of “Active Learning” Activities

The literature shows that people learn significantly when they construct knowledge and “active learning” activities support learners to generate new knowledge and/or integrate new information with existing knowledge (e.g., Chi, 2009; Chi et al., 1994; Palinscar & Brown, 1984). Some exemplary activities such as comparing and contrasting (Schwartz & Bransford, 1998), note taking (Klein, 1999), summarizing (King, 1992), matching (Menekse et al., 2011), self-explanation (Chi et al, 1994), concept-mapping (Novak, 1990), making graphs (Friel, Curcio, & Bright) , generating predictions (Klahr, & Nigam, 2004), underlining, highlighting (Igo, Bruning, & McCrudden, 2005), constructing analogies (Chinn & Malhorta, 2002), copying (VanLehn et al.,2007), reflecting



(Katz, O'Donnell, & Kay, 2000) and monitoring (Schwartz, et al., 2009) have been classified as the effective methods to promote meaningful learning.

Active learning methods are usually contrasted with the traditional passive methods, in which learners receive information passively to build more complex skills. Although, there are studies showing active is not always better than the passive methods (e.g., (e.g., Kirschner, Sweller, & Clark, 2006; Klahr & Nigam, 2004; Mayer, 2004; Montpas, 2004) or “active” is not always better than “passive” (e.g., Colliver, 2000; Hundley, 2007, Martin, 2009; Osman, 2008a; Osman2008b; Sadler, 2002; Stull & Mayer, 2007; Sendag & Odabasi, 2009), research comparing active and passive approaches is often favoring the former one in terms of students' learning outcomes (e.g., Chi, 2009; Minner, Levy, & Century, 2010; Prince & Felder, 2006; Schroeder, Scott, Tolson, Huang, & Lee, 2007; Springer, Donovan, & Stanne, 1999; Terenzini, et al., 2001).

However, since the “active learning” methods are very diverse, we know very little about the relative effectiveness of the “active learning” methods in terms of students' cognitive learning outcomes. From the instructional perspective, the scope of active learning in the literature is very broad and includes all sorts of classroom activities that engage students with the learning experience. However, classifying all classroom activities as a mode of active learning simply ignores the unique cognitive processes associated with the type of activity. The lack of an extensive framework and taxonomy regarding the relative effectiveness of these “active” activities makes it difficult to compare and contrast the value of conditions in different studies in terms of student learning. Recently,

Chi (2009) proposed a framework of differentiated overt learning activities (DOLA) as *active*, *constructive*, and *interactive* based on their underlying cognitive principles and their effectiveness on students' learning outcomes. The motivating question behind this framework is whether some types of engagement are better than others. The literature review by Chi (2009) based on the experimental studies in the learning sciences literature revealed that while all three modes are better than *passive* learning in terms of students' learning, a comparison of the literature on the three modes indicates the following: interactive activities are more likely to be better than constructive activities, which in turn are better than active activities.

#### DOLA Framework

Chi's (2009) DOLA framework differentiates a variety of overt engagement activities that have all been considered "active learning" methods in previous studies. More specifically, this DOLA framework asserts that different modes of overt engagement activities have differential learning effectiveness because they have different attributes and involve different cognitive processes. Many types of activities fit into each mode. The assumption is that the activities designed as *active* are expected to involve learners in doing some manipulation with the learning materials; the activities designed as *constructive* are expected to facilitate the generation of new ideas, beyond those directly presented; and the activities designed as *interactive* are often expected to generate ideas that build on each other, but only when both students are contributing substantial joint

intellectual effort. These overt engagement activities, as defined, predict learning effectiveness such that *interactive* activities are more likely to be superior to *constructive* activities, which in turn are almost always better than *active* activities, and all three “active” modes are better than a “passive” mode such as receiving instruction only (referred to as the ICAP hypothesis). In essence, the framework differentiates “active learning methods” into three modes: *active*, *constructive*, and *interactive*.

Chi (2009) discusses three main advantages of this framework: 1) the classification of overt activities helps researchers, instructors, and instructional designers decide what type of activity or intervention would be appropriate for the intended research or instruction; 2) the hypothesized underlying cognitive processes of each mode of activity predicts the relative effectiveness of the activities in terms of learning; and 3) the differentiation of activities or interventions based on the underlying cognitive processes allow us to re-analyze and/or re-interpret the studies in the literature and to clarify the inconsistent findings.

Note that this framework differentiates and makes a claim only about overt or observable engagement activities. Clearly, students may also covertly interact cognitively with information, (e.g. construct knowledge while self-explaining silently), but this behavior is difficult to assess reliably in a classroom and may only occur with a small portion of students in any given classroom. Similarly, it is possible that overt activities may be provided to students and yet they still do not cognitively interact with the information; their attention may be

focused elsewhere at that moment. Despite these caveats, the framework suggests that overall, different modes of engagement activities differentially affect the amount of learning.

A possible barrier to results as predicted by Chi's hypothesis is proper implementation of activities. In other words, even if researchers properly design and classify activities as *active*, *constructive* or *interactive*, there still may be obstacles to successful implementation of those activities in the classroom, and students' learning outcomes may not match with the expectations. For example, in an *interactive* activity such as argumentation, if students are not actively challenging each other's claims (Hausmann, 2006), or if only a few of the students participate in the discussion, the activity may not provide the anticipated benefits for those who do not contribute.

### *Being Active*

The active mode refers to students undertaking overt activities that activate their own knowledge within the boundaries of the desired content. Chi (2009) defined being active as doing something or manipulating the instructional information overtly, rather than passively receiving information or instruction while learning or studying. *Active* activities essentially emphasize the selected passages or manipulated components of a task, thus allowing students to pay more attention to them. The cognitive processes hypothesized by Chi (2009) that correspond with *active* activities are activating and searching for related knowledge, and encoding, storing, or assimilating new information with activated

knowledge. This results in strengthening of existing knowledge and filling a gap in knowledge, making it more retrievable and more complete. Based on these cognitive processes, Chi (2009) predicted that students who engage in *active* learning activities will learn better than students who are more *passive*, and therefore not engaging in any observable learning activities, even though these *passive* students are oriented toward instruction and are receiving the learning materials.

Examples of the *active* mode include: following the procedure of a highly structured experiment, repeating sentences out loud after hearing them, underlining or highlighting some sentences while reading, copying the solution of a problem from the board while the teacher is solving it, selecting from a list of choices as in matching tasks, looking and searching for specific information in a text or problem, or playing a video game without making strategic decisions. For example, an in-class activity demonstrating the relationship of macroscopic properties to the strength of atomic bonding of pure metals could be implemented in an *active* mode if students underline the text sentences explaining this topic in their class notes, or if students flex 3 rods of 3 different metals to feel the stiffness of each rod at its respective melting points. Students may be able to link this experience to their prior hands-on "everyday experience" or knowledge of materials when they see and feel the flexing of the rods. Table 1 shows the four modes (*passive*, *active*, *constructive*, *interactive*) of activities in the context of illustrating the relationship of the stiffness and melting points of rods with the

atomic bonding strength of pure metals. This table also shows the associated underlying cognitive processes with each type of activity.

### *Being Constructive*

The *constructive* mode subsumes the *active* mode and refers to learners undertaking activities in which they produce knowledge that extends beyond the presented materials. The main difference between a *constructive* and an *active* mode is that in the latter case, learners do not produce outputs that go beyond the given information. For example, simply repeating a paragraph or underlining text would be classified as *active*, because these activities do not extend beyond what was presented. But self-explaining, or explaining aloud to oneself a concept presented in a text, is constructive because it constructs meaning beyond the given content (Chi, Bassok, Lewis, Reimann & Glaser, 1989; Chi, de Leeuw, Chiu, & Lavancher, 1994). The following types of activities can all be considered to be *constructive*: drawing a concept map, constructing notes from a lecture, generating self-explanations, comparing and contrasting different situations, asking comprehension questions, solving a problem that requires constructing knowledge, justifying claims with evidence, designing a study, posing a research question, generating examples from daily lives, using analogy to describe certain cases, monitoring one's comprehension, making strategic decisions in a video game, converting text-based information into symbolic notation, drawing and interpreting graphs, or hypothesizing and testing an idea.

Table 1

*Example of Four Modes of Presenting an In-class Student Activity with the Associated Cognitive Processes*

	Passive	Active	Constructive	Interactive
Exemplary In-class Activity	Each student reads a text or watches a video explaining that the higher melting point of pure metals gives them greater bond strength and higher elastic modulus than the metals with lower melting point temperatures.	Each student <i>underlines</i> the text sentences explaining that the higher melting point of pure metals gives them greater bond strength and higher elastic modulus; or each student <i>flexes</i> 3 rods of 3 different metals to feel the stiffness of each rod with the associated melting points.	Each student <i>flexes</i> 3 rods and after finding that the stiffest rod has the highest melting point, the student is then asked to <i>draw</i> a microscopic model of the stiffer metal, showing a matrix array of small spheres (atoms) connected to each other by thick, strong, stiff springs.	Pairs of students can flex rods and discuss to agree on selecting the stiffest rod with the highest melting point, then the two or more students collaboratively construct the microscopic representation of the stiffer metal by building on, or challenging each other's contributions.
Cognitive Processes	Storing new information directly, without assimilating it with relevant knowledge	Activate/retrieve search existing knowledge; Strengthen knowledge; Encode/assimilate new information	Create & infer new knowledge; Integrate newly created knowledge with old knowledge; Re-Organize knowledge; Repair/Accommodate old knowledge	Co-construct new knowledge that is novel to both partners; Build on each other's knowledge; Resolve own conflicts based on partner's comment

A *constructive* version of the metal rod activity described earlier could be offered if after flexing the rods of 3 different metals and finding the stiffest rod with the highest melting point, students then represented that macroscopic property by drawing a microscopic model of the stiffer metal, showing a small matrix array of small spheres (atoms) connected to each other by thick, strong, stiff springs. Thus, from bending the metal rods, students will have recognized the stiffest rod and related that to the normative bonding structure. From that, they can then construct a microscopic representation of the metal. Students will have provided information beyond what was observed; they will have created an explanatory model that is *constructive* because they produced additional outputs containing new content-relevant ideas that go beyond the information given.

The cognitive processes hypothesized to underlie being *constructive* are those that can generate new ideas, insights, and conclusions in a way that allows learners not only to infer new knowledge, but also to repair or improve their existing knowledge. Repairing one's existing knowledge makes it more coherent, more accurate, and better-structured, which serves to deepen one's understanding of new information. Research has shown that a variety of *constructive* activities, such as self-explaining (Chi, 2000) and explaining-to-others (Roscoe & Chi, 2007) can improve learning (Chi, 2009).

### *Being Interactive*

The *interactive* mode subsumes both the *active* and *constructive* modes. It refers to two or more learners undertaking activities that develop knowledge and



understanding extending beyond the materials being studied (similar to *constructive*), but the interaction of the learners further enables them to build upon one another's understanding. The main (but surface level) difference between the *interactive* and *constructive* mode is that learners in the *constructive* condition engage in activities alone. However, interaction between learners affords the benefit of receiving feedback or prompting from each other, with each partner having some complementary knowledge or perspectives. The different knowledge and perspectives further provide the opportunity for co-creation or joint-construction, which is not possible in solo activities.

Examples of *interactive* activities are studying/working in dyads or groups; reciprocal teaching; interacting with feedback from a teacher, an expert or a computer agent; arguing or defending one's position with evidence. Overall, *interactive* conditions essentially bring about co-construction of knowledge between pairs or group members. Chi (2009) cautions that it is not appropriate to classify any group work as an *interactive* activity however. For example, if one group member dominates the discussion or if one group member does not contribute to the discussion or product, then the group is not fully interacting. Therefore, the quality of discourse among group members is critical for determining the degree of interactivity in *interactive* activities. For instance, research shows that challenging each other by using normative scientific evidence provides high quality interaction, thus, leading to enhanced learning for all group members (e.g., Clark, D'Angelo, & Menekse, 2009; Sampson & Clark, 2009). Thus, the effectiveness of *interactive* activities may depend on numerous factors,

such as the degree of interactivity, the degree of student knowledge construction, and also student characteristics such as their willingness to challenge or criticize each other (Hausmann, 2006).

An *interactive* version of the metal rod activity could be two students working together on the activity of flexing rods, questioning each other about the rationale for selecting the stiffest rod with the highest melting point, and discussing how they should draw the microscopic representation of the stiffer metal. Through this give-and-take discussion, students would be building knowledge in a way that would not have occurred if they had been working alone, since they can build on each other's contributions, or refine and modify an original idea in ways that can produce novel ideas. Thus, *interactive learning* has the potential to be more beneficial than *constructive learning*, in which a single individual can only extend beyond the given information with their own ideas; in *interactive learning*, two individuals can further enrich the topic of discussion through jointly extending on a given content topic from two different perspectives and sets of ideas.

### An Application of DOLA Framework

This section includes the classification of inquiry studies in science education literature according to Chi's DOLA framework. First, I provided a review for inquiry literature in science education, and then I presented the classification of inquiry studies based on DOLA framework. Because there are

hundreds of inquiry studies in science education literature, I limited the classification for a sample of recent studies that have experimental design.

### *Inquiry Based Instruction in Science Classrooms*

Inquiry based instruction has been a common method and prominent theme of the science education literature since early 1960s (e.g., Anderson, 1983; Schroeder, Scott, Tolson, Huang, & Lee, 2007; Shymansky, Kyle Jr, & Alport, 1983). Especially in the past two decades, organizations such as the National Research Council (NRC), the National Science Foundation (NSF), the American Association for the Advancement of Science (AAAS), and the National Science Teachers Association (NSTA) supported inquiry as a standard method of teaching in science classes and funded hundreds of proposals regarding inquiry. The reform documents such as *Benchmarks for Scientific Literacy* (AAAS, 1993), the *National Science Education Standards* (NRC, 1996), *Inquiry and the National Science Education Standards* (NRC, 2000), and the *Standards for Science Teacher Preparation* (NSTA, 2003) describe scientific inquiry as the “heart” of the science education.

The *National Science Education Standards* heavily emphasize inquiry in science teaching, professional development, and science content standards. For example, the first teaching standard states “teachers of science plan an inquiry based science program for their students” (p. 30). As a content standard for students in grade 9-12, all students are expected to develop “abilities necessary to do scientific inquiry” and “understandings about scientific inquiry” (p. 173). Also,

the *Standards for Science Teacher Preparation* state that science teachers must “engage students successfully in developmentally appropriate inquiries that require them to develop concepts and relationships from their observations, data, and inferences in a scientific manner” (p. 18). Taken as a whole, these documents describe and recommend inquiry oriented standards to educate all students; so students will be able to understand and apply the processes, principles and methods of inquiry leading to scientific knowledge, and “experience the richness and excitement of knowing about and understanding the natural world” (NRC, 1996, p. 13).

An enormous number of studies have been published on inquiry during past 50 years. A significant amount of these studies investigated the effectiveness of inquiry based science instruction on student learning and/or achievement. In general, research show inquiry based science education significantly improves students’ learning outcomes (e.g., Anderson, 2007; Sadeh & Zion, 2009), and conceptual understanding (e.g., Frailich, Kesner, & Hofstein, 2009; Minner, Levy, & Century, 2010), students in inquiry settings generate more and better questions (e.g., Hofstein, Navon, Kipnis, & Mamlok Naaman, 2005), students from less privileged demographic groups gain more in inquiry based science than their more privileged counterparts (e.g., Lee, Buxton, Lewis, & LeRoy, 2006), and students in inquiry settings understand the Nature of Science better than students in traditional settings (e.g., Flick & Lederman, 2004).

Because there is a rich body of literature on inquiry, meta-analysis studies provide valuable information in order to get a broader perspective for the findings

of single studies. A special issue of the *Journal of Research in Science Teaching (JRST)* in 1983 reported meta-analyses of science education research for the studies published between 1950 and 1982. Also, Schroeder and colleagues (2007) synthesized the studies regarding the effects of different teaching strategies on science learning published between 1980 and 2004 in their meta-analysis. Finally, Minner and colleagues (2010) synthesized the findings of research published between 1984 and 2002 to address the effect of inquiry based science instruction on students' outcomes.

The first meta-analysis in the special issue of JRST synthesized the results of 105 experimental studies in order to explore the effects of different curricula on students' performance (Shymansky, et al., 1983). They differentiated the conditions in studies as either "new" or "traditional" curricular projects. The new curricula includes the ones developed after 1955; emphasize the nature, structure, and processes of science; integrate lab activities as a fundamental component of science classes; and put emphasis on higher cognitive skills of science. Their analyses of effects sizes across studies show that students in "new" science curricula achieved 0.43 standard deviations above than students in "traditional" science curricula exposed to. This effect size indicates a remarkable deviation for the effectiveness of "new" curricula over "traditional" ones. However, the "new" curricula do not completely represent the "inquiry" and, therefore, the inferences based on this meta-analysis may lack of internal validity to reach robust conclusions.

Another meta-analysis in this special issue addressed the effects of various science teaching strategies, including inquiry, on students' achievement (Wise & Okey, 1983). They synthesized 160 studies and produced 400 effect sizes for various science teaching strategies such as questioning and using manipulative. Thirty-eight of these effect sizes obtained to explore whether inquiry is effective on students' achievement. They found inquiry strategies resulted 0.41 standard deviations above than the strategies used in control conditions. Here, inquiry strategies were defined as the teaching techniques that involved more student-centered approach. Also, inquiry category included the studies with guided discoveries and inductive laboratories in this meta-analysis.

A third meta-analysis from the same special issue of JRST investigated the effect of inquiry teaching by comparing inductive versus deductive approaches (Lott, 1983). Lott defined inductive approaches as the "experiences in which examples or observations were provided to students prior to formalizing generalizations" (p. 440). A composite effect size from 38 studies published between 1955 and 1980 revealed an effect size of 0.06 in favor of inductive approaches over deductive approaches. While this result barely supports the superiority notion of inductive approaches over deductive approaches in science teaching, the further analysis showed that the studies with less structured guidance have a greater effect size, 0.43. In other words, when Lott (1983) classified these 38 studies according to amount of guidance given for the exploration, those labeled "guided exploration" had an effect size of 0.43 ( $n = 15$ ).

A final meta-analysis from this special issue of JRST synthesized the studies focusing on science teacher education practices associated with inquiry strategies (Sweitzer & Anderson, 1983). One category in this meta-analysis classified teacher education practices as traditional versus inquiry. While the traditional practices generated the effect size of 0.30 ( $n = 5$ ), the inquiry oriented practices generated an effect size of 0.63 ( $n = 9$ ).

Almost 25 years later than the JRST meta-analysis special issue, Schroeder and colleagues (2007) synthesized the studies published between 1980 and 2004 in order to investigate the effects of various science teaching strategies on achievement, and Minner and colleagues (2010) addressed what is the impact of inquiry based science instruction on K-12 student outcomes. Schroeder et al. (2007) defined inquiry strategies as “the student-centered approaches in which students answer research questions by analyzing data” (p.1446). They found an effect size of 0.63 for the effectiveness inquiry strategies based on 12 quasi-experimental studies.

On the other hand, Minner et al. (2010) did not find a statistically positive relation between amount of inquiry and increased student science conceptual learning based on their review of 138 studies published between 1984 and 2002. They used the descriptions, categories and definition of National Science Education Standards (1996) in order to classify studies to use in their meta-analysis. They coded studies based on students’ involvement/responsibility on investigation and motivation, and generated a continuous scale called “inquiry saturation”. Seventy-one inquiry based science instruction studies among 138

reported some level of positive impacts on students learning and retention. However, overall, no statistically significant relation observed between the inquiry saturation level and the students learning of science concepts.

In sum, all of these meta-analyses provide some level of positive trend favoring inquiry based science instruction over traditional methods or control conditions. Even though some of the meta analyses found modest gains in support of inquiry (e.g., Lott, 1983; Minner, et al., 2010), the detailed analysis in each meta-analysis showed the teaching strategies that promote active engagement of students and make students to take responsibility for knowledge construction in the learning process through scientific investigations increased students' conceptual understanding more than the strategies that make students passive recipients of the fact based knowledge.

#### *Classification of Inquiry Studies based on the DOLA Framework*

I first reviewed Klahr and Nigam's (2004) study based on the DOLA framework. The importance of this study is that too many studies have cited it as a seminal work to argue the "ineffectiveness" of inquiry. However, this study has two major flaws; first, the "direct instruction" method is not really lecture based direct instruction; and second, the role of teacher, especially feedback and scaffolding from teacher in "direct instruction" group but not in "discovery learning" condition make it complicated to evaluate their findings through the lens of "direct" versus "discovery". However, DOLA framework may provide a better explanation for their findings.



Based on Chi's framework, "direct instruction" condition might be classified as *interactive* because first, there is a continuous interaction at the exploration phase between teacher and students. For example, after each experiment designed by teacher, students were asked to determine whether a variable had an effect on the outcome. Also, after students' responses, teacher explained (i.e., feedback) the effects of variables on outcome for each experiment. Second, all students either in "discovery learning" or "direct instruction" condition were working individually except the fact that students in "direct instruction" group were interacting with teacher at the exploration phase. Therefore, based on Chi's (2009) framework, the "discovery learning" condition in that study can be classified as *constructive* mode at most. So, Klahr and Nigam's (2004) findings that the students in "direct instruction" condition are performing better than the students "discovery learning" condition is consistent with the proposed framework which hypothesizes *interactive* activities and/or interventions are most likely better than the *constructive* ones in terms of students' learning.

Another inquiry study with experimental design was conducted by Toth, Suthers and Lesgold (2002). They contrasted the learners (i.e., seventy-three 9<sup>th</sup> grade students) with the type of external representation (evidence mapping versus prose writing) and being the presence of reflective assessment rubrics during the use of these representations or not (p. 7). Overall, they had four conditions as follows: map and reflect, map but no reflect, prose and reflect, prose but no reflect. All conditions worked in small groups. So, a shallow categorization may

result in calling all conditions as *interactive*. However, a finer grain size is required in order to understand the possible differences among these four conditions. First of all, the main difference between “mapping” and “prose writing” conditions is that the students in mapping condition used BELVEDERE software to share a digital workspace for constructing evidence maps in order to examine the relations between data and hypotheses. Also, BELVEDERE software provided scaffolding in which students were prompted to find data and generate hypothesis, and develop relationships between data and the hypothesis. Thus, basically, students in mapping condition created concept maps in small groups with software scaffolding whereas students in prose writing condition wrote paragraphs in small groups without scaffolding. Obviously, students creating map and receiving scaffolding are more *constructive* than only writing paragraphs without scaffolding. Therefore, according to DOLA framework, I expect students in mapping condition would learn more than the students in writing condition. Second, reflective assessment rubrics function as a tool to help student monitor their comprehension. Consequently, I expect students in “map and reflect” condition would outperform the students in other conditions according to DOLA framework. The results fit with my expectations; the students in “mapping” conditions recorded significantly more inferences than the students in “prose writing” conditions. Also, groups with reflective assessment rubrics did better than the groups with no rubrics. Moreover, a post hoc comparison revealed that “map and reflect” condition outperformed other conditions for the number of inferences

generated and the number of information units labeled but not for the final reasoning scores.

A recent study by Chang and colleagues (Chang, Quintana, & Krajcik, 2010) examined the impact of designing and evaluating molecular animations on students' understanding of nature of matter in inquiry based interventions. They assigned middle grade students (N = 271) into three treatments: (1) design, interpret and evaluate animations (T1); (2) design and interpret animations (T2); and (3) view and interpret teacher-made animations (T3). Students work in small groups for interpret and evaluate phases, but work individually in design phase. So, again, a shallow categorization implies all three treatment conditions are closer to *interactive* modes. However, there are important differences among conditions. First, students in T1 condition might be more *interactive* due to evaluation phase in which students in small groups determine the adequacy of models in group members' animation, compare the trajectory in each other's animation, make suggestion to improve the quality of animations and revise their own animation. Thus, T1 condition is clearly more *interactive* than T2 and T3 conditions. Second, while students in T3 condition work on and explain the correct models (i.e., teacher-made animations) in interpret phase, students in T2 and T1 condition explain their own models which might have incorrect aspects as well. The possibility not to see and/or interpret an correct model/animation might have significant effects especially for T2 condition because they do not have the opportunity to determine the adequacy of the models as students in T1 condition have in the evaluation phase. Third, because students in T3 condition interpret

teacher-made models/animations, the lack of evaluation phase for this condition might not have significant negative impact on students understanding the nature of matter. Overall, according to underlying principles of DOLA framework, both T1 and T3 conditions might outperform T2 condition but it is not easy to make any comparison between T1 and T2 because while T1 condition seems have more *interactive* aspects, T2 condition has other advantages like generating meanings and explaining reasons for perfectly correct models. The results confirmed my reasoning; both T1 and T3 students outperformed T2 students in total test scores, content knowledge, constructing, interpreting and evaluating. Also, T1 students outperformed T3 students in constructing related test items but no other significant differences were observed between these two conditions. Overall, these findings provide a model fit with Chi's (2009) framework.

Similarly, the findings from the inquiry studies of Blanchard et al., (2010), Jaakkola et al., (2010), Hoffman et al., (2003), Frailich et al., (2009) and Sadeh & Zion (2009) provide supporting results for the active-constructive-interactive framework (Blanchard, et al., 2010; Frailich, et al., 2009; Hoffman, Wu, Krajcik, & Soloway, 2003; Jaakkola, Nurmi, & Veermans, 2011; Sadeh & Zion, 2009). Table 2 provides a classification for the comparison of inquiry studies with control conditions based on DOLA framework.

