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A Tutorial Design Process Applied to an Introductory Materials Engineering Course

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ABSTRACT

We apply a "tutorial design process", which has proven to be successful for a number of physics topics, to design curricular materials or "tutorials" aimed at improving student understanding of important concepts in a university-level introductory materials science and engineering course. The process involves the identification of instructional goals, the identification of specific student difficulties, the iterative design of interactive tutorials, the implementation of interactive group-work recitations, and assessment. The project, which involved over 1000 students, included extensive interviewing, testing, and iterative classroom implementation over a period of three years. Here we report on some of the identified student difficulties, several of the tutorials designed to address the difficulties, and the results of the implementation. The project has yielded 9 field-tested 48 minute tutorials in which students work together in small groups on the tutorials in the presence of teaching assistants who assess and facilitate student progress. To determine the learning outcome, we analyzed final exam scores and found that, even accounting for the fact that slightly "better" students tended to attend recitations more often, there was a significant valued-added effect of the recitations on final exam performance. These results suggest that these recitation methods and materials are effective in teaching students the difficult and important conceptual materials which they were designed to address. Furthermore, since this process was initially designed for physics courses yet is also successful for an engineering course, this implies that this process may be successful for a wide range of STEM courses.

Key Words: Conceptual difficulties, Graphs and diagrams, Group-work, Materials Science, Tutorials

INTRODUCTION

In the area of physics education, an iterative process of design and implementation of instructional units called "tutorials" has been shown to be very effective in improving student understanding of a wide variety of physics topics. In this paper, we describe the application of a version of this highly successful process to a university-level introductory materials science and engineering course. We begin with a brief general description of the tutorial design process. Following this, the remainder of the paper consists of a description of our application of this process in a multi-year project to design, implement and assess of the effectiveness of tutorials for an introductory course in materials science and engineering.

TUTORIALS AND THE TUTORIAL DESIGN PROCESS

The process of curricular and instructional development which we will refer to as the *tutorial design process* was first developed and implemented over 20 years ago by the University of Washington's Physics Education Research group, led by Lillian McDermott (McDermott et al., 2002; McDermott 1991; Shaffer & McDermott, 1992). It has been applied to numerous topics in Physics including electric circuits (Shaffer & McDermott, 1992), force and motion (e.g., McDermott, Shaffer, & Somers, 1994; Shaffer & McDermott, 2005; Heron et al., 2003), intermediate mechanics, (Ambrose, 2004), geometric optics, (Wosilait et al., 1998), interference and diffraction of light, (Wosilait et al., 1999), pressure, (Loverude, Heron & Kautz, 2010), sound (Wittmann, Steinberg & Redish, 2003), quantum mechanics (Singh, 2008; Wittmann, Morgan & Bao, 2005; Bao & Redish, 2002), and special relativity (Scherr, Shaffer & Vokos, 2002). These studies have also demonstrated that the implementation in the classroom has resulted in significant, consistent gains in conceptual understanding, reasoning and simple problem solving. Based on much of this research, several groups have published tutorial workbooks for introductory physics (McDermott et al., 2002; Wittmann, Steinberg & Redish, 2005). A large and comprehensive study has demonstrated that application of the tutorial method in introductory mechanics (using the workbook