Table 2

*Classification of Inquiry Studies based on DOLA Framework*

Comparison	Study	Context	Grade Level	Experimental Condition	Control Condition	Results
Inquiry vs. Passive	Wong & Day (2009)	Human reproduction and density	12 and 13 years old students	Inquiry oriented problem based learning	Teacher centered lectures	Inquiry > lecture
	Lewis & Lewis (2008)	General chemistry	College students	Peer led guided inquiry	Teacher centered lectures	Inquiry > lecture
	Chang & Mao (2001)	Earth science: Earth-Sun system, rotation, seasons	9 <sup>th</sup> grade students	Hands-on inquiry activities	Teacher centered lectures	Inquiry > lecture
Inquiry vs. Active	Sesen & Tarhan (2011)	Electrochemistry (e.g. redox reactions.)	10 <sup>th</sup> grade students	Inquiry based laboratory	Traditional laboratory (e.g. explicit procedure for students to follow)	Inquiry lab > cook-book lab

Wilson et al. (2010)	BSCS Curriculum (e.g. biological rhythms, sleep disorders)	14-16 years old students	Inquiry based group work	Note taking and working on worksheets	Inquiry > routine learning strategies
Hofstein et al. (2005)	High School Chemistry (e.g. bonding, energy, chemical equilibrium)	12 <sup>th</sup> grade students	Inquiry based laboratory	Traditional laboratory (e.g. explicit procedure for students to follow)	Inquiry lab > cook-book lab
Manlove et al. (2009)	Physics (e.g. Fluid Dynamics)	High school students	Collaborative learning in inquiry based learning environment	Individual learning in inquiry based learning environment	Pairs > Individuals
Sampson & Clark (2009)	Chemistry : Thermal energy, conductivity	10 <sup>th</sup> , 11 <sup>th</sup> and 12 <sup>th</sup> grade students	Inquiry oriented group argumentation	Inquiry oriented individual argumentation	Group > Individual
Toth et al. (2002)	Fundamental reasoning skills (e.g. evaluation, reasoning)	9 <sup>th</sup> grade students	Evidence mapping and reflecting (plus scaffolding)	Prose writing (no reflection, no scaffolding)	Mapping + reflecting > Prose writing

Inquiry vs. Constructive

Inquiry vs.  
Interactive

Chang et al. (2010)	Chemistry: Nature of matter	7 <sup>th</sup> grade	T1: Design, interpret and evaluate animations in small groups	T3: View, compare and contrast teacher made animations in small groups	T1 = T3 based on chemistry achievement
Klahr & Nigam (2004)	General science: Control of variables strategy	3 <sup>rd</sup> and 4 <sup>th</sup> grade students	“Discovery learning” (individual students, no interaction, no feedback, no scaffolding)	“Direct-instruction” (continuous feedback and scaffolding from teacher)	“Discovery learning” < “Direct instruction”
Leonard (1989)	General Biology	College students	Extended discretion (more independence in decision making)	Guided inquiry	Extended discretion = guided inquiry

Overall, Chi's (2009) framework provided a good model to interpret the results in inquiry based science education literature. The classification of overt activities and /or interventions based on underlying cognitive principles offers a finer grain size to analyze and understand the discrepant findings in different studies as well.

### Summary

In this chapter, I reviewed the research and theoretical foundations regarding the “active learning” and its effectiveness on student learning. Active learning methods and activities have long been used in classrooms; however the relative effectiveness of these “active learning” methods on learning outcomes are not very clear. Chi's (2009) provided the DOLA framework differentiating *active*, *constructive*, and *interactive* in terms of their overt activities and their potential corresponding cognitive processes. Chi also proposed the ICAP hypothesis which states that student learning is more effective in *interactive* activities than *constructive* activities, which are more effective than *active* activities, which are more effective than *passive* activities. In my review, I first defined the learning activities for being *active*, *constructive* and *interactive*. I then revised its underlying processes to explain why one type of learning activity set might be better than the other type.



## Chapter 3

### STUDY 1

In first study, I investigated the DOLA framework in a real classroom setting. In particular, this study tested the ICAP hypothesis, which predicts that *interactive* activities should result in better learning than *constructive* activities, which in turn should result in better learning than *active* activities in introductory materials science and engineering context. The *passive* condition was not included in this study. Therefore, the Study 1 only focused on my first two research questions: (1) Do students participating *interactive* activities perform better on learning measures than the students participating *constructive* activities? (2) Do students participating *constructive* activities perform better on learning measures than the students participating *active* activities?

#### Participants

The sample for Study 1 consisted of 42 undergraduate engineering students enrolled in an introductory materials science and engineering class at ASU. Thirty-five of the students were male and seven of the students were female. The mean age of the participants was 19 with a range from 18 to 21 years old. Each student enrolled in the class had already completed a college level general chemistry class as a prerequisite. Participation in the project was voluntary and students were assured that their participation would have no effect on their grades (see Appendix A for the IRB approved consent form for Study 1). Data collection was completed on five different days during the first three weeks

of the semester. Participants were asked to stay for 15 to 20 minutes after the regular class hours during these five days. Student received \$5 per day for their participation.

### Development of the Activities

I attended the introductory materials science and engineering class at ASU for a semester prior to the study to document all learning activities already used in class. I gathered instructional materials used for each class (i.e. slides and handouts) as well as assessment measures that were used, (i.e. concept tests, unit tests, and homework assignments). In preparation for the study, I classified the 19 overt activities that were used as being *active*, *constructive* or *interactive*, based on Chi's (2009) framework.

I selected two units, atomic bonding and crystal structures, and eight activities to be used for this study. After negotiating with the faculty, we agreed on the mode of activities (*active*, *constructive*, or *interactive*) that would be offered within each of these two units. I used only one type of activity per class period, regardless of how many activities were offered, so that I could test for learning that could be attributed to that one particular type of activity. For example, if a *constructive* activity was implemented on a specific day, no *active* or *interactive* modes of activities were used on that day.

Modifications were made to some of the existing class activities to allow testing of the ICAP hypothesis. For example, in previous semesters, students learned about features of a face centered cubic (FCC) structure via a *constructive*

activity in which they used given indices to draw unit cell directions on a worksheet. They also used a given set of directions to determine the indices of unit cells. I modified this activity to be *active* by having the instructor demonstrate both processes and instructing students to simply copy the instructor's work. This activity then met the *active* mode criteria of having students manipulate the information in some way, without generating new information from it.

I planned the modes of activities so that a contrast could be made between *active* and *interactive* activities in the atomic bonding unit, and between *active*, *constructive*, and *interactive* activities in the crystal structures unit. For example, on day 1 for the atomic bonding unit, students participated in an *active* activity, consisting of *selecting* the most likely material, property of that material, type of bonding, and processing method from a given list of motorcycle parts such as motorcycle fender or seat. On day 2, they participated in an *interactive* activity, consisting of *drawing* and *completing* a partially constructed concept map for bonding, and *explaining* their reasoning for every single decision they made to complete the concept map. The final study design included three *active*, two *constructive* and three *interactive* activities for the two units. There was one activity per day for the atomic bonding unit and two activities per day for crystal structures unit. Table 3 presents the mode (e.g., *active*, *constructive*), task names (e.g., Materials selection, Unit cell directions), and order of activities used for both atomic bonding and crystal structures units (see Appendix B for a detailed description of each activity).

In an effort to promote high quality productive interaction between students during the *interactive* activities, written guidelines was also developed to help group leaders facilitate discussion. The guidelines included detailed directions for the task, timelines for completion of the activity, and ideas for probing questions that could stimulate knowledge construction by group members.

Table 3

*Names, Type and Order of Activities Used (See Appendix A for the detailed descriptions of each activity)*

	Atomic Bonding		Crystal Structures		
	Day 1	Day 2	Day 3	Day 4	Day 5
Active	Materials selection		Unit cell directions		
			Unit cell families of directions		
Constructive			Unit cell planes		
			Unit cell worksheet		
Interactive	Bonding concept map		Concepts in context		
			Hidden treasurers		

## Measures

Student learning from in-class activities was measured immediately after each class period in which the two topics were studied. I chose to measure student learning at this time in an attempt to differentiate between learning that may have resulted from the in-class activities and learning that may have resulted from homework or alternate learning strategies that students employed outside of class. Daily quiz questions for each activity were generated in order to measure students' learning and comprehension of the content covered in the activities. Because the content and activities were different each day, I measured knowledge gained from them on a common metric in order for the ANOVA significance tests to be meaningful. Due to my interest in examining the depth of processing and resultant knowledge associated with each activity, "cognitive level of quiz questions" was chosen as the common metric. The "cognitive level of quiz questions" will be defined below.

There were a total of 16 two-tiered quiz questions; two for each activity. The first tier questions were in a multiple-choice format, consisting of one *verbatim* type question, and one *integration* type question for each activity. The second tiers of each of the 16 questions were in an open-ended format, consisting of two *inference* questions for each activity. Thus, counting each part as a question, there were in total 32 questions.

The three categories of questions represent different levels of cognitive activity required to respond to the question, which was also considered to be indicative of question difficulty (Chi et al., 1994). Here I will present examples to

illustrate each type of question. *Verbatim* type questions were generated from ideas and information explicitly stated in the activity. They required students to merely recall the correct responses and thus required the shallowest understanding in order to answer them correctly. For example, to correctly answer the *verbatim* question in the *concepts in context* activity, students needed to select a disaster/failure that occurred as a result of an incomplete phase transformation; this information was explicitly stated in the activity. The *integration* type questions were also generated from the ideas and information explicitly stated in the activity but they required students to integrate two or more different ideas from the activity, thus they required a slightly deeper level of understanding. For instance, to correctly answer the *integration* question from the activity mentioned above, students needed to integrate the ideas of the most likely condition for phase change, properties of materials, and unit cell transformation. These three ideas are explicitly covered in the activity, but they need to be integrated in order to answer the question. Finally, the *inference* type questions required students to generate ideas beyond the information presented in the activity, thus they required the deepest understanding. For example, one of the *inference* questions for the *concepts in context* activity asked students to specify recommendations to prevent disaster/failure based on the relationship between a component material's macroscopic properties and its atomic level structure. The activity itself did not include any discussion about recommendations to prevent disasters/ failures, so this question required students to think about these recommendations like a consulting engineer giving advice about failure prevention to a company.

Accordingly, our question categories had an ordinal relationship in which *inference* questions were considered to be more difficult than the *integration* questions, which in turn, were considered to be more difficult than the *verbatim* questions. Table 4 summarizes the characteristics and associated cognitive processes for the question categories used in daily quizzes.

Table 4

*Characteristics and Associated Cognitive Processes for the Question Categories Used in Daily Quizzes*

	Verbatim	Integration	Inference
Characteristics	<ul style="list-style-type: none"> <li>• Single idea/concept</li> <li>• Explicit information</li> </ul>	<ul style="list-style-type: none"> <li>• Multiple ideas/concepts</li> <li>• Explicit information</li> </ul>	<ul style="list-style-type: none"> <li>• Multiple ideas/concepts</li> <li>• Implicit information</li> </ul>
Cognitive Processes	Recall	Integrate	Construct

Evidence for content validity was obtained by having an expert from the materials science and engineering department as well as an expert in measurement and test development provided continuous feedback and suggestions for improvement during question development. They approved the final version of each question. The quiz questions were closely aligned with the content covered in each activity, thus ensuring representative sampling of content in the assessment of student learning (See Appendix C & D for activity samples and Appendix E & F for quiz samples).

## Procedure

The data was collected over five days in an introductory materials science and engineering class. The class topic was atomic bonding during the first two days and crystal structures during the last three days. Students completed one activity per day during the atomic bonding units and two activities per day during the crystal structures unit. The activities each took approximately 15 minutes of class time. On the first day, each student was given an activity worksheet and completed the *active* version of the *materials selection* individually. The instructor told students to work alone and not to interact with peers during this activity. After the regular class hour, participating students stayed in the classroom and completed the daily quiz questions individually, which took 10 minutes. The students were not allowed to use any instructional materials to answer the quiz questions.

On the second day, students completed the *interactive* version of the *bonding concept map* activity in small groups (approximately five students in each group). One activity worksheet was provided for each of the nine groups in the class. The students were encouraged to question each other's reasoning and reach a group consensus for their final answers before recording their responses on their group worksheet. Similar to the first day, participating students stayed after class and took the daily quiz questions individually.

On the third day, students completed the *interactive* versions of the *concepts in context* and *hidden treasures* activities in small groups. Similar to the *bonding concept map* activity, they were encouraged to question each other and



reach a consensus as a group before recording their responses on their group worksheets. After the regular class hour, participating students stayed in the classroom and took two daily quizzes (one for each activity) individually, which took a total of 20 minutes.

On the fourth day, students completed the *active* versions of the *unit cell directions* and the *unit cell families of directions* activities. Each student copied the activity answers given by the faculty onto their worksheet for each activity and selected the Miller indices of unit cells from a given set of unit cell directions. After the regular class hour, the participants again took two daily quizzes individually, which took a total of 20 minutes.

On the last day, students completed the *constructive* version of the *unit cell planes* activity and the *unit cell worksheet* activity individually during the regular class hour. Again, an activity worksheet was provided for each student for each activity. Each student was asked to draw unit cell planes by using given the Miller indices and determine the Miller indices of unit cells for various unit cell planes. After class, the participants stayed and took two daily quizzes individually, which took a total of 20 minutes. During the activities on these five days, the instructor did not provide any feedback or instructional support to students about the subject matter regarding activities.

### Scoring the Quizzes

The multiple choice questions were dichotomously scored based on whether student responses were correct or incorrect. The correct responses

received three points and incorrect responses received no points. Unanswered questions were scored as incorrect. I developed a rubric to score students' responses to open-ended questions (See Appendix G for a rubric sample). The open-ended responses were scored as being fully correct, partially correct or incorrect. Fully correct responses referred to those that were complete and contained no inaccurate explanations, ideas or solutions. Partially correct responses referred to those that contained some correct explanations, ideas or solutions, but were not complete. Fully correct responses received four points; partially correct responses received one, two or three points based on the rubric criteria; and incorrect responses received no points. Incorrect responses referred to those containing erroneous and/or inconsistent explanations. Student's open-ended responses were not penalized for spelling or grammar errors. Overall, the maximum score was 14 for each daily quiz of two questions.

Twenty-five percent of the daily quizzes were scored individually by two raters to calculate inter-rater reliability. The percent agreement between the two raters was 94 percent for the open-ended questions. The rest of the quizzes were scored by one of the raters.

### Results for Study 1

To evaluate the effectiveness of differentiated overt learning activities on students' learning, I conducted a one way repeated-measure analysis of variance (ANOVA). The within-subject factor was type of activity, and the dependent

variable was students' total scores on daily quiz questions. The means and standard deviations for students' scores are presented in Table 5.

Table 5

*Means and Standard Deviations for Students' Scores for each Type of Activity by Topic*

Type of Activity	Atomic Bonding		Crystal Structures	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Active	6.69	3.19	7.74	2.76
Constructive	NA	NA	9.14	1.52
Interactive	9.67	2.49	9.03	2.67

Because the topics, atomic bonding, and crystal structures, have different characteristics and difficulty levels, it is not meaningful to directly compare the effectiveness of activities across topics. Therefore, I compared the students' achievement scores within each topic across different activities. Accordingly, the analysis involved the comparison of *active* and *interactive* activities for the atomic bonding unit, and the comparison of *active*, *constructive* and *interactive* activities for the crystal structures unit.

#### *Results for Atomic Bonding*

A one way repeated-measures ANOVA was conducted with the factor being type of activity (*active*, *interactive*), and the dependent variable being the

students' achievement scores on the daily quiz questions corresponding to each atomic bonding activity. The ANOVA results indicated a significant effect of activity type, Wilks'  $\Lambda = .57$ ,  $F(1, 38) = 28.69$ ,  $p < .01$ , multivariate  $\eta^2 = .43$ . These results suggested that students learned significantly more from *interactive* activities than they learned from *active* ones. See Table 5 for the means and standard deviations across type of activities for the atomic bonding unit.

I was also interested in determining how students performed based on the type of questions (i.e., *verbatim*, *integration*, *inference*). Figure 1 shows students' total mean scores for each activity and the mean scores for *verbatim*, *integration* and *inference* questions within each activity. Three separate one way repeated measures ANOVAs comparing each question type across two atomic bonding activities showed significant effects of activity mode for all questions types (for *verbatim* questions, Wilks'  $\Lambda = .77$ ,  $F(1, 38) = 11.40$ ,  $p < .01$ , multivariate  $\eta^2 = .23$ ; for *integration* questions, Wilks'  $\Lambda = .86$ ,  $F(1, 38) = 6.02$ ,  $p < .05$ , multivariate  $\eta^2 = .14$ ; and for *inference* questions, Wilks'  $\Lambda = .62$ ,  $F(1, 38) = 23.57$ ,  $p < .01$ , multivariate  $\eta^2 = .38$ ). Overall, students performed significantly better on all types of question when undertaking the *interactive* activity than when undertaking the *active* activity.

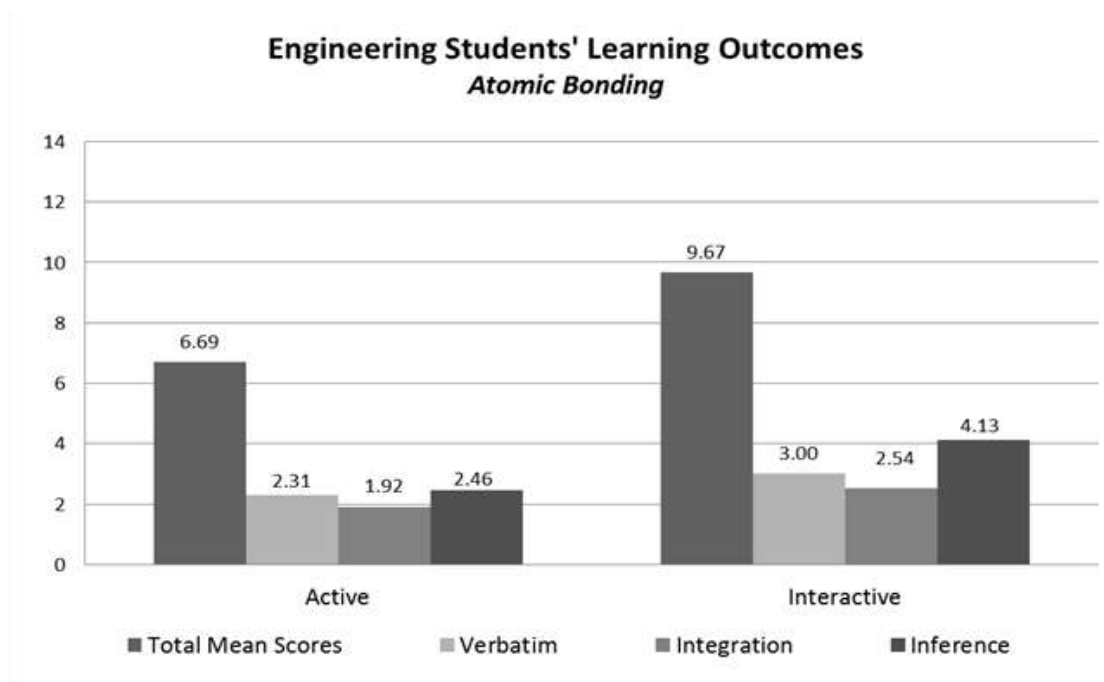


Figure 1. The mean scores for *verbatim*, *integration* and *inference* questions by type of activity for atomic bonding.

### Results for Crystal Structures

To evaluate the overall effect of the different types of activities on the students' daily quiz question scores for the crystal structures unit, I initially conducted a one-way repeated measures ANOVA with the activity type as a factorial variable, and students' total scores as dependent variables. The results showed a significant main effect for the type of activity on learning, Wilks'  $\Lambda = .76$ ,  $F(2, 34) = 5.40$ ,  $p < .01$ , multivariate  $\eta^2 = .24$ . See Table 5 for the means and standard deviations across type of activities for crystal structures unit.

Next, three unique pairwise comparisons were conducted among the means of students' scores for *active*, *constructive* and *interactive* activities. Two of the three pairwise comparisons were significant, controlling for familywise error rate across the three tests at the .05 level using the Holm's sequential Bonferroni procedure. *Active* versus *constructive*, with means of 7.74 (for *active*) and 9.14 (for *constructive*), were significantly different, with a  $p$  value of .004 that was less than  $\alpha = .05/3 = .017$ . *Active* versus *interactive*, with means of 7.74 (for *active*) and 9.03 (for *interactive*), were also significant, with a  $p$  value of .006 that was less than  $\alpha = .05/2 = .025$ . Lastly, the comparison of *constructive* and *interactive* was not significant. Taken as a whole, there were significant differences between the total scores resulting from *interactive* and *active* activities, as well as *constructive* and *active* activities, but not between *interactive* and *constructive* activities.

As I did for the atomic bonding activities, three separate one-way repeated measures ANOVAs were conducted to compare each question type across three crystal structures activities. The results were significant for all three one-way repeated measures ANOVAs: Wilks'  $\Lambda = .66$ ,  $F(2, 34) = 8.65$ ,  $p < .01$ , multivariate  $\eta^2 = .34$  for *verbatim* questions; Wilks'  $\Lambda = .67$ ,  $F(2, 34) = 8.55$ ,  $p < .01$ , multivariate  $\eta^2 = .34$  for *integration* questions; Wilks'  $\Lambda = .76$ ,  $F(2, 34) = 5.28$ ,  $p < .01$ , multivariate  $\eta^2 = .24$  for *inference* questions. Figure 2 shows students' mean scores for *verbatim*, *integration* and *inference* questions, and total mean scores for *active*, *constructive* and *interactive* activities.

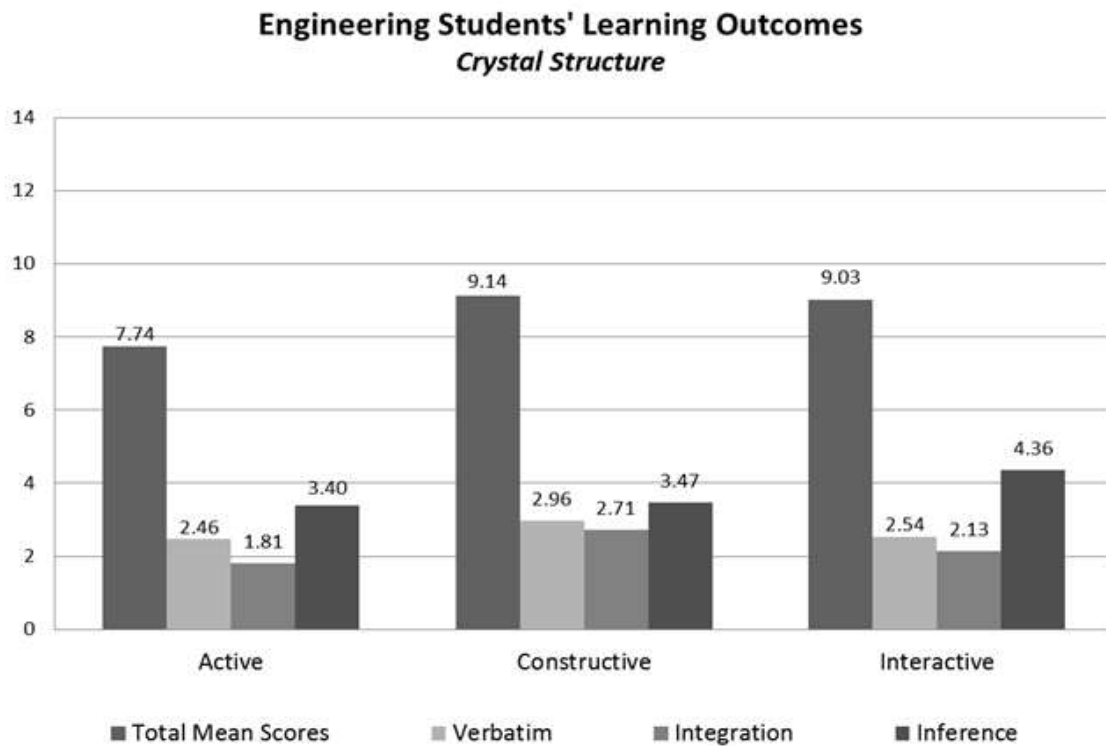


Figure 2. The mean scores for *verbatim*, *integration* and *inference* questions by type of activity for crystal structures.

In addition, pair-wise comparisons were also conducted to determine how type of activity affected students' scores on the different question types. I conducted three unique pairwise comparisons for each question type by controlling for familywise error across the three tests at the .05 level using Holm's sequential Bonferroni procedure. For the *verbatim* questions, two of the three pairwise comparisons were significant: *constructive* was significantly better than *active*, with means of 2.96 and 2.46; *constructive* was significantly better than *interactive*, with means of 2.96 and 2.54. For the *integration* questions, two of the three pairwise comparisons were significant: *constructive* was significantly better

than *active*, with means of 2.71 and 1.81; *constructive* was significantly better than *interactive*, with means of 2.71 and 2.13. Finally, for the *inference* questions, two of the three pairwise comparisons were significant: *interactive* was significantly better than *active*, with means of 4.36 and 3.40; *interactive* was significantly better than *constructive*, with means of 4.36 and 3.47.

### Summary of Study 1

In study 1, I compared the effects of three types of activities for two topic areas in an introductory materials science engineering class. For the atomic bonding unit, the results showed that students' scores on post class quizzes were significantly better after engaging in *interactive* activities compared to *active* activities. For the crystal structures unit, students did significantly better after both the *interactive* and *constructive* activities when compared to *active* activities.

Although there were no significant differences between *constructive* and *interactive* activities in terms of total scores, when I analyzed students' performance by the type of question, students' *inference* scores (indicative of the deepest learning and understanding) for the *interactive* activities was significantly higher than their *inference* scores in both *constructive* and *active* activities for both units. Thus, the comparison of scores from *inference* questions revealed that after engaging in *interactive* activities, students were better able to respond to more difficult, challenging questions about their engineering course material.

When I examined overall scores, the results for the study 1 provided preliminary evidence to support Chi's (2009) hypothesis that *constructive*



activities provide greater returns in terms of student learning than *active* activities, and that *interactive* activities provide greater returns than either *constructive* or *active* activities. However, this classroom study had several limitations, as well as a counter-intuitive result.

When I analyzed performance per question type, students performed better on *verbatim* and *integration* questions after engaging in *constructive* activities than after engaging in *interactive* activities. This should not be the case, as *interactive* activities should involve construction of new knowledge with the added enhancement of contributions from one's peers. However, this finding could be influenced by the nature of the *verbatim* and *integration* questions because they ask for information that is explicitly presented in the instructional materials. Thus, additional benefits may not be derived from having complementary knowledge or an alternative perspective from a partner, in order to answer these questions. However, additional perspectives, feedback and elaborations from a partner may be particularly useful for answering the more challenging and deeper *inference* questions, as our results show. Also, there is a possibility of order effects from the activities which may have influenced the students' learning. Students may acquire more knowledge from the later activities due to the cumulative effect of several days of class activities. For instance, in the crystal structures unit, students participated in the *interactive* activities on day 3, the *active* activities on day 4, and the *constructive* activities on day 5, so if students benefited from the cumulative effect of several days of class activities,

they might have more prior knowledge for the *constructive* activities compared to the *interactive* and *active* activities.

### Limitations of Study 1

The study 1 also had several other limitations. It was difficult to control for confounding factors like the level of students interaction and time spent to complete tests and activities. Moreover, there were no pretests to measure students' prior knowledge. There was also no *passive* condition, which can be thought of as a control condition that often reflects standard instruction in college classrooms. In addition, I used a within-subject design in which the same group of students were engaged in different activities on different days and completed tests with different questions. This introduced a possibility of order effects from the activities which may have influenced the degree of learning students experienced. Finally, the different activities may have inherently different requirements, some requiring conceptual understanding and others requiring procedural understanding.

## Chapter 4

### STUDY 2

Based on the limitations cited in Study 1, I designed Study 2 with a more controlled between-subjects design in which the participants were randomly assigned into one of four experimental conditions - *passive*, *active*, *constructive*, or *interactive*. All students took pre and posttests in this study. Similar to Study 1, introductory materials science and engineering concepts were used to create the activities for the four conditions in Study 2. I constructed the ‘*connecting atomic bonding and physical properties*’ activity which required students to understand the relations between bonding energy, elastic modulus, melting points, and coefficient of thermal expansion concepts.

Study 2 allowed me to investigate all of my five research questions. In this chapter, I described the findings related to first three questions:

1. Do students participating *interactive* activities perform better on learning measures than the students participating *constructive* activities?
2. Do students participating *constructive* activities perform better on learning measures than the students participating *active* activities?
3. Do students participating *active* activities perform better on learning measures than the students participating *passive* activities?

And in the following chapter (chapter 5), I described the findings regarding my last two research questions:

4. How do students' co-construction of knowledge influence students' learning outcomes in *interactive* conditions?
5. What kinds of discourse moves have significant effects on students' knowledge construction while working collaboratively?

### Participants

The sample for Study 2 included 120 undergraduate engineering students at ASU. Seventy-two of the participants were male and 48 of them were female. The mean age of the participants was 20 with a range from 18 to 23 years old. The study participants were recruited through announcements via posters and flyers across campus, and emails sent to engineering instructors and department secretaries. A prerequisite to study participation was that participants had completed a college level general chemistry class with a grade of 'B' or better, so that they were familiar with terminology used in the activities (Please see Appendix H for IRB approved consent form for Study 2)

### Materials

#### *Introductory Short Text*

A two-page long introductory text was created, consisting of definitions and short descriptions for concepts used in this study, such as chemical bonding, bond energy and tensile properties. The materials used in this two-page

introductory text were based on materials science and engineering textbooks that are used in universities and colleges across US, written by William D. Callister's (2006) and James Newell's (2009). We used definitions of terms such as bond strength and tensile properties directly from relevant chapters of these texts. All participants read the introductory text to get familiar (or as a reminder) with the terminology used before taking the pretest (see Appendix I for the introductory short text).

### *Long Text*

The same materials science and engineering textbooks cited above were used to create a longer text for delivery of content. This text described bonding energy, elastic modulus, melting points, and coefficient of thermal expansion concepts and included examples related to each concept. We selected the relevant sections/paragraphs that provided fundamental definitions and descriptions for each concept, and I created related examples for each concept. The long text content was conceptual; I avoided using complex mathematical representations or statements, and there were no questions embedded in the reading. The long text was eight pages in 12 point font, double-spaced, and formatted in one column (see Appendix J for the long text).

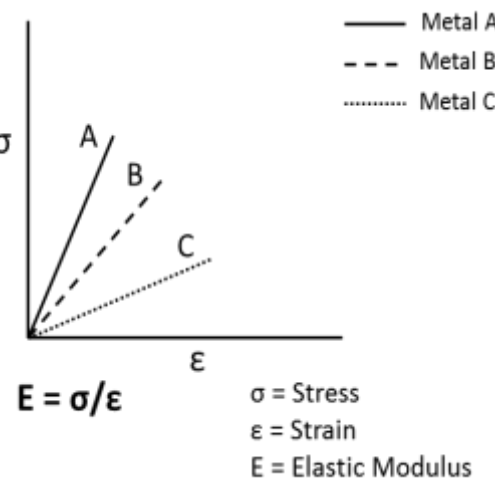
### *Graphs, Figures, and Activity Sheet*

I created two graphs, two figures and an activity sheet based on the information and examples given in the long text. The graphs and figures

illustrated the properties of three metals in terms of elastic modulus, bond energy, thermal expansion and melting points. For example, the long text provided the definition of the elastic modulus of an object as the slope of its stress-strain graph and included an example of three metals with different slopes. So, I created the stress-strain graph of the same example by using the three metals that were described in the long text. Table 6 shows the constructed graph of three metals and the corresponding text paragraph that described the elastic modulus concept.

Table 6

*Exemplary Text Scrap and Graph for the Elastic Modulus Concept*

Text scrap for the elastic modulus concept	Graph for the elastic modulus concept
<p>The degree to which a structure deforms or strains depends on the magnitude of an imposed stress. For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each other through the relationship <math>E = \sigma/\epsilon</math> where <math>E</math> is the elastic modulus, <math>\sigma</math> (sigma) represents stress, and <math>\epsilon</math> (epsilon) represents strain. For example, assume we have three metals: metal A, metal B and metal C. The metal A has the greatest elastic modulus among all three and the metal B has greater elastic modulus than metal C. This relationship also implies that the metal A has the greatest slope in a stress-strain curve and the metal C has the smallest slope in the same curve.</p>	

An activity sheet with five short answer questions was constructed to scaffold and guide students to interpret specific aspects of the information provided in the graphs and figures. For example, one of the questions asked

students to compare values for the three metals in each graph and figure, and explain their findings for each comparison. Students were asked to write their responses on the worksheets. Taken together, the graphs/figures accompanied by the activity sheet provided a guided inquiry-oriented activity in which the data and/or information embedded within graphs/figures followed by question prompts supported students toward construction of their own reasoning and conclusions (see Appendix K graphs, figures, and activity sheet).

### Measures

I used a pretest-posttest design to measure students' prior knowledge and learning from the activities intervention. The pretest consisted of 15 true and false, seven multiple-choice and two open-ended questions which totaled to 24 questions. The true and false questions were two-tiered in that the first part required students to determine the correctness of a given statement, and the second part required students to explain their selection. The multiple choice questions had five response options that included one correct answer and four distractors. The open ended questions required short answers. The posttest consisted of the same 24 questions along with six additional questions. Overall, the posttest consisted of 16 true and false, 11 multiple choice and three short answer open-ended question.

The questions were closely aligned with the content covered in the learning materials, thus ensuring representative sampling of content in the

assessment of student learning (see appendix L and M for pretest and posttest, respectively).

### Design and Procedure

The study consisted of four intervention conditions, *passive*, *active*, *constructive* and *interactive*, corresponding to the DOLA framework. Content about the materials science concepts was presented in a different manner in each of the conditions. In the *passive* condition, students read the long text passage out loud. Students were not allowed to use highlighters or pens while reading the text. In the *active* condition, students read the same long text as described above. Students were given highlighters and instructed to highlight the most important and/or critical sentences in the text. In the *constructive* condition, students completed the graphs/figures interpretation activity. Students in this condition did not read the long text that was used in the *passive* and *active* conditions. Instead, they were instructed to study the graphs and figures and provide written responses to the questions on the activity sheet. In the *interactive* condition, pairs of students completed the same graphs/figures interpretation activity (as in the *constructive* condition), also without reading the long text. Student pairs in the *interactive* condition shared one activity sheet and completed it collaboratively. At the beginning of the activity, pairs were told to reach consensus for each question before writing their answers on the activity sheet. Pairs in the *interactive* condition were videotaped to record their dialogues. For all the conditions, no



feedback in terms of content-related help was provided during any of the sessions across any condition.

The recruited participants were randomly assigned to one of the four conditions. Each participant was scheduled to a particular session based on her/his availability. We scheduled pairs in the *interactive* condition whenever two students were available at the same time. All participants started by reading the 2-page introductory text for ten minutes. Then, participants were given 25 minutes to complete the pretest. There were 24 students in each of the three conditions-- *passive*, *active* and *constructive*; and 48 students (24 pairs) in the *interactive* condition. All students were given 25-30 minutes to complete their learning activity. Finally, all participants took the posttest individually. Figure 2 shows the basic research design in this study. Each session took approximately 90 minutes to complete. Data collection was completed in one session. Participants received \$15 after they completed the study.

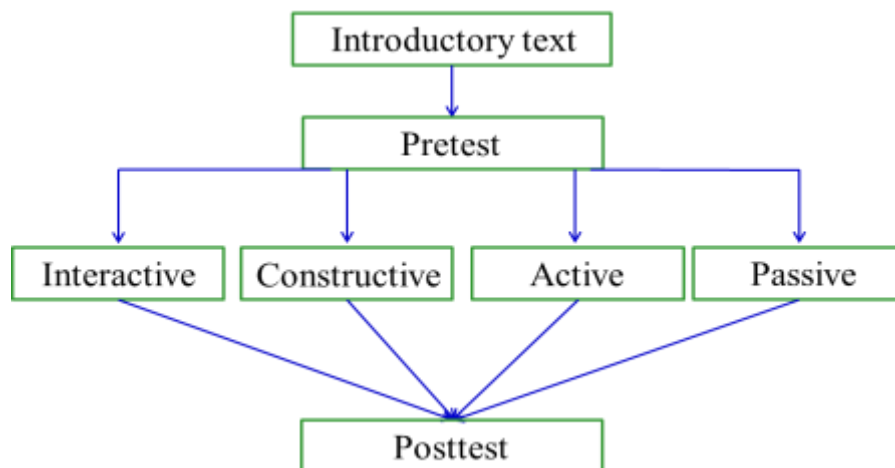


Figure 3. The research design of the Study 2. Please note that the participants were randomly assigned to one of the four conditions.

## Scoring the Tests

The multiple choice questions were dichotomously scored as being correct or incorrect. The correct responses received two points and incorrect responses or blank answers received no points. The first tier true-false questions were scored dichotomously as correct or incorrect, and the second tier open-ended questions were scored as being fully correct, partially correct or incorrect. A rubric was developed for scoring these open-ended questions. Fully correct responses referred to those that were complete and contained no inaccurate explanations, ideas or solutions; partially correct responses referred to those that contained some correct explanations, ideas or solutions, but were not complete; and incorrect responses referred to those containing erroneous and/or inconsistent explanations. Student received three points for a correct true/false response and a fully correct explanation; two points for a correct true/false response and a partially correct explanation; one point for a correct true/false response and an incorrect explanation; and no points for an incorrect true/false response.

The same rubric was used to score the additional open-ended questions as fully correct (3 points), partially correct (1 or 2 points) or incorrect (0 points). The maximum scores were 65 for the pretest and 79 for the posttest.

Thirty percent of the pre- and post-tests were scored individually by two raters to calculate inter-rater reliability. The percent agreement between the two raters was 96 percent for the second tier of the true-false questions, and 93 percent for the open-ended questions. The rest of the pre- and posttests were scored by one of the raters.

## Results for Study 2

First, I wanted to evaluate the randomness of participants' assignment into conditions by conducting a one-way ANOVA to assess whether there were differences between students' pretest scores across conditions. The results indicated no significant difference for students' pretest scores across conditions. Figure 4 shows percentages of students' pretest and posttest scores for all conditions.

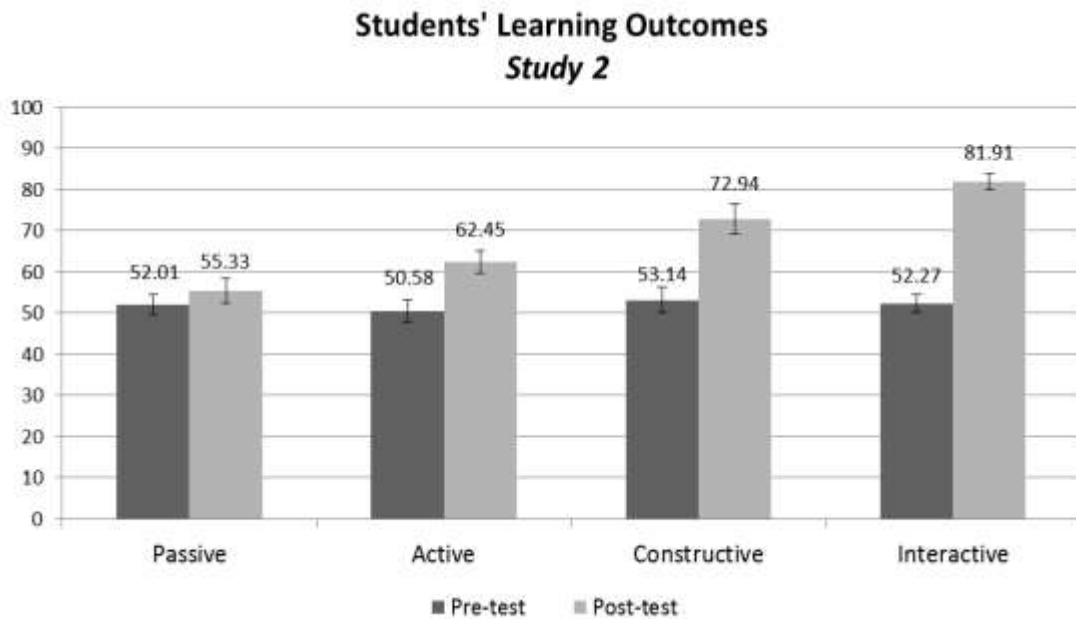


Figure 4. Percentages of students' pretest and posttest score across conditions.

Based on the null result from pretest scores, I used students' gain scores from pretest to posttest to evaluate the relationship between the conditions and students' gain scores. I conducted a one-way ANOVA in which the within-subject factor was condition, or activity type (*interactive, constructive, active* and

*passive*) and the dependent variable was percentages of students' gain scores from pretest to posttest. I used percentages of gain scores instead of raw scores due to the six additional questions in the posttest. The results for the ANOVA indicated a significant effect of condition,  $F(3, 116) = 25.34, p < .00$ . The strength of the relationship between the conditions to which students were assigned and their gain scores, as assessed by  $\eta^2$ , was strong, with the condition factor accounting for 40% of the variance of the dependent variable. The means and standard deviations for students' raw scores and percent values of pre and posttests are presented in Table 7.

Table 7

*Means and Standard Deviations of Students' Raw Scores and Percentages for Pretest and Posttest by Intervention*

	Pretest			Posttest		
	Raw (Max = 65)	Percentage		Raw (Max = 79)	Percentage	
Intervention	<i>M</i>	<i>SD</i>	<i>M (%)</i>	<i>M</i>	<i>SD</i>	<i>M (%)</i>
Interactive	33.98	9.86	52.28	64.71	11.03	81.91
Constructive	34.54	9.82	53.14	57.63	13.54	72.94
Active	32.86	8.76	50.58	49.33	10.89	62.45
Passive	33.79	8.01	51.99	43.71	11.40	55.33

Follow up tests were conducted to evaluate pairwise differences among the means of the four conditions. I used Holm's sequential Bonferroni method to control for Type I error at the .05 level across all six comparisons. All pairwise

comparisons were significant. Table 8 shows mean differences,  $p$  values and alpha values for all comparisons.

Table 8

*Results for Pairwise Comparisons Using Holm's Sequential Bonferroni Method*

Comparison	Mean Difference	$p$ value	Alpha value
Interactive vs. passive*	26.29	.000	.008
Interactive vs. active*	17.76	.000	.01
Constructive vs. passive*	16.46	.000	.013
Interactive vs. constructive*	9.83	.003	.017
Active vs. passive*	8.53	.023	.025
Constructive vs. active*	7.93	.035	.05

\* donates significant comparison ( $p$  value < alpha value)

*Analysis by Question Types*

Three separate one-way analyses of variance (ANOVAs) were conducted to evaluate the relationship between percentages of students' gain scores on question types (multiple choice, true-false and open-ended) and conditions. All three ANOVAs were significant for multiple choice, true-false and open-ended;  $F(3, 116) = 8.58, p < .00, \eta^2 = .18$ ;  $F(3, 116) = 16.44, p < .00, \eta^2 = .30$ ;  $F(3, 116) = 8.86, p < .00, \eta^2 = .19$ , respectively.

Follow-up tests were conducted for each question type to evaluate the pairwise differences among the means. I used the Bonferroni test as post-hoc comparisons. First, for multiple-choice type questions, there were significant differences in the means between *interactive* and *active*, *interactive* and *passive*, and *constructive* and *passive* conditions. Second, for true-false type questions, there was the similar pattern as the one in multiple-choice questions in which there were significant differences in the means between *interactive* and *active*, *interactive* and *passive*, and *constructive* and *passive* conditions. Third, for open-ended type questions, there were significant differences in the means between *interactive* and *constructive*, *interactive* and *active*, and *interactive* and *passive*.

### Summary of Study 2

Using an experimental design with random assignment, I compared four learning activity conditions using introductory materials science concepts to test the ICAP hypothesis. Based on the results, students' gain scores were increased systematically from the *passive* condition to the *active* condition to the *constructive* condition and to the *interactive* condition, as predicted by the ICAP hypothesis. So, for my first three research questions, I can conclude:

1. Students engaged in *interactive* activities performed better than the students engaged in *constructive* activities.
2. Students engaged in *constructive* activities perform better than the students engaged in *active* activities.

3. Students engaged in *active* activities perform better than the students engaged in *passive* activities.

The learning materials in this study were presented in the format of text with definitions and examples for each concept in the *passive* and *active* conditions, and in the format of graphs/figures for the same concepts in the *constructive* and *interactive* conditions. Although the learning materials in the *passive* and *active* conditions clearly provided the normative information such as definitions and examples for each concept, students did significantly better in the *constructive* and the *interactive* condition even without such information being directly stated, by constructing their own knowledge and understanding from the guided inquiry-oriented activity sheet that contained only question prompts. Also, I hypothesize that students in the *interactive* condition did significantly better than the students in the *constructive* condition since the students in the *interactive* condition had a chance to enrich their understanding socially via jointly constructing knowledge with a partner. I tested this hypothesis in the next chapter, “Verbal Analysis.”

## Chapter 5

### VERBAL ANALYSIS

This chapter provides the verbal analysis of the *interactive* data in Study 2 in order to investigate why students in *interactive* condition perform better than the students in other conditions? Specifically, this chapter examines the 4<sup>th</sup> and 5<sup>th</sup> research questions of my dissertation:

4. How do students' co-construction of knowledge influence students' learning outcomes in interactive conditions?
5. What kinds of discourse moves have significant effects on students' knowledge construction while working collaboratively?

I first provide a brief review for two of the effective *interactive* learning methods: (1) collaborative learning, and (2) peer tutoring/peer teaching. Then, I present the verbal analysis for pairs' co-construction of knowledge and the characteristics and function of the individual students' contributions during discussion.

#### Collaborative Learning

Collaborative learning is an instructional method in which two or more people work in small groups to construct knowledge jointly and/or to achieve a common goal (Roschelle, 1992; Webb, Troper, & Fall 1995). In literature, some studies used the term “cooperative learning” interchangeably with “collaborative learning” (e.g., Slavin, 1996), however some distinguished them and defined cooperative learning as a more structured method with assigned roles to do



specific roles (e.g. Prince, 2004). For example, jigsaw technique is a good example of cooperative learning methods where group members become responsible of certain pieces of information and each student teach her piece to other group members. So, clearly, jigsaw technique is closer to the peer teaching than the collaborative learning.

Collaborative learning in different settings has been extensively studied and many studies showed collaboration improved learning outcomes (e.g., Kaartinen & Kumpulainen, 2002; O'Donnell, 2006; Schroeder et al., 2007; Slavin, 1996). Studies illustrated the cognitive benefits of collaborative learning as comprehension of ideas, retention of knowledge, integration of new and old knowledge, and transfer of knowledge (Fischer & Mandl, 2005; King, 1990; Peters & Armstrong, 1998; Roschelle & Teasley, 1994; Slavin, 1996; Stahl & Hesse, 2009; Webb, Troper, & Fall, 1995).

Even though the value of collaborative learning has been well documented across domains, there is no single definite description in order to explain the effective mechanisms of collaborative learning (e.g., Hausmann, Chi & Roy, 2004; O'Donnell, 2006; Slavin, Hurley & Chamberlain, 2003). Co-construction, a process of group members to construct knowledge and joint elaboration of learning material, is one of the proposed mechanisms to explain the effectiveness. Hausmann, Chi and Roy (2004), for instance, investigated this potential mechanism to explain the effectiveness of collaborative problem solving. They contrasted other-directed learning (i.e., one student tutors other students in small group), co-construction of knowledge (i.e., students jointly build on each other's

knowledge), and self-directed explaining (i.e., group members listen the self-explanation of one student while solving the problem by talking out-loud). Results showed co-construction condition outperformed the other conditions in terms of learning outcomes. Similarly, Hogan et al. (2000) illustrated the significance of co-construction by stating knowledge building discourse and Berg (1993) found a significant correlation between co-construction of knowledge during collaboration and algebra performance.

Some studies showed, under some conditions, collaboration do not help learning (e.g., Barron, 2003; Dillenbourg et al., 1996; Phelps & Damon, 1989). For example, Lou and colleague's (1996) meta-analysis showed almost 25% of the published studies in collaborative learning showed null or even unpredicted effects when compared to individual learning conditions. Dillenbourg and Hong (2008) argued that the lack of the elaborated explanations, the mismatch in mutual regulations of cognitive processes between group members, low quality of arguments and the nonexistence of negotiation of meanings reduces the effectiveness of collaborative learning.

Barron's (2003) work showed students' supportive communication and responsiveness toward proposed ideas significantly affected the learning outcomes of the collaborative group. She found less successful groups did not discuss the proposed ideas or directly rejected them compare to successful groups. Sampson and Clark (2011) found that high performing and low performing collaborative learning groups differ based on the (1) number of unique ideas generated, (2) whether group members discuss the proposed ideas or simply

accept/reject them, (3) frequency of oppositional discourse moves that group members generated, (4) criteria that group members used to distinguish ideas, and (5) time that groups spent evaluating the alternative explanations.

In addition, numerous studies found that argumentation based collaborative learning methods promote students' usage of more scientific evidence in their claims and rebuttals while engaging in discussions with partners (e.g., Asterhan & Schwarz, 2009, Clark, D'Angelo & Menekse, 2009; Kelly, 2007). Sampson and Clark (2009) proposed argumentation based collaborative learning may be more beneficial than any other unstructured collaborative learning method since argumentation may simultaneously activate some critical processes such as receiving or providing critique; observing the strategies of other group members, and resolving conflicting ideas through social exchanges.

### Peer Tutoring and Peer Teaching

Peer tutoring is defined as “the recruitment of one student to provide one-on-one instruction for another student, accompanied by explicit assignment of participants to “tutor” and “tutee” roles” (Roscoe & Chi, 2007, p. 2). Peer teaching, on the other hand, is broader and includes peer tutoring, reciprocal peer tutoring, learning by teaching, other directed learning, and teaching of more advanced student to small groups. Some of these terms are used interchangeably as well.

There are several benefits of peer tutoring. Effective tutoring advances mastery of academic skills (Chi et al., 2001) improves self-esteem (Gaustad,

1992); reduces social barriers and builds new friendships (Miller et al., 1993); and provides positive role models (Rekrut, 1994).

The effectiveness of peer tutoring on tutee learning has been studied extensively across domains and age groups. Hattie (2009) synthesized 14 meta-analyses relating to peer tutoring and calculated the average effect size as .55 (Cohen's *d*). Roscoe and Chi (2007) also synthesized the five meta-analyses (meta-analysis by Cohen, Kulik & Kulik., 1982; Cook, Scruggs, Mastropieri, & Casto, 1986; Mastropieri, Spencer, Scruggs, & Talbott, 2000; Mathes & Fuchs, 1994; Rohrbeck, Ginsburg-Block, Fantuzzo, & Miller, 2003). They calculated the effect sizes as ranging from .10 to .94. Some of the findings based on their meta-review are: (1) Same age peer tutoring is not as effective as cross-age tutoring, (2) shorter peer tutoring programs are more effective than longer tutoring programs, (3) peer tutor training is important and training sessions that teaches tutors to use constructivist learning theories increase the effectiveness of peer tutoring.

Studies also indicate peer tutoring becomes more effective when tutors allow and help tutees to be more constructive in knowledge generation. In general, successful tutors (1) scaffold tutees rather than directly telling the knowledge, (2) encourage tutees to participate by asking questions and providing feedback, (3) provide conceptual explanations with using real life examples and analogies, and (4) do not interrupt tutees' explanations even if these explanations are incorrect, but listen and try to understand the potential problems and errors in tutees' thinking (Roscoe & Chi, 2007).

Peer tutoring increases learning outcome and academic mastery of tutors as well (Bargh & Schul, 1980; Chi et al., 2001). For example, Hausmann and colleagues (2004) found that the gain scores of tutors (called as other directed speaker in their study) were significantly higher than the gains scores of tutees (called as other directed listener in their study).

Successful tutoring requires questioning, explanation and feedback. All these methods entail tutors to construct good questions that help tutees to monitor and reflect; tailor their explanations based on the prior knowledge of tutees; and provide meaningful feedback that allow tutees to see flaws in their reasoning and revise their knowledge. Subsequently, constructing questions, making self-explanations, and providing feedback helps tutors to monitor and revise their knowledge as well. In addition, deep questions from tutees elicit elaborated tutor responses, so overall both asking and answering questions help tutors learning (Graessaer, Person, & Maglian, 1995).

Especially, the studies designed to investigate learning by teaching shows teaching others significantly increase learning (e.g., Biswas et al., 2001; 2005). Even, studies with computer based teachable agents showed students that tutor teachable agents (not human tutees) learned more than when they were studying alone (e.g., Chase et al., 2009). In learning by teaching environments, by anticipating what their students already know and what their students need to learn, teachers monitor and structure their own knowledge initially. Then, the interaction with students and receiving questions and feedback make teachers notice the errors and misconceptions that their students have. All these interaction

and continuous knowledge construction help teacher to notice the problems in her knowledge and facilitate the reflection as well.

### Co-Construction of Knowledge

In this section, I investigated how students' co-construction of knowledge influences students' learning outcomes in *interactive* conditions. I used the transcribed protocols of the pairs in the *interactive* condition in the Study 2. In total, I had 24 pairs for this analysis.

I define co-construction in this study as the generation of knowledge by extending the ideas of one's partner in dialog. Studies have shown co-construction of knowledge is an effective dialog pattern to support learning (e.g., Chi, 2009; Hausmann, Chi & Roy, 2004; Hogan, Nastasi, & Pressley, 1999, Tao & Gunstone, 1999). Also, studies that I reviewed in the previous sections indicate students' joint construction advances students learning outcomes both in collaborative learning and peer teaching settings.

### *Coding the Dialogues*

Students' dialogue was coded based on the frequency of the co-construction of knowledge in the each segment. I coded the dialogue segment as highly co-constructive (score 3 in my coding scheme) when substantive statements and responses of each student build upon those of the other throughout the question segment. The spectrum of the co-construction quality ranged from pairs who largely construct their ideas and write them down independently with

only minor statements of approval from the other, to collaborative discussions in which both students reach a shared understanding indicated by the proportion and/or frequency of substantive statements and responses of clarifying statements and restatements. Therefore, co-construction in each segment were coded based on an ordinal scale from score 1 (i.e., mostly one-sided/one student dominant) to score 3 (i.e. mostly co-constructive/both students contributing). Table 9 shows my coding scheme for this analysis.

Table 9

*Coding Scheme to Investigate the Co-Construction of Knowledge*

Coding Scores	Description
Score 1	<ul style="list-style-type: none"> <li>• There is little substantive discussion or only one student’s statements are substantive.</li> <li>• Students do not clarify or complete their partners’ statements, instead voicing generic responses of agreement.</li> <li>• One student decides what to write while the other agrees but contributes very little or nothing.</li> </ul>
Score 2	<ul style="list-style-type: none"> <li>• One student’s statements are mostly substantive and the other varies between substantive and shallow statements and responses.</li> <li>• Statements and responses are discontinuous as each student makes assertions independent from those of the other.</li> <li>• One student contributes most to what will be written while</li> </ul>

the other takes a smaller, though substantive, role.

- Score 3
- Substantive statements and responses of each student build upon those of the other, indicating a shared line of reasoning.
  - Students clarify or complete their partners' statements through expanding, elaborating, restatement or rebuttal.
  - Conclusions are co-constructed with both students involved fairly equally in determining what to write.
- 

In my coding scheme, I focused on to capture instances of a shared line of reasoning rather than two distinct lines. In addressing a specific problem each student may assert a position, but one will then give in and go along with the other without going through the process of co-construction in which a single line of reasoning is fleshed out over time and fully understood by both partners. As an indication of the shared or separate nature of reasoning, when writing down conclusions I noticed two varieties: the one who developed the conclusion writes it out after the partner notes affirmation. For example, one of the students explains and the partner says “ok, that sounds good,” and first student writes silently. Alternatively, with another pair, both students engaged in constructing the written explanation verbally even though one physically wrote. For example, both students discuss a conclusion back and forth; one student verbalizes while writing and other student offers suggestions for wording and verifies/repeats aloud the ideas written.



I used a more holistic approach in this coding, therefore the segments of the transcribed protocols were taken at the level of each question on the worksheets (Please see Appendix K for the worksheet questions). In other words, in this coding, both students' contributions throughout the question segment were more important for me than their contributions in single turns. The important metric here was the proportion of substantive statements from each student, with a more equal distribution reflecting better joint construction. In terms of actual task performance, the pairs may be dominated by one person or alternate in dominance, but the amount and distribution of intra-problem clarifying/discussing/debating/refining/concluding should correlate with individual learning gains as a result of the group exercises.

Ten of 24 transcribed protocols were coded individually by two raters. The initial percent agreement was 82 % for the co-construction scores. The disagreements between raters were discussed and resolved. Rest of the transcripts was coded by one of the raters.

In order to illustrate how co-construction scores were assigned, consider the following examples. First example is a question segment with Score 1, second example is a question segment with Score 2, and third example is a question segment with Score 3.

1) Exemplary excerpt with co-construction score of 1:

1. Student A1: Have you seen this first graph before?
2. Student A2: No.
3. Student A1: I learned this in my material class before; strain and stress. It shows the relationship between these two.

4. Student A2: So, E is the energy?
5. Student A1: E is the elastic modulus.
6. Student A2: Oh elastic modulus.
7. Student A1: It is elastic modulus and it was elastic modulus in the pre-test.
8. Student A2: Yeah.
9. Student A1: But that number is just the relationship. It shows the relationship between these two. And so it is the slope. A has the higher elastic modulus because it has a greater slope.
10. Student A2: Yeah, relationship.
11. Student A1: Does that make sense?
12. Student A2: Yeah.
13. Student A1: So, It is a really easy graph if you know what it is looking for.
14. Student A2: Yeah. It was in the pre-test. I do not know what...
15. Student A1: Yeah, you do not know but it is really easy.
16. Student A2: Ok...
17. Student A1: So the characteristics in figure 1. It shows the relationship between stress and strain.
18. Student A2: What information does each figure provide? Figure 1 [Reading the question 1 from worksheet].
19. Student A1: It is this one.
20. Student A2: Figure 1 is this one. The relationship between strain and stress, which is elastic modulus.
21. Student A1: Modulus, yeah. What characteristics...
22. Student A2: The relationship between strain and stress.
23. Student A1: yeah. [Starts writing] What information does each figure provide? This provides that A has the highest elastic modulus. Elastic modulus of A is greater than B which is greater than C.
24. Student A2: Okay...

The excerpt above is representative for the segments scored with lowest co-construction scores. In this segment, student A2 is initiating all the ideas and Student A1 is simply accepting the initiated ideas without discussing and expanding. Also, student A1 is asking only one question which is a yes/no type question that does not anything new to discussion.

2) Exemplary excerpt with co-construction score of 2:

1. Student B2: [Reading question 4] how do modulus, bond energy, coefficient of thermal expansion again modulus... I do not know. Ohh...uhmmm... A greater modulus probably means the greater bond strength, right?
2. Student B1: Yeah
3. Student B2: Okay so, bonding energy lower that's so except for coefficient of thermal expansion. The greater modulus, greater bonding energy and a greater melting point all relate to higher bond strength.
4. Student B1: Okay so, a greater modulus has greater bond energy and...
5. Student B2: uhmmm will result in a higher melting point.
6. Student B1: Yeah...well yeah... will result in a higher melting point
7. Student B2: And this all relates to a higher bond strength, greater bond strength
8. Student B1: What? Okay... All characteristics...
9. Student B2: All relates to...
10. Student B1: Relates to...
11. Student B2: Higher bond energy bond strength
12. Student B1: All relates to higher bond energy, uhmmm...
13. Student B2: But the coefficient of thermal expansion...
14. Student B1: It has an inverse relationship so that's negative

15. Student B2: Yeah.
16. Student B1: As bond energy increases it decreases.
17. Student B2: Explain your reasoning.
18. Student B1: Yeah.
19. Student B2: Yeah.
20. Student B1: Coefficient of thermal expansion decreases as the modulus...
21. Student B2: As the bond energy increases.
22. Student B1: As the bond ... yeah...
23. Student B2: Related to bond strength.
24. Student B1: Yeah, as the bond strength increases.
25. Student B2: So, as the bond strength increases. So, Here it can be reasoning it will probably mean that greater bond strength means more amount of temperature is required to break it
26. Student B1: Okay...
27. Student B2: And uhh... I do not know how to relate it modulus again I was not sure. It just means the thing is more elastic, I think.
28. Student B1: Which one? This one?
29. Student B2: No, relation between bond strength and elastic modulus.
30. Student B1: Oh yeah.
31. Student B2: Is that like that makes it more elastic? Because that would make sense if greater bond strength means
32. Student B1: Haha...
33. Student B2: Metal is more elastic
34. Student B1: Okay.
35. Student B2: Okay. The reasoning will be greater bond strength means that metal will be more elastic.
36. Student B1: Yeah. That's good.
37. Student B2: And more temperature is required to break the bonds so a higher melting point.
38. Student B1: Cool.

39. Student B2: Did you write for this one? [Showing figure 3]
40. Student B1: Ohh... I did
41. Student B2: No like. Did you give any explanation for that?
42. Student B1: Okay, okay uhmmm... so, it expands because the bond
43. Student B2: Weaker the bond, more expansion
44. Student B1: Weaker the bond more expansion yeah. The weaker the bonds have higher expansion. Thermal expansion.

The second example above is a representative segment which was scored with the score 2. In this segment, similar to first example, one of the students, student B2, is proposing most of the ideas initially. Even though student B1 is not expanding or opposing with most of the B1's statements, she/he is not simply accepting the proposed ideas with comments like "yes" and/or "I agree", but restating and repeating the B2's proposed ideas. So, B1 is acting "actively" in this dialogue rather than passively voices agreement with B2. Also, student B1 is adding critical information at comment lines #14, #16, #24, and #42.

3) Exemplary excerpt with co-construction score of 3:

1. Student C2: [Reading Question 4] how do modulus, bonding energy, coefficient of thermal expansion and melting point affect bond strength? Explain your reasoning?
2. Student C2: It is just intuitively, metal A is the strongest because it does not deform as much when you apply the same strain to it and it takes a lot more ripped part of a bond, I guess.
3. Student C1: And its melting point, more energy is required to melt.
4. Student C2: Make it destabilize, yeah.
5. Student C1: So,

6. Student C2: And when you heat it, it does not change its shape as easily as metal C.
7. Student C1: So, how do we handle bond... metal A would be strongest per se. All four contributing the bond strength...
8. Student C2: How about elastic modulus, bond energy and melting point all increase bond strength while high coefficient of thermal expansion decreases bond strength?
9. Student C1: How this decreases bond strength? [Showing figure 3]
10. Student C2: I am not sure it decreases it directly; I just notice it is the opposite of these three.
11. Student C1: So, I guess thermal expansion does not contribute to the other three.
12. Student C2: Possibly, I am remembering that the thing we read mentions that thermal expansion means the molecules are getting further apart, like I guess that would also means it is easier to tear down apart because there is like metallic attraction
13. Student C1: Ok, so, these three would help, but this not...
14. Student C2: You want these to be high and this to be low to maximize bond strength
15. Student C1: Yes.
16. Student C2: Alright [Writing on the worksheet]. And then for explaining that...
17. Student C1: Less stress, more is energy is required, uhmm, more... more energy is required for this...
18. Student C2: Take more energy for any change happens, whereas this means less energy is needed for change.
19. Student C1: Yes.
20. Student C2: Okay [Writing on the worksheet].

In the third example above, both students proposes fairly equal amount of substantive statements and responses and each student build upon those of the other. For example, as student C2 initiate the statement as “metal A is the strongest because it does not deform as much when you apply the same strain to it and it takes a lot more ripped part of a bond, I guess”, student C1 is expanding this statement by adding “And its melting point, more energy is required to melt.” Also, both students are asking information seeking questions by referring to each other’s comments like “How this decreases bond strength?”

#### *Analysis for Co-Construction of Knowledge*

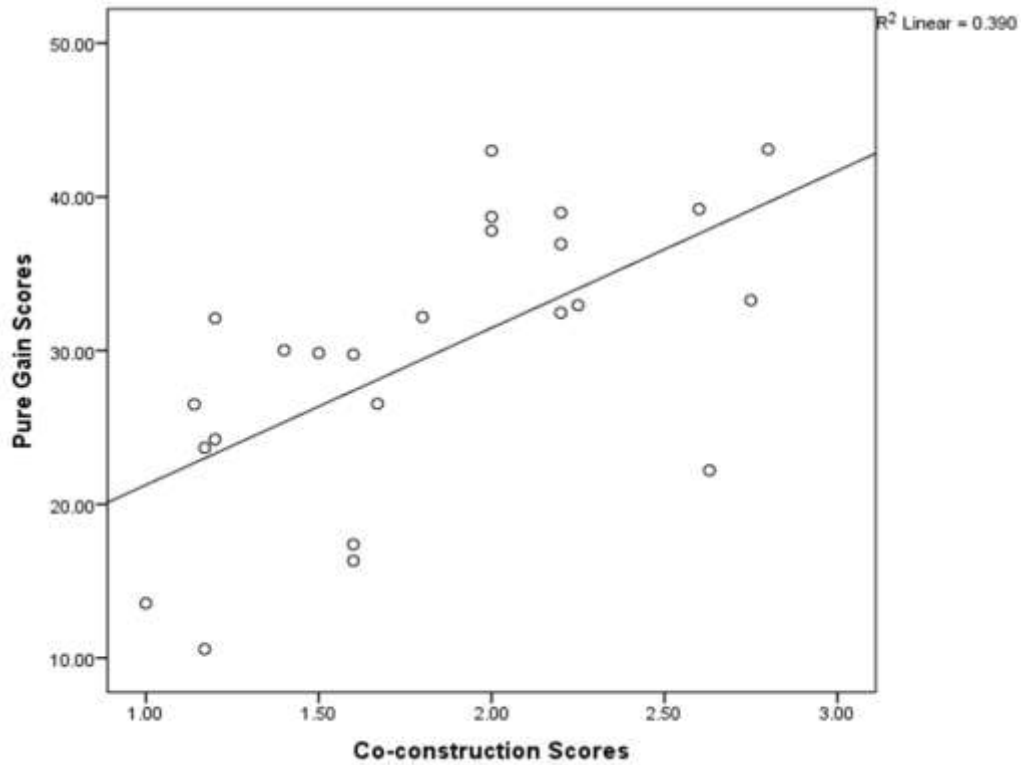
Each pair received a co-construction score as an average score of co-construction scores across five question segments. Overall, the average co-construction scores for pairs ranged from 1.00 to 3.00. The average co-construction scores across 24 pairs was 1.83.

I conducted correlation analysis by using Pearson product moment correlation coefficient. First, I investigated the relation between pairs’ co-construction scores and their average gain scores. Then I did the same analysis by using pairs’ adjusted gain scores by using the following formula:

$$\text{Adjusted Gain Scores} = (\text{posttest \%} - \text{pretest \%}) / (100 - \text{pretest \%})$$

*Results for Co-Construction of Knowledge*

The correlations were significant in both analyses;  $r(22) = .63, p < .0$  for co-construction scores and their average gain scores and  $r(22) = .47, p < .05$  for adjusted gain scores and adjusted gain scores. Figures 5 and 6 show the scatterplots for the relations.



*Figure 5.* Scatterplot showing the pairs' co-construction scores and pairs' average gain scores.



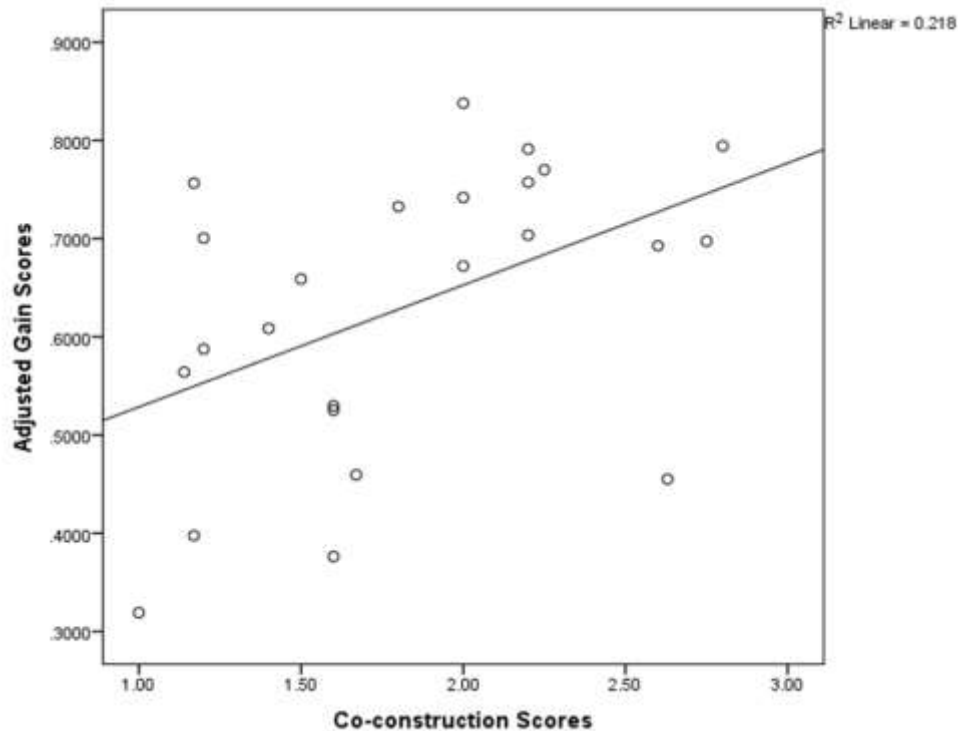


Figure 6. Scatterplot showing the pairs' co-construction scores and pairs' average adjusted gain scores.

I also conducted a one-way analysis of variance (ANOVA) to evaluate whether there is a significant difference in the adjusted learning gains between 12 pairs with low co-construction scores and other 12 pairs with higher co-construction scores. The ANOVA was significant,  $F(1, 22) = 14.10$ ,  $p < .01$ ,  $\eta^2 = .39$ , confirming the correlation results that there is a significant relation between students learning gains and co-construction of knowledge.

In addition, I conducted another one-way ANOVA to see whether there is a significant difference in terms of adjusted learning gains between 12 pairs with low co-construction scores in *interactive* condition and the students in

*constructive* condition. The ANOVA was not significant,  $F(1, 46) = 2.47$ ,  $p = .12$ ,  $\eta^2 = .05$ , indicating, on average, there is no difference between students in *constructive* and *interactive* condition when students do not co-construct knowledge effectively. Figure 7 shows the average adjusted gain scores for students in the *constructive* condition, 12 pairs with lower co-construction scores in *interactive* condition, and 12 pairs with higher co-construction scores in *interactive* condition.

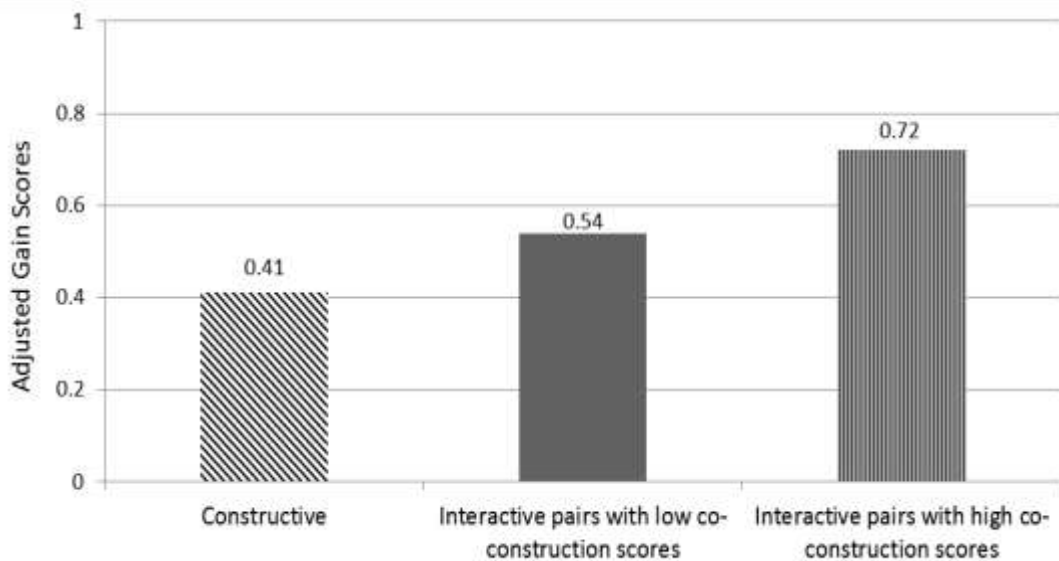


Figure 7. Average adjusted gain scores across students in the *constructive* condition, 12 pairs with lower co-construction scores in *interactive* condition, and 12 pairs with higher co-construction scores in *interactive* condition

Based on the no significant difference between students in the *constructive* condition and pairs with lower co-construction scores in *interactive* condition, I examined the adjusted learning gains of higher performing partner and lower

performing partner within the pairs with lower co-construction scores. As expected, the learning gains of high performing partners were significantly greater than the learning gains of low performing partners,  $F(1, 22) = 19.82$ ,  $p < .001$ ,  $\eta^2 = .47$ . Figure 8 shows the average adjusted gain scores for low performing partner and high performing partner within the pairs with lower co-construction scores.

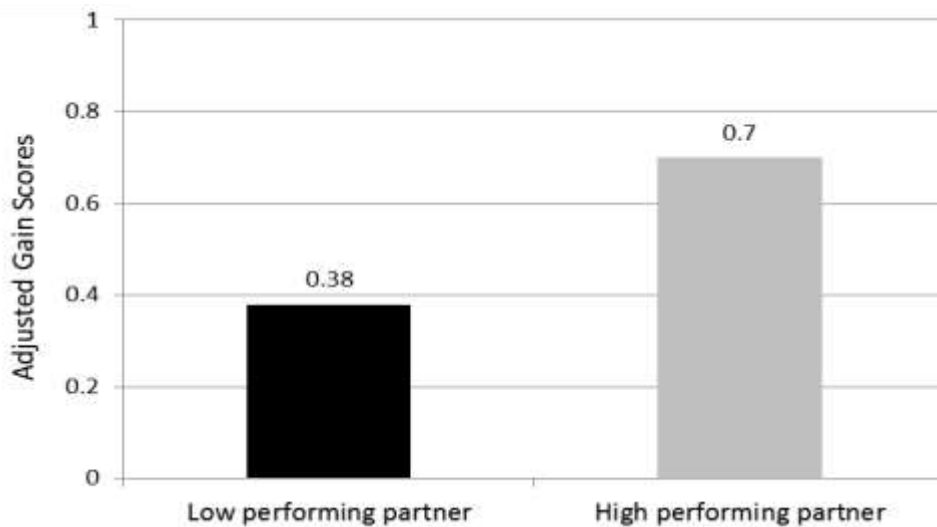


Figure 8. Average adjusted gain scores for low performing partner and high performing partner within the 12 pairs with lower co-construction scores.

I was also interested in to evaluate the relationship between low performing partners and high performing partners within the 12 pairs with lower co-construction scores and the 12 pairs with higher co-construction scores. Table 10 shows the means and standard deviations for the adjusted learning gains across four groups. I conducted a one-way ANOVA and main effect was significant,  $F(3, 44) = 19.31$ ,  $p < .001$ ,  $\eta^2 = .57$ .

Table 10

*Means and Standard Deviations for Low and High Performing Partners within the Pairs with Lower and Higher Co-Construction Scores*

Condition	<i>M</i>	<i>SD</i>
Low performing partners within the pairs with lower co-construction scores	.38	.18
High performing partners within the pairs with lower co-construction scores	.70	.17
Low performing partners within the pairs with higher co-construction scores	.63	.12
High performing partners within the pairs with higher co-construction scores	.81	.08

Follow-up tests were conducted to evaluate the pairwise differences among the means. Since the variances among four groups were different, I chose not to assume the variances were homogenous and conducted post hoc comparisons by using the Dunnett's *C* test. There were interesting findings: First, high performing partners within the pairs with higher co-construction scores received significantly higher adjusted gain score than all the students in three other groups. Second, low performing partners within the pairs with lower co-construction scores did significantly worse than all the students in three other group. Third, there was no difference between high performing partners within the pairs with lower co-construction scores and low performing partners within the pairs with higher co-construction scores. Figure 9 shows the adjusted gain

scores between low performing partners and high performing partners across pairs with lower and higher co-construction scores.

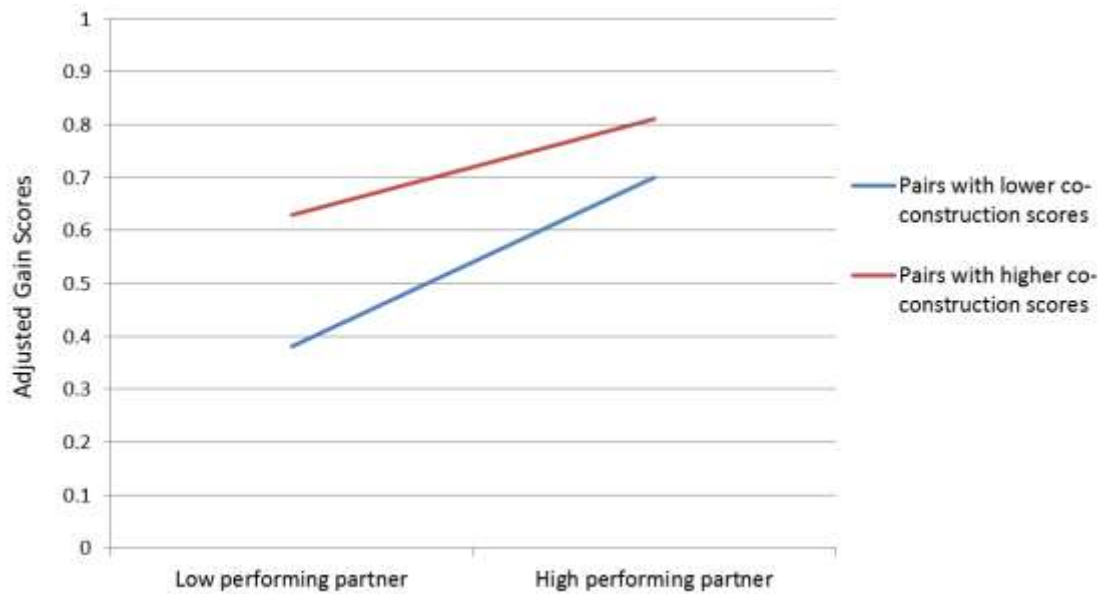


Figure 9. Average adjusted gain scores between low performing partners and high performing partners across pairs with lower and higher co-construction scores.

### Discourse Moves

In the previous section, my coding was more holistic and I segmented students' dialogue at the question level. In this section, I investigated students' discussion at a finer grain size by coding each utterance. Pairs' discussions were coded to investigate: (1) The characteristics and function of the individual students' contribution during discussion, and (2) the nature of discourse actions when individual students respond the proposed idea.

I iteratively developed a coding scheme to document students' discourse moves. I initially started with four categories as *claim, accept, reject, and discuss*. Then, I revised my discourse moves and added more categories as I needed to identify more specific utterances. For example, after reading couple of transcripts, I divided the "discuss" code into to four different codes as *elaborate, expand, question, and response* because I realized the "discuss" code alone was not sufficient for my purposes to examine the students' interaction at a finer grain size. Final protocol involved ten discourse moves as: *Claim, accept, oppose, elaborate, expand, change of claim, question, response, ignore, and off-task*. Table 11 provides descriptions and examples for each discourse move.

Table 11

*The Discourse Moves Used to Investigate the Characteristics and Function of the Individual Students' Contribution during Dialogue*

Moves	Description	Example
Claim	Proposing the initial idea; first response to questions on the activity sheet.	"Metal C has the greatest coefficient"  "So, elastic modulus of metal A is greater than metal B"
Accept	(1) Expression of acceptance and/or agreement with peer's claim; or (2) Repetition of the peer's comment, claim,	"I agree"  "Yeah, that sounds right"

explanation without adding anything new.

Oppose	(1) Raises an alternative to peer's claim; or (2) Challenges peer's claim; or (3) Briefly rejecting or disagreeing with peer's claim.	"No, I think it is the difference between both" "I do not think so" "It might be this"
Elaborate	(1) Completing <u>peer's</u> claim and/ or explanation; or (2) Adding new ideas on a <i>peer's</i> claim and/or explanation.	"Like this, it expands a little bit that's all I can tell. And then this one and this one seems equal" "Yeah, so the max highest is iron and then the one is the second lower actually this one is max highest."
Expand	(1) Reflecting on or clarifying <u>own</u> claim; or (2) expanding/elaborating <u>own</u> claim by adding explanations and/or new information.	"The melting point plus a greatest stretch expand" "We do not know the exact temperature but you can get a comparison"
Change of Claim	Changing the original claim	"Yeah, this has a greatest change, sorry"

		“Oh no, metal A was the greatest and for the melting point, it should be metal C”
Question	Asking for explanation, clarification or approval.	“That is the one, right?” “Does this make it more elastic?” “Which one?”
Response	Providing any type of response(s) to peer’s yes/no type or wh type questions.	“No, relation is between bond strength and elastic modulus” “Yes” “It depends”
Off-task	Comments that are not are not related to topic/content.	“ I am late” “You said you had chicken scratch”
Ignore	Ignoring peer’s claims and/or questions.	

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Two raters coded ten of the 24 transcripts individually. The initial percent agreement was 85 % for the discourse moves. The disagreements between raters were discussed and resolved. Rest of the transcripts was coded by one of the raters. Figure 10 shows the distribution of the percentages of discourse moves for all pairs.



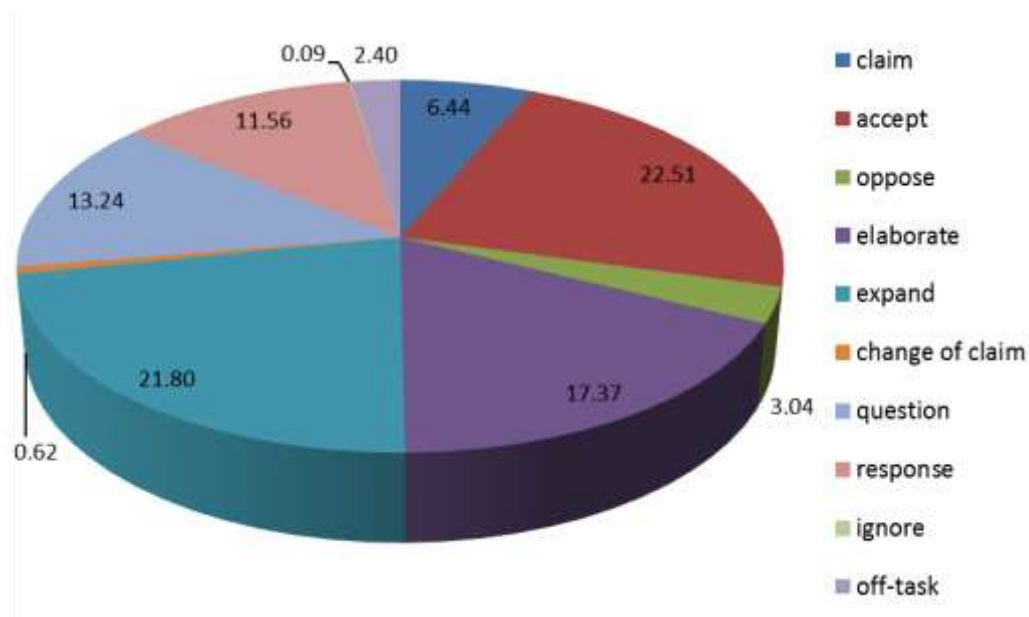


Figure 10. The percentages of discourse moves for all pairs.

#### *Analysis and Results for Discourse Moves*

I conducted a multiple regression to evaluate how well the discourse moves (*claim, accept, elaborate, expand, question, and response*) predicted the adjusted gain scores. As figure 10 indicates, most of the discourse moves were observed in *accept* (22.5%), *elaborate* (17.4%), and *expand* (21.8%) categories. On the other hand, *oppose* (3.04%), *change of claim* (.62%) and *ignore* (.09%) and *off-task* (2.40%) type moves were rarely observed in students' dialogue. Since my main goal was to investigate the effects of discourse moves on students' learning outcomes and there were very few of *oppose, change of claim ignore* and *off-task* categories, I excluded these categories for this multiple regression analysis.

The linear combination of discourse moves was significantly related to the adjusted gain scores,  $F(6, 17) = 4.74, p < .01$ . The sample multiple correlation coefficient was .79, indicating 63% of the variance of the adjusted learning gains can be accounted for by the linear combination of discourse moves. The prediction equation for the standardized variables is as follows:

$$Z_{Adjusted\ Gain} = .16 Z_{Claim} - .69 Z_{Accept} + .55 Z_{Elaborate} + .48 Z_{Expand} - 1.08 Z_{Question} + .72 Z_{Response}$$

Among the standardized coefficients of discourse moves, two were significant as *accept* and *elaborate* (both smaller than .05).

Based on these results, I created two scatterplots (Figure 11 and 12) to illustrate the relation between adjusted gain scores and the frequency of *accept* type moves; and the relation between adjusted gain scores and the frequency of *elaborate* type moves. As expected, the first scatterplot indicated a negative correlation between pairs' average learning outcomes and the frequency of *accept* type moves in a dialogue. On the contrary, figure 12 indicated a positive relation between pairs' average learning outcomes and the frequency of *elaborate* type moves in a dialogue. In other words, these results confirm the pairs that completing or adding new ideas to *peer's* claims and explanations learn significantly; whereas the pairs that simply accept *peer's* claims and explanations without adding anything new were not taken advantage of the benefit from the jointly construction of knowledge.

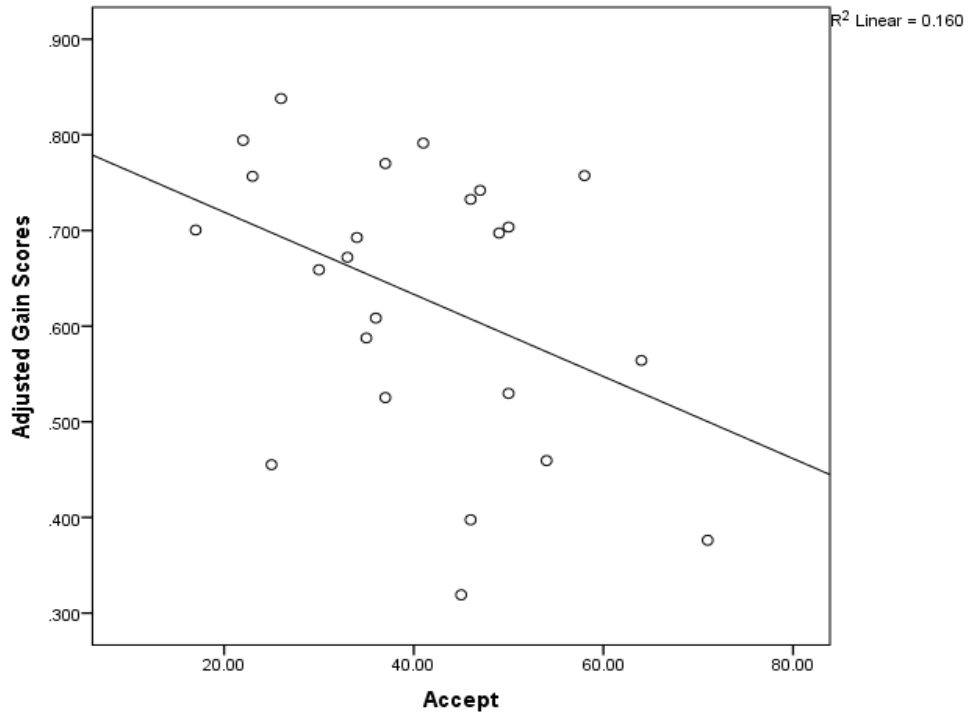


Figure 11. Scatterplot showing the correlation between the frequency of *accept* type moves in pairs' dialogue and adjusted learning gain scores.

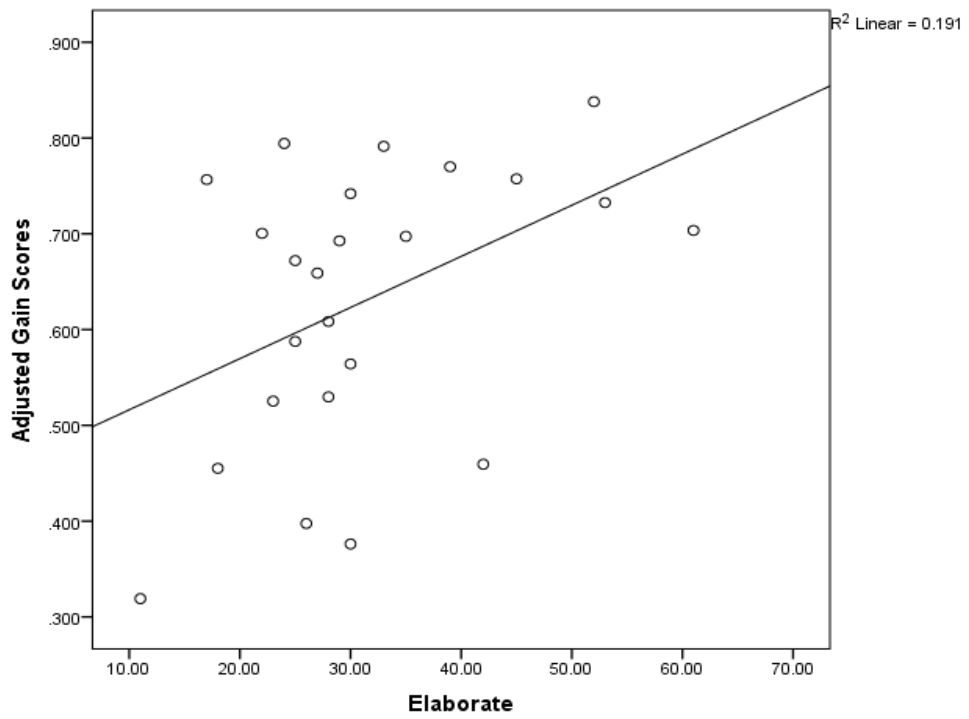


Figure 12. Scatterplot showing the correlation between the frequency of *elaborate* type moves in pairs' dialogue and adjusted learning gain scores

Similar to my analysis in “co-construction section”, I was interested in comparing pairs with lower adjusted learning gains and with higher adjusted learning gains. Figure 13 shows the percentages of discourse moves across these two clusters. Please note the *change of claim* and *ignore* type discourse moves were excluded in this figure due to their very low frequencies among all discourse moves in any cluster.

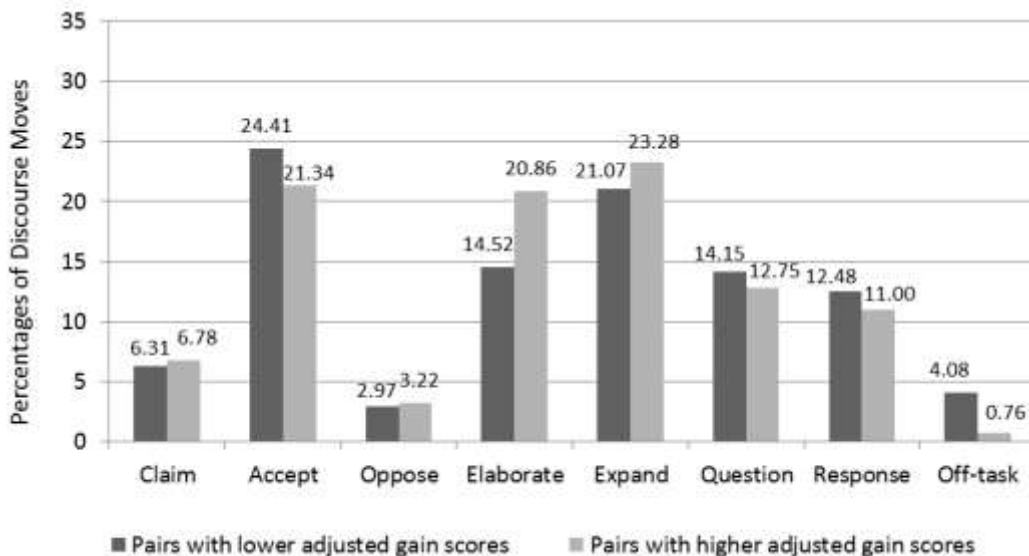


Figure 13. The percentages of discourse moves for 12 pairs with lower adjusted learning gains and other 12 pairs with higher adjusted learning gains.

The figure 13 shows there are differences for *accept*, *elaborate* and *off-task* moves but there are not major differences for the other discourse moves. Surprisingly, there were no differences for the *question* category between the pairs with lower and higher learning gains. One explanation for this finding would be the lack of a finer grain size in my coding to differentiate shallow and deep questions.

### Summary of the Verbal Analysis

In this chapter, I conducted verbal analysis to investigate why students in *interactive* condition perform better than the students in other conditions. In the light of the literature regarding peer interactions and peer learning, I first tested the effectiveness of co-construction of knowledge. My analysis revealed that pairs' co-construction scores significantly correlated with the learning outcomes. Also, I found that there is no significant difference between individual students in *constructive* condition and pairs with low co-construction scores in *interactive* condition. Therefore, these results confirmed that the co-construction of knowledge is a significant factor for the effectiveness of learning in dyads.

In addition, the detailed analysis for the comparison of the pairs with lower and higher co-construction scores indicated low performing students within the pairs with lower co-construction scores did significantly worse than all the students in *interactive* condition. Moreover, there was no difference between high performing students within the pairs with lower co-construction scores and low performing

students within the pairs with higher co-construction scores. These results align with the general assumptions in the “peer teaching” and “learning by teaching” literature.

Finally, I examined the discourse moves for the each utterance in pairs’ dialogue. I conducted a multiple regression to evaluate how well the discourse moves predicted the pairs’ learning gains. The discourse moves were significantly related to the adjusted gain scores with a high sample multiple correlation coefficient. Specifically, the bivariate correlations of *accept* and *elaborate* type moves were statistically significant with the learning gains.

## Chapter 6

### CONCLUSION

This article described my work to investigate the applicability of Chi's (2009) DOLA framework in an engineering context as well as to evaluate the ICAP hypothesis. In the first study, I explored the value and the usefulness of this framework by using it to classify the existing learning activities used in an engineering classroom, and to modify activities as needed in order to examine learning gains that coincided with each type of activity. In the second study, I used the framework to guide development of activities in order to examine subsequent learning gains from each activity type. In both studies, I evaluated students' cognitive gains following their participation in different types of learning activities.

In study 1, the analysis based on type of questions revealed that students' *inference* scores following *interactive* activities were significantly higher than their *inference* scores following *constructive* and *active* activities for both units. Since the *inference* type questions were the most challenging questions that required students to construct implicit knowledge from activities, these results provide information to understand where the real difference appears between conditions and how these differences can be detected.

Results from study 1 provided support for the ICAP hypothesis when the DOLA framework was used in a natural setting, despite confounding factors that were present such as differences in level of student interaction in the interactive activities, differences in time on task when completing the various types of

learning activities, and possible order effects. In study 2, I reduced these confounds significantly, which allowed me to compare all four conditions in a more controlled environment with a larger sample size. The results for study 2 provided strong support for the ICAP hypothesis in which *interactive* activities are expected to enhance learning better than *constructive* activities. In joint dialoguing and co-construction, not only is each student generative, but each student can further benefit from feedback, scaffolding, and contributions from the partner. *Constructive* activities are expected to enhance learning better than *active* activities because *constructive* activities allow students to generate new knowledge and repair old knowledge. Finally, *active* activities are expected to enhance learning better than *passive* activities because actively emphasizing a part of the learning materials allows the learner to attend to and activate relevant knowledge, thereby allowing the learner to assimilate novel information to fill knowledge gaps, whereas *passive* activities may only store novel information infrequently.

The verbal analysis chapter allowed me to investigate how students' co-construction of knowledge affects students' learning outcomes in *interactive* condition. Results showed a strong correlation between the joint construction of knowledge and learning gains. As the statements and responses of each student build upon those of the other, indicating a shared line of reasoning, both students benefited from the collaboration. On the other hand, when there is little substantive discussion and only one of the students contributes very little or nothing, there was no meaningful gain for the non-contributing partner. However,



the contributing partner was still benefiting which align with the findings of the “peer teaching” literature.

In addition, the analysis at a finer grain size by classifying each utterance based on the discourse moves revealed that the frequency of *elaborate* type moves in which student complete or add new ideas to *peer*'s claims and explanations positively correlated with learning outcomes; whereas the frequency of *accept* type moves in which students simply accept *peer*'s claims and explanations without adding anything new negatively correlated with the learning outcomes. Also, surprisingly, the *question* type moves were not significantly correlated with learning outcomes. However, I believe this result is due to insufficiency in my coding to differentiate questions as shallow and deep. In my current coding scheme, I coded all sorts of questions in the same category and the results show the number of questions in any given dialogue is not a significant factor to predict learning outcomes. So, in my future study, I need to differentiate the questions based on the deepness and quality.

In both studies, I worked with engineering students in a materials science and engineering context. The pivotal concepts in this domain require students to develop an understanding of how to engineer a material's macroscale properties based on knowledge and understanding of a material's structure from levels of nano to micro to macroscale. Achieving this understanding is a significant intellectual challenge and requires students to function at a complex level of cognitive processing like decision making, spatial reasoning, knowledge construction and integration. I argue that the principles of the DOLA framework

and the results supporting the ICAP hypothesis postulate a comprehensive methodology to create and design improved classroom materials and activities to promote effective learning in engineering classrooms.

Although this study results support the utility of the DOLA framework and ICAP hypothesis for selection or creation of learning activities that can lead to greater cognitive gains for students, it must be noted that this work only evaluated short term gains. Both study 1 and study 2 lack long-term retention data (i.e., delayed post-test) which could provide further evidence to support the benefit of constructive and interactive activities as a means to increase students' cognitive gains. Future work should investigate long term gains or retention of material following different types of learning activities.

In conclusion, data from two studies provide evidence to support Chi's ICAP hypothesis (2009), which proposes a classification of overt learning activities to help researchers, instructional designers and instructors determine what type of activity would be appropriate for their intended research or instruction. This research suggests that when implemented properly: (1) *interactive* modes are the most effective ones, (2) *constructive* modes are better than *active* and *passive* modes, and (3) *active* modes are better than *passive* ones for student learning.

## REFERENCES

- Abrams, E., Southerland, S., & Evans, C. (2008). Inquiry in the classroom: Identifying necessary components of a useful definition. In E. Abrams, S. Southerland & P. Silva (Eds.), *Inquiry in the classroom: Realities and opportunities*: Information Age Publishing.
- Anderson, R. (2007). Inquiry as an organizing theme for science curricula. In A. Abell & N. Lederman (Eds.), *Handbook of Research on Science Education* (pp. 807–830). Mahwah, NJ: Lawrence Erlbaum Associates.
- Apedoe, X. (2008). Engaging students in inquiry: Tales from an undergraduate geology laboratory-based course. *Science Education*, 92(4), 631-663.
- Asterhan, C. S. C. & Schwarz, B. B. (2009). The role of argumentation and explanation in conceptual change: Indications from protocol analyses of peer-to-peer dialogue. *Cognitive Science*, 33, 373-399.
- Bargh, J. A., & Schul, Y. (1980). On the cognitive benefits of teaching. *Journal of Educational Psychology*, 72(5):593–604.
- Barron, B. (2003). When smart groups fail. *The Journal of the Learning Sciences*, 12, 307–359.
- Berg, K. F. (1993). *Structured cooperative learning and achievement in a high school mathematics class*. Paper presented at the Annual Meeting of the American Educational Research Association, Atlanta, GA.
- Biswas, G., Leelawong, K., Belyne, K., Viswanath, Vye, N., Schwartz, D. and Davis, J. (2001). Incorporating self-regulated learning techniques into learning by teaching environments. In *Proceedings of the 20th Annual Meeting of the Cognitive Science Society*, pages 120–125, Chicago, Illinois, USA.
- Biswas, G., Leelawong, K., Schwartz, D., & Vye, N. (2005). Learning by Teaching: A New Agent Paradigm for Educational Software. *Applied Artificial Intelligence*, 19(3/4), 363-392.
- Blanchard, M. R., Southerland, S. A., Osborne, J. W., Sampson, V. D., Annetta, L. A. and Granger, E. M. (2010), Is inquiry possible in light of accountability?: A quantitative comparison of the relative effectiveness of

guided inquiry and verification laboratory instruction. *Science Education*, 94: 577–616.

- Burleson, W., Ganz, A., & Harris, I. (2001). Educational innovations in multimedia systems. *Journal of Engineering Education*, 90(1), 21-31.
- Callister, W. D. (2006). *Materials Science and Engineering: An Introduction*. 7<sup>th</sup> Edition. John Wiley & Sons.
- Chang, H., Quintana, C., & Krajcik, J. (2010). The impact of designing and evaluating molecular animations on how well middle school students understand the particulate nature of matter. *Science Education*, 94(1), 73-94.
- Chang, C. & Mao, S. (1999). Comparison of Taiwan science students' outcomes with inquiry-group versus traditional instruction. *The Journal of Educational Research*, 92(6), 340-346.
- Chase, C., Chin, D., Opezzo, M., Schwartz, D. (2009). Teachable agents and the protégé effect. *Journal of Science Education and Technology* 18(4), 334–352.
- Chen, H., Lattuca, L., & Hamilton, E. (2008). Conceptualizing engagement: Contributions of faculty to student engagement in engineering. *Journal of Engineering Education*, 97(3), 339.
- Chi, M. T. H. (2009). Active-constructive-interactive: A conceptual framework for differentiating learning activities. *Topics in Cognitive Science*, 1(1), 73-105.
- Chi, M. T. H. (2000). Self-explaining expository texts: The dual process of generating inferences and repairing mental models. In R. Glaser (Ed.), *Advances in instructional psychology* (pp. 161–238). Mahwah, NJ: Erlbaum.
- Chi, M. T. H., Bassok, M., Lewis, M., Reimann, P., & Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science*, 13, 145-182.
- Chi, M. T. H., de Leeuw, N., Chiu, M.H., & LaVanher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science*, 18, 439–477.

- Chi, M.T.H., Siler, S., Jeong, H., Yamauchi, T., & Hausmann, R.G. (2001). Learning from tutoring. *Cognitive Science*, 25: 471-533
- Chi, M.T. H. & Wylie, R. (In preparation). ICAP: A hypothesis of differentiated learning effectiveness for four modes of engagement activities.
- Chinn, C., & Malhotra, B. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education*, 86(2), 175-218.
- Clark, D. B., D'Angelo, C. M., & Menekse, M. (2009). Initial structuring of online discussions to improve learning and argumentation: Incorporating students' own explanations as seed comments versus an augmented-preset approach to seeding discussions. *Journal of Science Education and Technology*, 18(4), 321-333.
- Cohen, P., Kulik, J., & Kulik, C. (1982). Educational outcomes of tutoring: A meta-analysis of findings. *American Educational Research Journal*, 19(2), 237-248.
- Cook, S., Scruggs, T., Mastropieri, M., & Casto, G. (1986). Handicapped students as tutors. *Journal of Special Education*, 19(4), 483-492.
- Colliver, J. A. (2000). Effectiveness of problem-based learning curricula: research and theory. *Academic Medicine*, 75(3), p 259-266.
- Dewey, J. (1933). *How we think: A restatement of the relation of reflective thinking to the educative process*: DC Heath, Boston.
- Dewey, J. (1938). *Experience and education* (Vol. 50). New York, NY: Simon & Schuster.
- Dillenbourg, P., & Hong, F. (2008). The mechanics of CSCL macro scripts. *International Journal of Computer Supported Collaborative Learning (ijCSCL)*, 3(1), 5-23.
- Dillenbourg, P., Baker, M., Blaye, A., & O'Malley, C. (1996). The evolution of research on collaborative learning. In E. Spada & P. Reiman (Eds.), *Learning in humans and machine: Towards an interdisciplinary learning science* (pp. 189-211). Oxford: Elsevier.

- Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences* 8(3/4), 391–450.
- Fischer, F., & Mandl, H. (2005). Knowledge convergence in computer-supported collaborative learning: The role of external knowledge representation tools. *The Journal of the Learning Sciences*, 14(3), 405-441.
- Frailich, M., Kesner, M., & Hofstein, A. (2009). Enhancing students' understanding of the concept of chemical bonding by using activities provided on an interactive website. *Journal of Research in Science Teaching*, 46(3), 289-310.
- Friel, S. N., Curcio, F. R., & Bright, G. W. (2001). Making sense of graphs: Critical factors influencing comprehension and instructional implications. *Journal for Research in Mathematics Education*, 32(2), 124-158.
- Ford, J., Smith, E., Weissbein, D., Gully, S., & Salas, E. (1998). Relationships of goal orientation, metacognitive activity, and practice strategies with learning outcomes and transfer. *Journal of Applied Psychology*, 83(2), 218-233.
- Furtak, E. (2006). The problem with answers: An exploration of guided scientific inquiry teaching. *Science Education*, 90(3), 453-467.
- Gaustad, J. (1992). *Tutoring for at-risk students*. Eugene, OR: Oregon School Study Council.
- Graesser, A. C., N. Person, and J. Maglian. (1995). Collaborative dialog patterns in naturalistic one-on-one tutoring. *Applied Cognitive Psychologist* 9:359–387.
- Harms, W., & DePencier, I. (1996). *Experiencing education: 100 years of learning at the University of Chicago Laboratory Schools*: University of Chicago Laboratory Schools.
- Hattie, J. (2009). *Visible learning. A synthesis of over 800 meta-analyses relating to achievement*. London: Routledge.
- Hausmann, R. G. M. (2006). Why do elaborative dialogs lead to effective problem solving and deep learning? In R. Sun & N. Miyake (Eds.),

*Proceedings of the 28th Annual Cognitive Science Society* (pp. 1465-1469). Alpha, NJ: Sheridan Printing.

Hausmann, R.G.M., Chi, M.T.H. & Roy, M. (2004). Learning from collaborative problem solving: An analysis of three dialogue patterns. *In the Twenty-sixth Cognitive Science Proceedings*.

Heller, R. S., Beil, C., Dam, K., & Haerum, B. (2010). Student and faculty perceptions of engagement in engineering. *Journal of Engineering Education*, 99(3), 253-261.

Higley, K., & Marianno, C. (2001). Making engineering education fun. *Journal of Engineering Education*, 90(1), 105-107.

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review*, 16, 235–266.

Hoffman, J., Wu, H., Krajcik, J., & Soloway, E. (2003). The nature of middle school learners' science content understandings with the use of on-line resources. *Journal of Research in Science Teaching*, 40(3), 323-346.

Hofstein, A., Navon, O., Kipnis, M., & Mamlok Naaman, R. (2005). Developing students' ability to ask more and better questions resulting from inquiry type chemistry laboratories. *Journal of Research in Science Teaching*, 42(7), 791-806.

Hogan, K., Nastasi, B., & Pressley, M. (2000). Discourse patterns and collaborative scientific reasoning in peer and teacher-guided discussions. *Cognition and Instruction*, 17(4), 379–432.

Hundley, S. A. (2007). *A comparative study of traditional lecture methods and interactive lecture methods in introductory geology courses for non-science majors at the college level*. (Doctoral dissertation). The Ohio State University, Columbus, OH. Retrieved from ProQuest. UMI Number: 3286820.

Igo, L. B., Bruning, R., & McCrudden, M. T. (2005). Exploring differences in students' copy-and-paste decision making and processing: A mixed-methods study. *Journal of Educational Psychology*, 97, 103–116.

Jaakkola, T., Nurmi, S., & Veermans, K. (2011). A comparison of students' conceptual understanding of electric circuits in simulation only and

simulation-laboratory contexts. *Journal of Research in Science Teaching*, 48(1), 71-93.

- Johnson, D.W., Johnson, R.T., and Smith, K. A. (1991). *Active Learning: Cooperation in the College Classroom*, Edina, MN: Interaction Book Company.
- Kaartinen, S., & Kumpulainen, K. (2002). Collaborative inquiry and the construction of explanations in the learning of science. *Learning and Instruction*, 12(2), 189–212.
- Kapur, M. (2008). Productive failure. *Cognition and Instruction*, 26(3), 379–424.
- Katz, S., O'Donnell, G., & Kay, H. (2000). An approach to analyzing the role and structure of reflective dialogue. *International Journal of Artificial Intelligence in Education*, 11(3), 320-343.
- Kelly, G. J. (2007). Discourse in science classrooms. In S. K. Abell, & N. G. Lederman (Eds.), *Handbook of Research on Science Education*. (pp. 443--469). Mahwah, NJ: Lawrence Erlbaum Associates.
- King, A. (1990). Enhancing peer interaction and learning in the classroom through reciprocal questioning. *American Educational Research Journal*, 27(4), 664.
- King, A. (1992). Comparison of self-questioning, summarizing, and note-taking review as strategies for learning from lectures. *American Educational Research Journal*, 29, pp. 303-323.
- Kirschner, P., Sweller, J., & Clark, R. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, 41(2), 75-86.
- Klahr, D., & Nigam, M. (2004). The equivalence of learning paths in early science instruction. *Psychological Science*, 15(10), 661.
- Klein, P. (1999). Reopening Inquiry into Cognitive Processes in Writing-To-Learn. *Educational Psychology Review*, 11(3), 203-270.
- Klimoski, R., & Mohammed, S. (1994). Team mental model: construct or metaphor? *Journal of Management*, 20(2), 403.



- Lambert, N., & McCombs, B. (1998). *How students learn: Reforming schools through learner-centered education*. Washington, DC: American Psychological Association
- Lederman, N., Lederman, J., Wickman, P. O., & Lager-Nyqvist, L. (2007, April). Development of a valid and reliable protocol for the assessment of early childhood students' conceptions of nature of science and scientific inquiry. *Paper presented at the annual conference of the National Association for Research in Science Teaching*, New Orleans, LA.
- Lederman, J. S., Lederman, N. G., & Wickman, P.-O. (2008, April). An international, systematic investigation of the relative effects of inquiry and direct instruction: A replication study. *Paper presented at the annual conference of the National Association for Research in Science Teaching*, Baltimore, MD.
- Lee, O., Buxton, C., Lewis, S., & LeRoy, K. (2006). Science inquiry and student diversity: Enhanced abilities and continuing difficulties after an instructional intervention. *Journal of Research in Science Teaching*, 43(7), 607-636.
- Leonard, W. H. (1989). An experimental test of an extended discretion laboratory approach for university general biology. *Journal of Research in Science Teaching*, 26, 79-91.
- Lewis, S., & Lewis, J. (2008). Seeking effectiveness and equity in a large college chemistry course: An HLM investigation of peer-led guided inquiry. *Journal of Research in Science Teaching*, 45(7), 794-811.
- Lin, C., & Tsai, C. (2009). The relationship between students' conceptions of learning engineering and their preferences for classroom and laboratory learning environments. *Journal of Engineering Education*, 98, 193-204.
- Lott, G. (1983). The effect of inquiry teaching and advance organizers upon student outcomes in science education. *Journal of Research in Science Teaching*, 20(5), 437-451.
- Lou, Y., Abrami, P. C., Spence, J. C., Poulsen, C., Chambers, B., & d'Apollonia, S. (1996). Within-class grouping: A meta-analysis. *Review of Educational Research*, 66(4), 423-458.

- Manlove, S., Lazonder, A. W., & de Jong, T. (2009). Collaborative versus individual use of regulative software scaffolds during scientific inquiry learning. *Interactive Learning Environments, 17*, 105–117.
- Martin, M. (2009). *The effect of active techniques combined with didactic lecture on student achievement*. (Doctoral dissertation). Arkansas State University, Jonesboro, AR. Retrieved from ProQuest. UMI Number: 1467105.
- Mastropieri, M., Spencer, V., Scruggs, T., & Talbott, E. (2000). Students with disabilities as tutors: An updated research synthesis. In T. E. Scruggs & M. A. Mastropieri (Eds.), *Educational interventions: Advances in learning and behavioral disabilities* (Vol. 14, pp. 247–279). Stamford, CT: JAI.
- Mathes, P., & Fuchs, L. (1994). The efficacy of peer tutoring in reading strategies for students with mild disabilities: A best-evidence synthesis. *School Psychology Review, 23*(1), 59–80.
- Mayer, R. (2004). Should there be a three-strikes rule against pure discovery learning? *American Psychologist, 59*(1), 14-19.
- Menekse, M., Stump, G., Krause, S., & Chi, M.T.H. (2011). Implementation of differentiated active-constructive-interactive activities in an engineering classroom. *Proceedings of the American Society for Engineering Education (ASEE) Annual Conference*. Vancouver, Canada.
- Messick, S. (1995). Validity of psychological assessment: Validation of inferences from persons' responses and performances as scientific inquiry into score meaning. *American Psychologist, 50*(9), 741-749.
- Miller, L., Kohler, F., Ezell, H., Hoel, K., & Strain, P. (1993). Winning with peer tutoring. *Preventing School Failure, 37*(3), 14-18
- Minner, D., Levy, A., & Century, J. (2010). Inquiry based science instruction—what is it and does it matter? Results from a research synthesis years 1984 to 2002. *Journal of Research in Science Teaching, 47*(4), 474-496.
- Montpas, M. M. (2004). *Comparison of “jeopardy” game versus lecture on associate degree nursing students’ achievement and retention of geriatric nursing concepts*. (Doctoral dissertation). Wayne State University, Detroit, MI. Retrieved from ProQuest. UMI Number: 3151328.

- National Research Council. (1996). *National Science Education Standards*. Washington, DC: National Academy Press.
- National Research Council. (2000). *Inquiry and the national science education standards: A guide for teaching and learning*. Washington, DC: National Academy Press.
- Newell, J. (2009). *Essentials of Modern Materials Science and Engineering*. Hoboken, NJ: John Wiley & Sons.
- Nietfeld, J., Cao, L., & Osborne, J. (2005). Metacognitive Monitoring Accuracy and Student Performance in the Postsecondary Classroom. *Journal of Experimental Education*, 74(1), 22.
- Novak, J. D. (1990). Concept mapping: A useful tool for science education. *Journal of Research in Science Teaching*, 27, 937-949.
- O'Donnell, A. M. (2006). The role of peers and group learning. In P. Alexander & P. Winne (Eds.) *Handbook of educational psychology* (2nd ed; pp. 781-802). Mahwah, NJ: Lawrence Erlbaum Associates.
- Osman, M. (2008a). Observation can be as effective as action in problem solving. *Cognitive Science*, 32, 162-183.
- Osman, M. (2008b). Positive transfer and negative transfer/antilearning of problem-solving skills. *Journal of Experimental Psychology: General*, 137, 97-115.
- Palinscar, A., & Brown, A. (1984). Reciprocal teaching of comprehension-fostering and comprehension-monitoring activities. *Cognition and instruction*, 1(2), 117-175.
- Pendergrass, N., Kowalczyk, R., Dowd, J., Laoulache, R., Nelles, W., Golen, J., et al. (2002). Improving first-year engineering education. *Journal of Engineering Education*, 90(1), 33-40.
- Peters, J. M., & Armstrong, J. L. (1998). Collaborative Learning: People Laboring Together to Construct Knowledge. *New Direction For Adult and Continuing Education*, 79, 75-85.

- Phelps, E., & Damon, W. (1989). Problem solving with equals: Peer collaboration as a context for learning mathematics and spatial concepts. *Journal of Educational Psychology, 81*, 639–646.
- Prince, M. (2004). Does active learning work? A review of the research. *Journal of Engineering Education, 93*, 223-232.
- Prince, M., & Felder, R. (2006). Inductive teaching and learning methods: Definitions, comparisons, and research bases. *Journal of Engineering Education-Washington, 95*(2), 123.
- Rekrut, M. (1994). Peer and cross-age tutoring: The lessons of research. *Journal of Reading, 37*(5), 356-362.
- Richmond, G., & Striley, J. (1996). Making meaning in the classroom: social processes in small-group discourse and scientific knowledge building. *Journal of Research in Science Teaching, 33*(8), 839–858.
- Rittle-Johnson, B. (2006). Promoting transfer: Effects of self-explanation and direct instruction. *Child Development, 77*, 1 – 15.
- Rochelle, J. (1992). Learning by collaborating: convergent conceptual change. *The Journal of the Learning Sciences, 2*, 235–276.
- Roschelle, J., & Goldman, S. (1992). Learning as social and neural. *Educational Psychologist, 27*, 435-453.
- Roschelle, J., & Teasley, S. D. (1994). The Construction of Shared Knowledge in Collaborative Problem Solving. *NATO ASI Series F Computer and Systems Sciences, 128*, 69-97.
- Rohrbeck, C., Ginsburg-Block, M., Fantuzzo, J., & Miller, T. (2003). Peer-assisted learning interventions with elementary school students: A meta-analytic review. *Journal of Educational Psychology, 95*(2), 240–257.
- Roscoe, R.D., & Chi, M.T.H. (2007). Understanding tutor learning: Knowledge-building and knowledge-telling in peer tutors' explanations and questions. *Review of Educational Research, 77*, 534–574.
- Rosenshine, B., & Meister, C. (1994). Reciprocal teaching: A review of the research. *Review of Educational Research, 64*(4), 479.

- Sadeh, I., & Zion, M. (2009). The development of dynamic inquiry performances within an open inquiry setting: A comparison to guided inquiry setting. *Journal of Research in Science Teaching*, 46(10), 1137-1160.
- Sadler, K. C. (2002). *The effectiveness of cooperative learning as an instructional strategy to increase biological literacy and academic achievement in a large, nonmajors biology class*. Tennessee State University, Nashville, TN. Retrieved from ProQuest. UMI Number: 3061781.
- Sampson, V. & Clark, D. B. (2009). The impact of collaboration on the outcomes of argumentation. *Science Education*, 93(3), 448-484.
- Schroeder, C., Scott, T., Tolson, H., Huang, T., & Lee, Y. (2007). A meta analysis of national research: Effects of teaching strategies on student achievement in science in the United States. *Journal of Research in Science Teaching*, 44(10), 1436-1460.
- Schwartz, D. L., & Bransford, J. D. (1998). A time for telling. *Cognition and Instruction*, 16, 475–522.
- Schwartz, D., Chase, C., Chin, D., Oppezzo, M., Kwong, H., Okita, S., et al. (2009). Interactive metacognition: Monitoring and regulating a teachable agent. In D. Hacker, J. Dunlosky & A. Graesser (Eds.), *Handbook of metacognition in education* (pp. 340–358): Taylor & Francis.
- Sesen, B. A., & Tarhan, L. (2011). Inquiry-Based Laboratory Activities in Electrochemistry: High School Students' Achievements and Attitudes. *Research in Science Education*, DOI 10.1007/s11165-011-9275-9. (published online first December 04, 2011).
- Shooter, S., & McNeill, M. (2002). Interdisciplinary collaborative learning in mechatronics at Bucknell University. *Journal of Engineering Education-Washington*, 91(3), 339-344.
- Shulman, L. S., & Keisler, E. R. (1966). *Learning by discovery*. Chicago: Rand McNally.
- Smith, K., Sheppard, S., Johnson, D., & Johnson, R. (2005). Pedagogies of engagement: Classroom-based practices. *Journal of Engineering Education*, 94(1), 87-101.

- Slavin, R. E. (1996). Research on cooperative learning and achievement: What we know, what we need to know. *Contemporary Educational Psychology*, 21(1), 43-69.
- Slavin, R. E., Hurley, E. A., & Chamberlain, A. (2003). Cooperative learning and achievement: Theory and research. In G. E. Miller & W. M. Reynolds (Eds.), *Handbook of psychology: Educational psychology* (Vol. 7, pp. 177–198). Hoboken, NJ: Wiley.
- Starrett, S., & Morcos, M. (2001). Hands-on, minds-on electric power education. *Journal of Engineering Education*, 90(1), 93-100.
- Stahl, G., & Hesse, F. (2009). Paradigms of shared knowledge. *Computer-Supported Collaborative Learning*, 4, 365-369.
- Stull, A.T., & Mayer, R.E. (2007). Learning by doing versus learning by viewing: Three experimental comparisons of learner-generated versus author-provided graphic organizers. *Journal of Educational Psychology*, 99(4), 808–820.
- Summers, J. J., Beretvas, N. S., Svinicki, M., & Gorin, D. J. (2005). Evaluating collaborative learning and community. *The Journal of Experimental Education*, 73(3), 165-188.
- Terenzini, P., Cabrera, A., Colbeck, C., Parente, J., & Bjorklund, S. (2001). Collaborative learning vs. lecture/discussion: Students' reported learning gains. *Journal of Engineering Education*, 90(1), 123-130.
- Tao, P.-K., & Gunstone, R. F. (1999). Conceptual change in science through collaborative learning at the computer. *International Journal of Science Education*, 21(1), 39-57.
- Toth, E. E., Suthers, D. D., & Lesgold, A. M. (2002). “Mapping to know”: The effects of representational guidance and reflective assessment on scientific inquiry. *Science Education*, 86, 264–286.
- VanLehn, K., Graesser, A. C., Jackson, G. T., Jordan, P., Olney, A., & Rose, C. P. (2007). When are tutorial dialogues more effective than reading? *Cognitive Science*, 31, 3–62.
- Webb, N. M. (1989). Peer interaction and learning in small groups. *International Journal of Educational Research*, 31, 21-40.

- Webb, N. M., Troper, J. D., & Fall, R. (1995). Constructive activity and learning in collaborative small groups. *Journal of Educational Psychology*, 87(3), 406-423.
- Wilson, C. D., Taylor, J. A., Kowalski, S. M. and Carlson, J. (2010). The relative effects and equity of inquiry-based and commonplace science teaching on students' knowledge, reasoning, and argumentation. *Journal of Research in Science Teaching*, 47(3), 276–301.
- Wilson, P. N. (1999). Active exploration of a virtual environment does not promote orientation or memory for objects. *Environment and Behavior*, 31(6), 752-763.
- Wise, K., & Okey, J. (1983). A meta analysis of the effects of various science teaching strategies on achievement. *Journal of Research in Science Teaching*, 20(5), 419-435.
- White, T., & Pea, R. (2011). Distributed by Design: On the Promises and Pitfalls of Collaborative Learning with Multiple Representations. *Journal of the Learning Sciences*, Vol. 20( 3), 489-547.
- Wong, K. K. H., & Day, J. H. (2009). A Comparative Study of Problem-Based and Lecture-Based Learning in Junior Secondary School Science. *Research in Science Education*, 39(5), 625-642.
- Yasar, S. (2008). *Discourse in freshman engineering teams: The relationship between verbal persuasions, self-efficacy, and achievement*. Unpublished Dissertation, Arizona State University, Tempe, AZ.

APPENDIX A  
CONSENT FORM FOR STUDY 1



Date \_\_\_\_\_

Dear Student:

We are conducting a research study to understand the effects of different class activities on learning of various introductory materials engineering science concepts.

Your responses on daily questions after class and your scores on tests, homework assignments, concept tests and material concept inventory will help us assess the effectiveness of the class activities on learning the concepts of this materials science course. You will receive \$5 for each day that you take the daily questions given after class. These questions will take 10-15 minutes.

On the last day of class, participating students will be asked to link their name and ASU affiliate ID to the anonymous ID so that the investigators can obtain the students' demographic data (age and ethnicity) and a grade from a previous required class from university records. This list of names / IDs will be kept separate from the data and only the investigators will have access to them to maintain confidentiality of the participants.

We invite you to participate. Your participation in this study is totally voluntary. Whether or not you participate has no effect on your grade. You must, however, be registered in the MSE 250 class at ASU in the Fall of 2010 and must be 18 or older to participate in this study. These results will facilitate our efforts to build a better curriculum for future engineering courses. There are no foreseeable risks or discomforts to your participation.

Your responses will be confidential. The results of this study may be used in reports, presentations, or publications but your name will not be reported.

If you have any questions concerning the research study, please contact the research team at 480-727-0041 and michelene.chi@asu.edu or at 480-370-9221 and muhsin@asu.edu. If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact the Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at (480) 965-6788. Please let me know if you wish to be part of the study.

Name: \_\_\_\_\_ signature: \_\_\_\_\_

\_\_\_\_ Yes, I would like to participate:

\_\_\_\_ Yes, I would like to participate but will not stay after class to take daily questions.

## APPENDIX B

### DESCRIPTION OF IN-CLASS ACTIVITIES USED IN STUDY 1

Topic	Name of the Activity	Type of the Activity	Description of the Activities
Atomic Bonding	Materials selection	Active	Selecting the most likely material, property of that material, type of bonding, and processing method from a given list for the motorcycle parts such as motorcycle fender or seat.
Atomic Bonding	Bonding concept map	Interactive	Drawing to complete the partially constructed concept map about atomic bonding. Also, students are asked to discuss and agree on what to draw and explain and write down their reasoning for every single decision they make to complete this concept map.
Crystal Structures	Concepts learning in context	Interactive	<p>Overall goal is matching the five different historical events (disasters involving failure of materials) with the scientific reasons for the occurrence. Students are asked to discuss and agree on their matching decisions. They are asked to write down their reasoning for their final answers as well.</p> <p>Task 1: Matching with the possible reason for the change of materials.</p> <p>Task 2: Matching with the type of transformation.</p> <p>Task 3: Matching for the condition for change.</p> <p>Task 4: Matching with the processing method.</p>
Crystal Structures	Hidden treasures	Interactive	Overall goal is to discover the properties of a face-centered cubic unit cell. Students are asked to discuss and agree on their

decisions. They also write down their rational on the activity sheet.

Task 1: Calculating the number of atoms on faces, edges and corners of a FCC unit cell.

Task 2: Calculating the length of the cube edge, face diagonal and body diagonal in terms of atomic radius.

Task 3: Calculating the coordination number and atomic packing factor of a FCC unit cell.

Crystal Structures	Unit cell directions	Active	<p>Overall goal is to reproduce the specified unit cell directions by copying; and selecting indices from a given set of unit cell directions.</p> <p>Task 1: Copying unit cell directions from a cubic unit cell diagram for specific Miller indices to a blank piece of paper.</p> <p>Task 2: Selecting the Miller indices of unit cells from a given set of unit cell directions.</p>
Crystal Structures	Unit cell families of directions	Active	<p>Overall goal is to reproduce the families of unit cell directions by copying; and selecting a family of directions.</p> <p>Task 1: Copying all unit cell families of directions from a cubic unit cell diagram to a blank piece of paper.</p> <p>Task 2: Selecting a family of directions that are equivalent in terms of properties and packing density.</p>
Crystal Structures	Unit cell planes	Constructive	<p>Overall goal is to construct unit cell planes and determine indices of unit cell planes.</p>

Crystal Structures	Unit cell worksheet	Constructive	Task 1: Drawing the planes in the unit cell by using given Miller indices.
			Task 2: Determining the Miller indices of unit cells from a given positions of planes.
			Overall goal is to construct the locations of atoms in a unit cell; and calculate total number of atoms for three different unit cells.
			Task 1: Drawing atom locations in two-dimensions based on the given indices of planes and atomic packing factor.
			Task 2: Drawing and calculating the total number of atoms per area for various planes.

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APPENDIX C  
MATERIALS SELECTION ACTIVITY

## Materials Selection Activity

### II Materials Selection.

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

	property	material	bonding	processing
i) motorcycle fender	_____	_____	_____	_____
ii) headlight lens	_____	_____	_____	_____
iii) motorcycle seat	_____	_____	_____	_____
iv) headlight filament	_____	_____	_____	_____
v) spark plug insulator	_____	_____	_____	_____



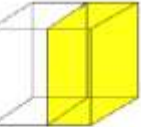
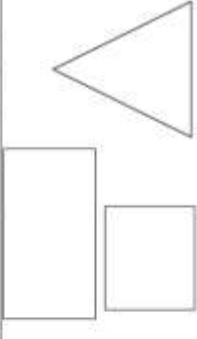

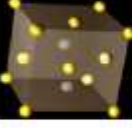
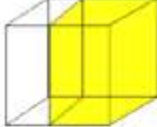
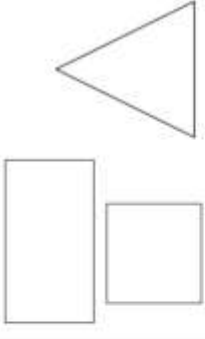

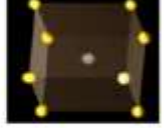
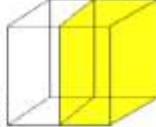
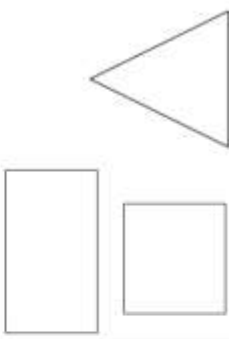

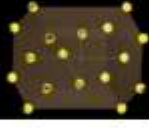
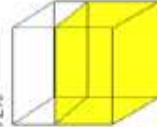
  

				
<b>PROPERTIES</b> I. transparent and impact resistant II. stiff and ductile III. flexible and tough IV. thermal & electrical resistance V. thermally stable electrical conductor	<b>MATERIAL</b> 1. tungsten - W 2. polyvinylchloride 3. polycarbonate 4. aluminum oxide (Al <sub>2</sub> O <sub>3</sub> ) 5. steel - Fe + .2%C	<b>BONDING</b> A. covalent B. ionic C. metallic D. van der Waals E. covalent & van der Waals	<b>PROCESSING</b> a. vacuum warm forming b. calendaring c. wire drawing d. metal stamping e. sintering	

APPENDIX D  
UNIT CELL WORKSHEET



### Unit Cell Worksheet

UC Type	UC atoms	Crystal Structure	CN	APF	lattice constant $a = f(R)$	Pack Dens (1 1 0)	Atom locations in (1 1 0) (1 0 0) and (1 1 1)
SC Simple Cubic			8	52%	 $a=2R$	$PD = \frac{1 \text{ atom}}{\sqrt{2}a^2}$ $= \frac{1a/\sqrt{2}4R^2}{\pi R^2/\sqrt{2}4R^2}$ $= \frac{\pi}{4\sqrt{2}}$	
FCC (Face Centered Cubic)			12	72%	 Atoms touch along face diag. $a=4R/\sqrt{2}$	$PD = \frac{2 \text{ atoms}}{\sqrt{2}a^2}$ $= \frac{2 \text{ atoms}}{(8R^2/\sqrt{2})}$ $= \frac{\pi}{(4\sqrt{2})}$	
BCC (Body Centered Cubic)			6	68%	 Atoms touch along cube dia. $a=(4R)/\sqrt{3}$	$PD = \frac{2 \text{ atoms}}{\sqrt{2}a^2}$ $= \frac{2 \text{ atoms}}{[\sqrt{2} * (4R/\sqrt{3})^2]}$ $= \frac{3\pi}{8\sqrt{2}}$	
HCP (Hexagonal close-packed)			12	72%			

Atomic Packing Factor APF= (volume of atoms in s unit cell)/(total unit cell volume) ; Coordination Number CN = number of nearest neighbor atoms (touching)  
 Planar Packing Density PD= (Number of atoms centered on a plane)/(Area of plane)  
 Linear Packing Density LD= (atoms centered on direction vector)/(length of direction vector)

APPENDIX E

QUIZ FOR CONCEPTS IN CONTEXT ACTIVITY


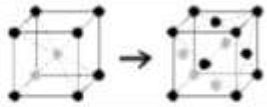
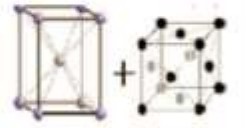
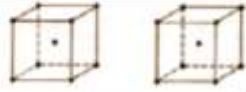
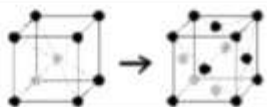
**1. A.** Which of the following disasters/failures has occurred as a result of an incomplete phase transformation?

- a) Helicopter crash (steel gear)
- b) Napoleon's failed winter invasion of Russia 1812 (tin button)
- c) The World Trade Center 9/11 (steel girders)
- d) Grandma's hip joint failed (ceramic ball cracked)
- e) The titanic sank (steel rivets)

**B.** Using your understanding of macroscopic properties and atomic level structure, explain what could have been done to avoid the disaster that you choose above?

2. A. A steel skeleton chemical processing plant collapses due to a steel beam failing prematurely a short time after a chemical explosion and a fire.

Choose the most likely condition for change, properties and change, and unit cell transformation for this disaster.

	<u>Condition for change</u>	<u>Properties and Change</u>	<u>Unit cell transformation</u>
a)	140° C sterilization phase change	Ductile metal to brittle powder	
b)	Loses strength above 730° C	Steel BCC transforms to FCC at higher temperatures	
c)	Incomplete phase transformation	Ductile metal to brittle powder	
d)	140° C sterilization phase change	Steel BCC transforms to FCC at higher temperatures	
e)	Loses strength above 730° C	BCC loses ductility at low temperature	

B. As a consulting engineer giving advice to the company, specify your recommendation to prevent this failure and justify it based on your understanding of the relationship between macroscopic properties and atomic level structure.

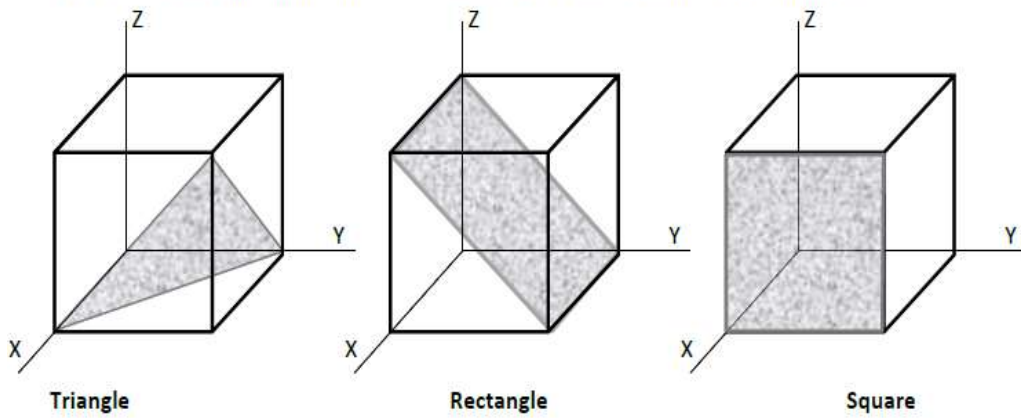
APPENDIX F

QUIZ FOR UNIT CELL PLANES ACTIVITY

1. A. Which of the following notations is correct for the Miller indices of a plane?

- a)  $(\bar{1}, 0, 0)$
- b)  $[-1, 0, 0]$
- c)  $(1, 0, 0)$
- d)  $[100]$
- e)  $(100)$

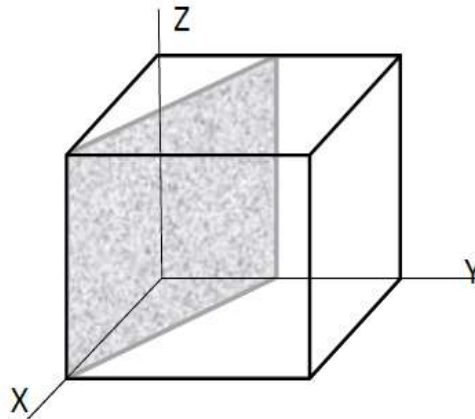
B. Based on the Miller indices you chose above, pick the correct drawing of the plane below.



Explain the relationship between the shapes of the given planes above (triangle, rectangle, and square) and the types of Miller indices generally associated with each shape.

2. A. Which of the following Miller indices represent the plane shown

- a)  $(1, \frac{1}{2}, 1)$
- b)  $(1 \frac{1}{2}, 1)$
- c)  $[1, 2, 1]$
- d)  $(1 \ 2 \ 1)$
- e)  $(\bar{1} \ \frac{1}{2} \ 1)$



**B.** Assume the plane shown above located in a simple cubic (SC) unit cell and another identical plane is located in a face centered cubic (FCC) unit cell. Sketch the atoms located on that plane for a SC unit cell and those located on that plane for a FCC unit cell. Also, calculate the number of atoms within the border of each plane.

Plane located in a SC unit cell



# of atoms within the border  
of the plane above: \_\_\_\_\_

Plane located in a FCC unit cell



# of atoms within the border  
of the plane above: \_\_\_\_\_

APPENDIX G

SAMPLE RUBRIC OF THE QUIZ FOR THE MATERIALS SELECTION  
ACTIVITY



1. A. What type of processing would be used to create a spark plug insulator?  
**[Verbatim type question]**

- a) Vacuum warm forming
- b) Calendaring
- c) Wire drawing
- d) Metal stamping
- e) Sintering

**[Sintering is correct answer]**

1. B. Based on your selection above, explain why this processing method is optimal to process the spark plug insulators. **[Inference type question]**

**Scoring Rubric for Question 1.B.:**

<b>4 Points</b>	<b>3 points</b>	<b>2 points</b>	<b>1 point</b>	<b>0 point</b>
Response includes at least four of the five correct statements. It may also include minor irrelevant information but no incorrect explanation.	Response includes three of the five correct statements. It may also include minor irrelevant information but no incorrect explanation.	Response includes at least two of the five correct statements. It may also include minor irrelevant information and/or minor incorrect explanation.	Response includes at least one of the five correct statements. It may also include major irrelevant information and/or minor incorrect explanation.	No response. Or, responses without any of the correct statements.

Correct Statements:

1. *A spark plug insulator must resist the flow of electric current and it needs to have a high melting point.*
2. *The metallic materials commonly have high melting points but they are not good insulator therefore, using a material with metallic bonds is not good to manufacture spark plug insulators.*
3. *Ceramics are good insulators and have high melting point due to ionic and covalent bonds. Therefore, using ceramics to manufacture spark plug insulators is ideal.*
4. *The processing method for ceramics should involve consolidation of ceramic powder particles by heating the part to a high temperature below the melting point.*
5. *Among the options above sintering is the only method that fires ceramic powders at high temperatures.*

APPENDIX H  
CONSENT FORM FOR STUDY 2

Dear Student,

My name is Muhsin Menekse and I am a PhD student working with Dr. Michelene Chi. She is professor in the Department of Psychology at Arizona State University. We are inviting you to participate in a research study that will examine the effects of different version of activities on learning of various introductory engineering science concepts.

If you choose to participate in this study, you will initially take a pre-test, and then work on an activity based on the condition you will be assigned, and finally you will take a post-test. Your participation will take 60-90 minutes based on the conditions you are assigned. Additionally, if you randomly assigned to “interactive” condition, you will be asked to complete the activity with another student and your interaction during the activity will be videotaped. These records will primarily be used for data analysis but they could also be used for publications and conference presentations. You will receive \$15 for your participation.

Participating students will be asked to share their name, GPAs and a grade from a previous required class. This list of names and information associated will be kept separate from the data and only the investigators will have access to them to maintain confidentiality of the participants.

Your participation in this study is totally voluntary. You must, however, be a registered ASU engineering student and you must be 18 or older to participate in this study. The results of this study will facilitate our efforts to build a better curriculum for future engineering courses. There are no foreseeable risks or discomforts to your participation.

Your responses will be confidential. The results of this study may be used in reports, presentations, or publications but your name will not be reported.

If you have any questions concerning the research study, please contact with me at 480-370 9221 and [muhsin@asu.edu](mailto:muhsin@asu.edu). If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact the Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at (480) 965-6788. Please print your name and sign these forms if you wish to be part of the study.

Thank you very much,

\_\_\_\_ Yes, I would like to participate

Name (please print): \_\_\_\_\_

Signature: \_\_\_\_\_

APPENDIX I

INTRODUCTORY SHORT TEXT

**Chemical Bonding:** A chemical bond is an attraction between atoms that allows the formation of chemical substances that contain two or more atoms. The bond is caused by the electromagnetic force attraction between opposite charges, either between electrons and nuclei, or as the result of a dipole attraction.

**Ionic Bond:** Ionic bonding is a type of electrostatic interaction between atoms which have a large electronegativity difference. In a simplified view of an ionic bond, the bonding electron is not shared at all, but transferred. Ionic bonding always found in compounds that are composed of both metallic and nonmetallic elements. Ionic bonding leads to separate positive and negative ions. Ionic charges are commonly between  $-3e$  to  $+3e$ . Ionic bonding commonly occurs in metal salts such as sodium chloride (table salt).

**Covalent Bond:** Covalent bonding is a common type of bonding, in which the electronegativity difference between the bonded atoms is small or nonexistent. Bonds within most organic compounds are described as covalent. Stable electron configurations are assumed by the sharing of electrons between adjacent atoms. Two atoms that are covalently bonded will each contribute at least one electron to the bond, and the shared electrons may be considered belong to both atoms.

**Metallic Bond:** In a metallic bond, bonding electrons are delocalized over a lattice of atoms. By contrast, in ionic compounds, the locations of the binding electrons and their charges are static. The freely-moving or delocalization of bonding electrons leads to classical metallic properties such as shininess (surface light reflectivity), electrical and thermal conductivity, ductility, and high tensile strength.

**Bond strength:** Bond strength is measured between two atoms joined in a chemical bond. It is the degree to which each atom linked to another atom contributes to the valency of this other atom. Bond strength is intimately linked to bond order.

**Bond energy:** Bond energy is a measure of bond strength in a chemical bond. It is the heat required to break Avogadro's number of molecules into their individual atoms. Bond energy can be directly related to the bond length. Therefore we can use the metallic radius, ionic radius, or covalent radius of each atom in the molecule to determine the bond strength. Bond length is the distance between nuclei in a bond.

**Tensile Properties:** The degree to which a structure deforms or strains depends on the magnitude of an imposed stress. For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each

other. This relationship is called as modulus of elasticity which is the mathematical description of an object or substance's tendency to be deformed elastically (i.e., non-permanently) when a force is applied to it (Note modulus of elasticity goes with three different names as well: elastic modulus, tensile modulus, Young's modulus). On an atomic scale, macroscopic elastic strain is manifested as small changes in the interatomic spacing and the stretching of interatomic bonds. As a consequence, the magnitude of the modulus of elasticity is a measure of the resistance to separation of adjacent atoms, that is, the interatomic bonding forces.

**Melting Point:** The melting point of a solid is the temperature at which it changes state from solid to liquid. At the melting point the solid and liquid phase exists in equilibrium. The melting point of a substance depends on pressure and is usually specified at standard atmospheric pressure.

**Thermal conductivity:** Thermal conductivity indicates property of a material that indicates its ability to conduct heat. Heat transfer by conduction involves transfer of energy within a material without any motion of the material as a whole. The rate of heat transfer depends upon the temperature gradient and the thermal conductivity of the material. For metals, the thermal conductivity is quite high, and those metals which are the best electrical conductors are also the best thermal conductors. At a given temperature, the thermal and electrical conductivities of metals are proportional, but raising the temperature increases the thermal conductivity while decreasing the electrical conductivity.

**Thermal expansion:** Thermal expansion is the tendency of matter to change in volume in response to a change in temperature. When a substance is heated, its particles begin moving more and thus usually maintain a greater average separation. Materials which contract with increasing temperature are rare; this effect is limited in size, and only occurs within limited temperature ranges. The degree of expansion divided by the change in temperature is called the material's coefficient of thermal expansion (shown as  $\alpha$ ) and generally varies with temperature. The coefficient of thermal expansion describes how the size of an object changes with a change in temperature. Specifically, it measures the fractional change in size per degree change in temperature at a constant pressure. There are several types of coefficients as volumetric, area, and linear.

APPENDIX J

LONG TEXT

## Section 1: Elastic Modulus

The elastic modulus is one of the fundamental properties of materials. When a stress is applied to a material a dimensional change, or strain, is developed and this strain is termed elastic if the material returns to its original dimensions when the stress is removed. The degree to which a structure deforms or strains depends on the magnitude of an imposed stress. Many materials including ceramics, glasses, and many thermosetting polymers, exhibit elasticity at all levels of stress up to their fracture stress. Metals and alloys are elastic up to a certain level, after which they deform plastically. The types of stress normally considered are tensile, compressive and shear stresses. When a material is in a state of stress, its dimensions will be changed. A tensile stress will cause an extension of the length of the material, while a compressive stress will shorten the length. Tensile and compressive stresses are termed direct stresses. A shear stress imparts a twist to the material. The dimensional change caused by stress is termed strain. In direct tension or compression the strain is the ratio of the change in length to the original length. As a ratio strain has no units and is simply a numerical value.

The degree to which a structure deforms or strains depends on the magnitude of an imposed stress. For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each other through the relationship  $E = \sigma/\epsilon$  where  $E$  is the modulus of elasticity,  $\sigma$  (sigma) represents stress, and  $\epsilon$  (epsilon) represents strain. Stress is a measure of the internal forces acting within a deformable body. Quantitatively, it is a measure of the average



force per unit area of a surface within the body on which internal forces act. These internal forces arise as a reaction to external forces applied on the body. Because the loaded deformable body is assumed to behave as a continuum, these internal forces are distributed continuously within the volume of the material body, and result in deformation of the body's shape. Beyond certain limits of material strength, this can lead to a permanent shape change or structural failure. A strain is a normalized measure of deformation representing the displacement between particles in the body relative to a reference length. Engineers often use the stress-strain relations for calculations in tensile tests. For most typical metals the magnitude of this modulus ranges between 45 GPa and 407 GPa (GPa is gigapascal)

The elastic modulus of an object is also defined as the slope of its stress-strain graph. For example, assume we have three pure metals as metal A, metal B and metal C and the metal A has the greatest elastic modulus among all three metals and the metal B has greater elastic modulus than metal C, this relationship also implies that the metal A has the greatest slope in a stress-strain graph and the metal C has the smallest slope.

On an atomic scale, macroscopic elastic strain is manifested as small changes in the interatomic spacing and the stretching of interatomic bonds. As a consequence, the magnitude of the modulus of elasticity is a measure of the resistance to separation of adjacent atoms, that is, the interatomic bonding forces. Accordingly, materials with high bond energies also have high elastic moduli because more force is required to stretch them. For example, exemplary metal A

above has the greatest elastic modulus among three metals, so that means metal A has the highest bond energy as well.

## **Section 2: Interatomic Bonding**

Many of the physical properties of materials are predicated on knowledge of the interatomic forces that bind the atoms together. Perhaps the principles of atomic bonding are best illustrated by considering the interaction between two isolated atoms as they are brought into close proximity from infinite separation. At large distances, the forces are negligible, but as the atoms approach, each exerts forces on the other. These forces are two types: attractive and repulsive, and the magnitude of each force is a function of the separation or interatomic distance. The origin of an attractive force depends on the particular type of bonding exists between the two atoms. The magnitude of the attractive forces varies with distance. The bonding energy for these two atoms corresponds to the energy that would be required to separate these two atoms to an infinite separation.

The interaction between atoms is a blend of attractive and repulsive forces. Atoms that are far apart have almost no interaction, but as they draw closer together, a blend of attractive and repulsive forces begins. Valence electrons are repelled by the negatively charged electron cloud of the adjacent atom but are attracted to the positive nucleus. The specific nature of the interaction between atoms depends on the state of the valence electrons and the type of bonding that forms.

Bond strength is measured between two atoms joined in a chemical bond. It is the degree to which each atom linked to another atom contributes to the valency of this other atom. Bond strength is intimately linked to bond order. Bond strength can be quantified by bond energy which requires lengthy calculations, even for the simplest bonds. Another criterion of bond strength is the qualitative relation between bond energies and the overlap of atomic orbitals of the bonds. The more these overlap, the more the bonding electrons are to be found between the nuclei and hence stronger will be the bond.

Bond energy is a measure of bond strength in a chemical bond. It is the heat required to break Avogadro's number of molecules into their individual atoms. Potential energy versus interatomic separation curves illustrates the bonding energy for two isolated atoms. These curves plot attractive, repulsive, and the net potential energies as a function of interatomic separation for two atoms. The net curve has a potential energy trough or well around its minimum. The bonding energy for these two atoms corresponds to the energy at this minimum point which represents the required energy to separate these two atoms to an infinite separation. Bond energy can be directly related to the bond length as well. Therefore, we can use the metallic radius, ionic radius, or covalent radius of each atom in the molecule to determine the bond strength. Bond length is the distance between nuclei in a bond.

A number of material properties depend on the bond energy. For example, the elastic modulus of a material is dependent on the shape of its potential energy versus interatomic separation curve. The slope of a metal with a high elastic

moduli value on the potential energy-versus-interatomic separation curve will be quite steep compare to a slope of a material with a low elastic module value. In other words, materials having large bonding energies typically also have high elastic modulus values. For instance, metal C in the three metals example (metal A, metal B, and metal C) from the previous section has the lowest elastic modulus value which also indicates it has the lowest bonding energy among these three metals.

### **Section 3: Thermal Expansion**

Thermal expansion is the tendency of matter to change in volume in response to a change in temperature. When a substance is heated, its particles begin moving more and thus usually maintain a greater average separation. Materials which contract with increasing temperature are rare; this effect is limited in size, and only occurs within limited temperature ranges. The degree of expansion divided by the change in temperature is called the material's coefficient of thermal expansion (shown as  $\alpha$ ) and generally varies with temperature.

When heat is added to most materials, the average amplitude of the atoms' vibrating within the material increases. This, in turn, increases the separation between the atoms causing the material to expand. If the material does not go through a phase change, the expansion can be easily related to the temperature change. The coefficient of thermal expansion describes how the size of an object changes with a change in temperature. Specifically, it measures the fractional change in size per degree change in temperature at a constant pressure. There are several types of coefficients as volumetric, area, and linear coefficients. Which

one of these coefficients is used depends on the particular application and which dimensions are considered important. For solids, one might only be concerned with the change along a length, or over some area. The linear thermal expansion coefficient relates the change in a material's linear dimensions to a change in temperature. It is the fractional change in length per degree of temperature change. The area thermal expansion coefficient relates the change in a material's area dimensions to a change in temperature. It is the fractional change in area per degree of temperature change.

Thermal expansion can be understood by examining the interaction potential, which can be compared to parabola near its minimum. But if we go farther it loses symmetry and consequently its harmonic character; this means that the interatomic distance expands if the temperature also rises.

Materials generally change their size when subjected to a temperature change while the pressure is held constant. In the special case of solid materials, the pressure does not appreciably affect the size of an object, and so for solids, it's usually not necessary to specify that the pressure be held constant. Notice that the thermal expansion coefficient is highly significant in many applications. It is necessary to have small coefficients in materials that should have a determined size, or in materials exposed to thermal shocks, which are thermal stresses due to fast or inhomogeneous changes of temperature. In these circumstances, isotropic and small coefficients are of interest. For joints between materials we need similar coefficients to avoid thermal stresses. Common engineering solids usually have coefficients of thermal expansion that do not vary significantly over the range of

temperatures where they are designed to be used, so where extremely high accuracy is not required, practical calculations can be based on a constant, average, value of the coefficient of expansion.

The magnitude of the coefficient of thermal expansion depends on the structure of the materials and many material properties are also linked to its coefficient of thermal expansion. Materials with larger elastic modulus values generally have small coefficients. Also, materials with greater bonding energy expand less compare to materials with lower bonding energy. For example, same pure metal A (exemplary metal from the previous sections) has the greatest bonding energy compare to other pure metals (metal B and metal C), this relationship also indicates the metal A most likely has the lowest coefficient of thermal expansion.

#### **Section 4: Melting Point**

The melting point of a solid is the temperature at which it changes state from solid to liquid. Such a change of a substance from one state to another is called a change of state or phase transition. At the melting point the solid and liquid phase exists in equilibrium. It is difficult, if not impossible, to heat a solid above its melting point because the heat that enters the solid at its melting point is used to convert the solid into a liquid. The melting point of a substance depends on pressure and is usually specified at standard atmospheric pressure. The melting point is one of a number of physical properties of a substance that is useful for characterizing and identifying the substance. When considered as the temperature

of the reverse change from liquid to solid, it is referred to as the freezing point or crystallization point.

The stability of a substance is related to the bond strength. One indicator of bond strength and stability is the melting point of a substance. When a substance is heated, the absorption of heat energy causes an increase in the vibrational amplitude of the atoms. A point will be reached when the vibrational energy is sufficient to overcome the interatomic bonding energy of the atoms in the solid and the atoms become mobile, in other words substance melts. Both ionic and covalent bonds are strong bonds that possess a similar range of bond energies. However, within both ionically and covalently bonded substances, there are major variations in melting point. Metals tend to have high melting points and boiling points suggesting strong bonds between the atoms. Although the strength of metallic tends to be less than that of ionic and covalent bonds, the close packing of atoms in metal crystals leads towards relatively high melting points in many cases. When a substance melts, some of the attractive forces holding the particles together are broken or loosened so that the particles can move freely around each other but are still close together. Pure, crystalline solids have a characteristic melting point. Melting point temperatures for common pure metals range from 249 to 1649 °Celsius. The chemical element with the highest melting point is tungsten, at 3410 °Celsius making it excellent for use as filaments in light bulbs. Unlike pure metals, most alloys do not have a single melting point, but a melting range in which the material is a mixture of a solid and liquid phase.

As one of the main physical properties, melting point indicates essential information for the mechanical or thermal properties of a material as well. For example, a material with a high melting point tends to have a high elastic modulus value but a low coefficient of thermal expansion since the energy required to separate the atoms of this material should be relatively high. Accordingly, in the pure metals example, metal A most likely have the highest melting point temperature compare metal B and metal C.



APPENDIX K  
GRAPHS, FIGURES AND ACTIVITY SHEET

Figure 1- Modulus

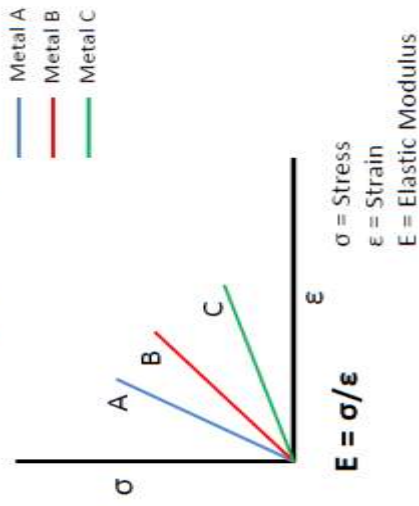


Figure 2- Bond Energy

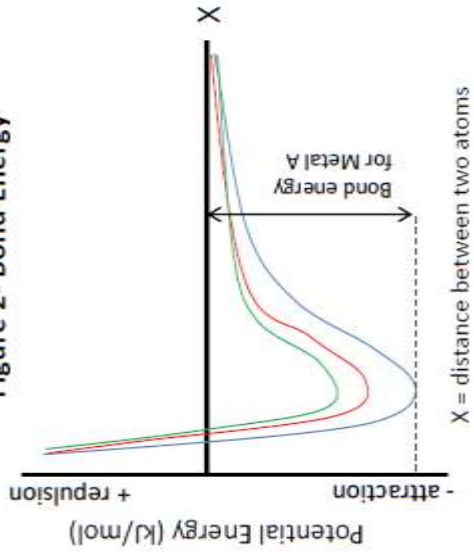


Figure 3 - Expansion

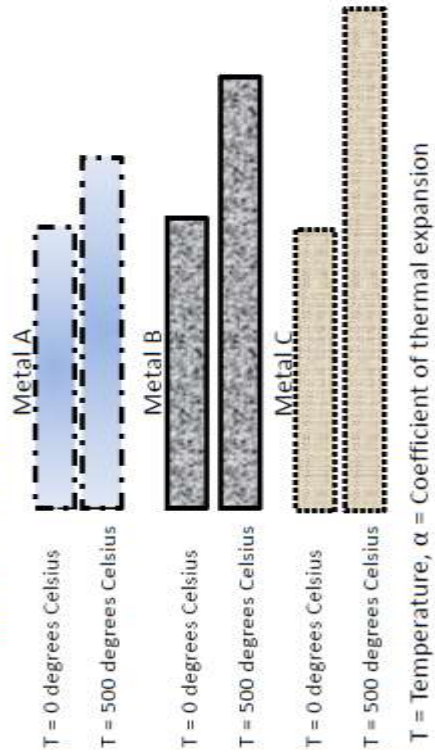
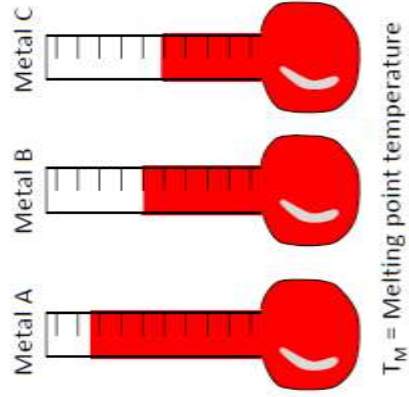


Figure 4- Melting Points



Name: \_\_\_\_\_

Characteristics of three pure metals, metal A, metal B and metal C, are pictured on four figures. Please answer the following questions based on the given information from these figures.

1) What characteristics/properties is shown in each figure? What information does each figure provide?

Figure 1:

Figure 2:

Figure 3:

Figure 4:

2) Compare the values for metal A, metal B, and metal C from each figure by using *equal to* (=), *greater than* (>), or *less than* (<) signs. Also, explain your reasoning for each comparison.

▪  $E_A$  \_\_\_\_\_  $E_B$  \_\_\_\_\_  $E_C$

Explanation:

▪ Bond Energy  $_A$  \_\_\_\_\_ Bond Energy  $_B$  \_\_\_\_\_ Bond Energy  $_C$

Explanation:

▪  $\alpha_A$  \_\_\_\_\_  $\alpha_B$  \_\_\_\_\_  $\alpha_C$

Explanation:

▪  $T_{M,A}$  \_\_\_\_\_  $T_{M,B}$  \_\_\_\_\_  $T_{M,C}$

Explanation:

3) What kind of relations do exist between these characteristics/properties based on the figures? Come up with a *rule* that explains all the relations between three metals in these figures.

4) How do modulus, bonding energy, coefficient of thermal expansion and melting point affect *bond strength*? Explain your reasoning?

Material	Coefficient of Thermal Expansion ( $10^{-6} (^{\circ}\text{C})^{-1}$ )	Melting Point Temperature (K)
Iron (Fe)	11.1	1811
Aluminum (Al)	23	933.47
Copper (Cu)	17	1357.77
Lead (Pb)	29	600.61
Tungsten (W)	4.5	3695

- 5) Table above contains linear coefficient of thermal expansions and melting point temperatures for iron, aluminum, copper, lead, and tungsten at room temperature. Based on the given information, select two possible sets of metals that can fit all the figures in place of metal A, metal B, metal C.

Set 1: Metal A \_\_\_\_\_, Metal B \_\_\_\_\_, Metal C \_\_\_\_\_

Explain your reasoning:

Set 2: Metal A \_\_\_\_\_, Metal B \_\_\_\_\_, Metal C \_\_\_\_\_

Explain your reasoning:

APPENDIX L  
PRETEST FOR STUDY 2

**Test I**

Name: \_\_\_\_\_

Date: \_\_\_\_\_

1. If atomic bond strength in metal A is weaker than metal B, then metal A has:
- a) lower thermal expansion coefficient
  - b) lower melting point temperature
  - c) lower brittleness
  - d) lower electrical conductivity
  - e) lower specific heat

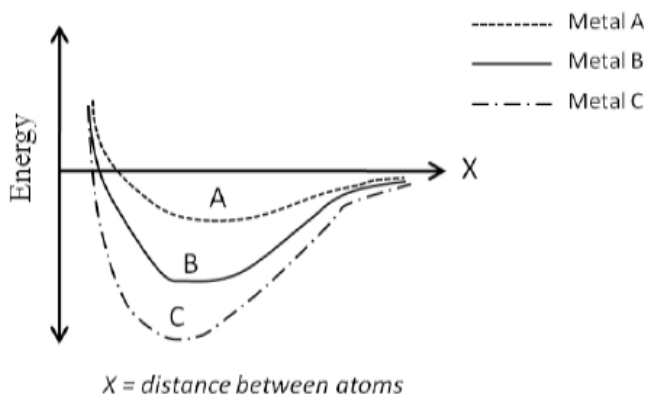
A student makes some observations about four solids and summarizes the results in the table below.

	Mass	Melting Point	Color
<b>Solid 1</b>	3.6 g	776 °C	White
<b>Solid 2</b>	9.8 g	445 °C	White
<b>Solid 3</b>	9.8 g	445 °C	White
<b>Solid 4</b>	9.8 g	776 °C	White

Please answer the questions **2-5** based on the table above. Carefully read each of the following statements. If the statement is true, circle "T". If the statement is false, circle the "F".

2. T F Solids 1 and 4 could be same substance.  
Explain why?
3. T F Solids 2 and 4 could be same substance.  
Explain why?
4. T F Solids 2 and 3 could be same substance.  
Explain why?
5. T F Solids 2, 3 and 4 could be same substance.  
Explain why?
6. What macroscopic properties are affected by the atomic bond strength of a pure material?

Use the following graph to answer questions 7-11.



Carefully read each of the following statements. If the statement is true, circle "T". If the statement is false, circle the "F".

7.    T   F            Metal A could have the highest freezing point temperature.  
      **Explain why?**
  
8.    T   F            Metal C could have the greatest elastic modulus value.  
      **Explain why?**
  
9.    T   F            Metal A could have the highest coefficient of thermal expansion.  
      **Explain why?**
  
10.   T   F            Metal A could have greater bonding energy than metal B.  
      **Explain why?**
  
11.   Based on the given figure above, which one of the following relations best describes the relative bond strengths of Metals A, B and C?
  - a) Bond strength<sub>A</sub> > Bond strength<sub>B</sub> > Bond strength<sub>C</sub>
  - b) Bond strength<sub>A</sub> < Bond strength<sub>B</sub> < Bond strength<sub>C</sub>
  - c) Bond strength<sub>A</sub> = Bond strength<sub>B</sub> = Bond strength<sub>C</sub>
  - d) Bond strength<sub>A</sub> = Bond strength<sub>B</sub> > Bond strength<sub>C</sub>
  - e) Bond strength<sub>A</sub> < Bond strength<sub>B</sub> = Bond strength<sub>C</sub>

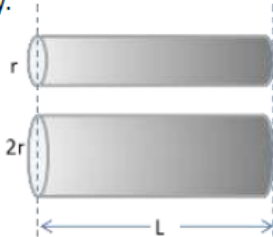
Use the following information to answer questions 12-15.

Suppose two metal rods, made of metal X and metal Y, have same length  $L_0$  at some initial temperature  $T_0$ . When the temperature changes by  $\Delta T$ , the length of metal rods change by  $\Delta L_x$  and  $\Delta L_y$ , respectively, and the  $\Delta L_x$  is greater than  $\Delta L_y$ .

Carefully read each of the following statements. If the statement is true, circle "T". If the statement is false, circle the "F".

12. T F Metal X could have greater bulk modulus value than metal Y.  
Explain why?
13. T F Metal X could have greater boiling point temperature than metal Y.  
Explain why?
14. T F Metal X could have greater coefficient of thermal expansion than metal Y.  
Explain why?
15. T F Metal X could have greater bonding energy than metal Y.  
Explain why?

16. The figure below shows two cylindrical metal rods made of the same material with diameters of  $r$  and  $2r$ , respectively.

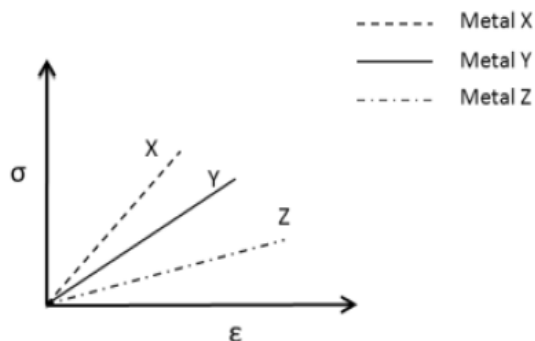


These two metal rods are at the same length ( $L$ ) when the temperature is equal to  $50^\circ\text{C}$ . If we increase the temperature to  $100^\circ\text{C}$ , which of the following measures would be equal for both of the metal rods:

- I. **Density**
  - II. **Final length**
  - III. **Coefficient of thermal expansion**
- a) Only I  
b) I and II  
c) II and III  
d) Only III  
e) I, II and III



Use the following graph to answer questions 17-20.



Carefully read each of the following statements. If the statement is true, circle "T". If the statement is false, circle the "F".

17. T F Elastic modulus for metal X is lower than metal Z  
Explain why?
  
18. T F Melting point for metal Y is greater than metal Z.  
Explain why?
  
19. T F Coefficient of thermal expansion for metal Y is lower than metal Z.  
Explain why?
  
20. Based on the given graph above, which one of the following relations best describes the relative bond strengths of Metal X, Y and Z?
  - a) Bond strength<sub>X</sub> < Bond strength<sub>Y</sub> < Bond strength<sub>Z</sub>
  - b) Bond strength<sub>X</sub> = Bond strength<sub>Y</sub> < Bond strength<sub>Z</sub>
  - c) Bond strength<sub>X</sub> = Bond strength<sub>Y</sub> = Bond strength<sub>Z</sub>
  - d) Bond strength<sub>X</sub> > Bond strength<sub>Y</sub> = Bond strength<sub>Z</sub>
  - e) Bond strength<sub>X</sub> > Bond strength<sub>Y</sub> > Bond strength<sub>Z</sub>
  
21. A tight aluminum metal lid on a glass jar of pickles may loosen when it has been held in hot water. This is because the hot water causes the
  - a) Metal lid to expand more than the glass jar expands
  - b) Glass jar to expand more than the metal lid expands
  - c) Metal lid to contract
  - d) Glass jar to contract
  - e) Glass jar to contract more than the metal lid contracts

Use the following table to answer questions 22-24.

The table contains bonding energies for Nickel, Magnesium and Molybdenum elements.

<u>Substance</u>	<u>Bonding Energy</u>
Nickel (Ni)	394 kJ/mol
Magnesium (Mg)	148 kJ/mol
Molybdenum (Mo)	600 kJ/mol

22. Based on the table above, which of the following would be the best option for the melting point temperatures of Nickel, Magnesium and Molybdenum elements?

	<u>Nickel (Ni)</u>	<u>Magnesium (Mg)</u>	<u>Molybdenum (Mo)</u>
a)	923 K	2896 K	1728 K
b)	923 K	1728 K	2896 K
c)	1728 K	923 K	2896 K
d)	1728 K	2896 K	923 K
e)	2896 K	923 K	1728 K

23. Based on the table above, which of the following would be the best option for the coefficients of thermal expansion of Nickel, Magnesium and Molybdenum elements?

	<u>Nickel (Ni)</u> $10^{-6} (^{\circ}\text{C})^{-1}$	<u>Magnesium (Mg)</u> $10^{-6} (^{\circ}\text{C})^{-1}$	<u>Molybdenum (Mo)</u> $10^{-6} (^{\circ}\text{C})^{-1}$
a)	5	16	9
b)	9	5	16
c)	9	16	5
d)	16	5	9
e)	5	9	16

24. Which one of these three substances could be the most resistant to change in volume in response to a change in temperature? Explain why?

APPENDIX M  
POSTTEST FOR STUDY 2

**Test II**

Name: \_\_\_\_\_

Date: \_\_\_\_\_

1. If atomic bond strength in metal A is weaker than metal B, then metal A has:
- a) lower thermal expansion coefficient
  - b) lower melting point temperature
  - c) lower brittleness
  - d) lower electrical conductivity
  - e) lower specific heat

A student makes some observations about four solids and summarizes the results in the table below.

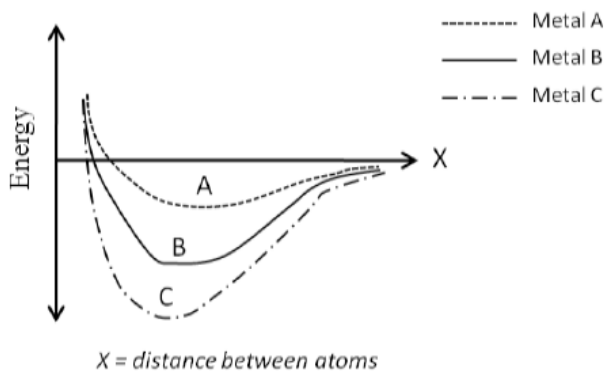
	Mass	Melting Point	Color
Solid 1	3.6 g	776 °C	White
Solid 2	9.8 g	445 °C	White
Solid 3	9.8 g	445 °C	White
Solid 4	9.8 g	776 °C	White

Please answer the questions 2-6 based on the table above. Carefully read each of the following statements. If the statement is true, circle "T". If the statement is false, circle the "F".

2. T F Solids 1 and 4 could be same substance.  
Explain why?
3. T F Solids 2 and 4 could be same substance.  
Explain why?
4. T F Solids 2 and 3 could be same substance.  
Explain why?
5. T F Solids 2, 3 and 4 could be same substance.  
Explain why?
6. Which one of the following macroscopic properties is NOT strongly related to bond strength?
- a) Melting Point Temperature
  - b) Elastic Modulus
  - c) Heat Capacity
  - d) Coefficient of Thermal Expansion
  - e) Shear Modulus

7. A tight aluminum metal lid on a glass jar of pickles may loosen when it has been held in hot water. This is because the hot water causes the
- Metal lid to expand more than the glass jar expands
  - Glass jar to expand more than the metal lid expands
  - Metal lid to contract
  - Glass jar to contract
  - Glass jar to contract more than the metal lid contracts

Use the following graph to answer questions 8-12.



Carefully read each of the following statements. If the statement is true, circle "T". If the statement is false, circle the "F".

- T F** Metal A could have the highest freezing point temperature.  
**Explain why?**
- T F** Metal C could have the greatest elastic modulus value.  
**Explain why?**
- T F** Metal A could have the highest coefficient of thermal expansion.  
**Explain why?**
- T F** Metal A could have greater bonding energy than metal B.  
**Explain why?**
- Based on the given figure above, which one of the following relations best describes the relative bond strengths of Metals A, B and C?

  - Bond strength<sub>A</sub> > Bond strength<sub>B</sub> > Bond strength<sub>C</sub>
  - Bond strength<sub>A</sub> < Bond strength<sub>B</sub> < Bond strength<sub>C</sub>
  - Bond strength<sub>A</sub> = Bond strength<sub>B</sub> = Bond strength<sub>C</sub>
  - Bond strength<sub>A</sub> = Bond strength<sub>B</sub> > Bond strength<sub>C</sub>
  - Bond strength<sub>A</sub> < Bond strength<sub>B</sub> = Bond strength<sub>C</sub>

*Use the following information to answer questions 13-16.*

Suppose two metal rods, made of metal X and metal Y, have same length  $L_0$  at some initial temperature  $T_0$ . When the temperature changes by  $\Delta T$ , the length of metal rods change by  $\Delta L_x$  and  $\Delta L_y$ , respectively, and the  $\Delta L_x$  is greater than  $\Delta L_y$ .

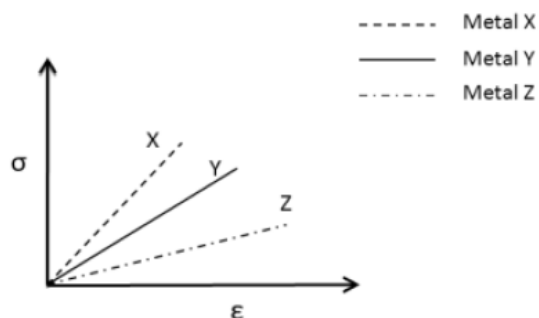
*Carefully read each of the following statements. If the statement is true, circle "T". If the statement is false, circle the "F".*

13. T F Metal X could have greater bulk modulus value than metal Y.  
Explain why?
14. T F Metal X could have greater boiling point temperature than metal Y.  
Explain why?
15. T F Metal X could have greater coefficient of thermal expansion than metal Y.  
Explain why?
16. T F Metal X could have greater bonding energy than metal Y.  
Explain why?

17. What macroscopic properties are affected by the atomic bond strength of a pure material?

18. As a new engineer for General Motors, you have been assigned to design brass pistons to slide into steel cylinders. The engines in which these pistons will be used will operate between 10.0 °C and 180.0 °C. If the piston just fits inside the chamber at 10.0 °C, will the engines be able to run at higher temperatures? Explain.

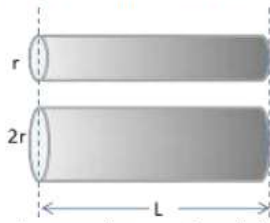
Use the following graph to answer questions 19-23.



Carefully read each of the following statements. If the statement is true, circle "T". If the statement is false, circle the "F".

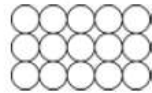
19.    **T F** Density for metal X is greater than metal Y  
       **Explain why?**
  
20.    **T F** Elastic modulus for metal X is lower than metal Z  
       **Explain why?**
  
21.    **T F** Coefficient of thermal expansion for metal Y is lower than metal Z.  
       **Explain why?**
  
22.    **T F** Melting point for metal Y is greater than metal Z.  
       **Explain why?**
  
23.    Based on the given graph above, which one of the following relations best describes the relative bond strengths of Metal X, Y and Z?
  - a)    Bond strength<sub>X</sub> < Bond strength<sub>Y</sub> < Bond strength<sub>Z</sub>
  - b)    Bond strength<sub>X</sub> = Bond strength<sub>Y</sub> < Bond strength<sub>Z</sub>
  - c)    Bond strength<sub>X</sub> = Bond strength<sub>Y</sub> = Bond strength<sub>Z</sub>
  - d)    Bond strength<sub>X</sub> > Bond strength<sub>Y</sub> = Bond strength<sub>Z</sub>
  - e)    Bond strength<sub>X</sub> > Bond strength<sub>Y</sub> > Bond strength<sub>Z</sub>
  
24.    If atomic bond strength in Copper is stronger than Aluminum, then Copper has:
  - a)    lower elastic modulus
  - b)    lower atomic mass
  - c)    lower bulk modulus
  - d)    lower thermal expansion coefficient
  - e)    lower melting point temperature

25. The figure below shows two cylindrical metal rods made of the same material with diameters of  $r$  and  $2r$ , respectively.



These two metal rods are at the same length ( $L$ ) when the temperature is equal to  $50\text{ }^{\circ}\text{C}$ . If we increase the temperature to  $100\text{ }^{\circ}\text{C}$ , which of the following measures would be equal for both of the metal rods:

- I. **Density**
  - II. **Final length**
  - III. **Coefficient of thermal expansion**
- a) Only I  
 b) I and II  
 c) II and III  
 d) Only III  
 e) I, II and III
26. The diagram represents the arrangement of particles in a metal before it has been heated.



Which diagram represents the arrangement of particles in the metal after it has been heated?

- a)
- b)
- c)
- d)
- e)



Use the following table to answer questions 27-30.

The table contains bonding energies for Nickel, Magnesium and Molybdenum elements.

<u>Substance</u>	<u>Bonding Energy</u>
Nickel (Ni)	394 kJ/mol
Magnesium (Mg)	148 kJ/mol
Molybdenum (Mo)	600 kJ/mol

27. Based on the table above, which of the following would be the best option for the melting point temperatures of Nickel, Magnesium and Molybdenum elements?

	<u>Nickel (Ni)</u>	<u>Magnesium (Mg)</u>	<u>Molybdenum (Mo)</u>
a)	923 K	2896 K	1728 K
b)	923 K	1728 K	2896 K
c)	1728 K	923 K	2896 K
d)	1728 K	2896 K	923 K
e)	2896 K	923 K	1728 K

28. Based on the table above, which of the following would be the best option for the coefficients of thermal expansion of Nickel, Magnesium and Molybdenum elements?

	<u>Nickel (Ni)</u> $10^{-6} (^{\circ}\text{C})^{-1}$	<u>Magnesium (Mg)</u> $10^{-6} (^{\circ}\text{C})^{-1}$	<u>Molybdenum (Mo)</u> $10^{-6} (^{\circ}\text{C})^{-1}$
a)	5	16	9
b)	9	5	16
c)	9	16	5
d)	16	5	9
e)	5	9	16

29. Based on the table above, which of the following would be the best option for the elastic modulus values of Nickel, Magnesium and Molybdenum elements?

	<u>Nickel (Ni)</u>	<u>Magnesium (Mg)</u>	<u>Molybdenum (Mo)</u>
a)	200 GPa	45 GPa	329 GPa
b)	45 GPa	329 GPa	200 GPa
c)	329 GPa	45 GPa	200 GPa
d)	200 GPa	329 GPa	45 GPa
e)	329 GPa	200 GPa	45 GPa

30. Which one of these three substances could be the most resistant to change in volume in response to a change in temperature? Explain why?

## BIOGRAPHICAL SKETCH

Muhsin Menekse was born on 1982 in Gaziantep, Turkey. He completed his Bachelor of Science (BS) and Master of Science (MS) in Teaching Physics in 2006 at Bogazici University and listed in Dean's honor list. After completing his BS and MS degrees, he was accepted to pursue a doctoral degree in the Science Education Program at Arizona State University (ASU). During his time at the graduate school, he has worked as a graduate research assistant for numerous research projects that were funded by National Science Foundation and Spencer Foundation. He had research experiences in the areas of conceptual change of naïve ideas about science, argumentation in computer supported learning environments, video game design to support students' understanding of Newtonian mechanics, and designing and developing activities and learning materials for effective classroom instruction. In addition to his skills and experiences in learning sciences, Muhsin has a solid background of measurement theory and educational statistics. He has skills for the development and evaluation of techniques for the measurement of educational outcomes, and the design and interpretation of statistical methods for analyzing research data.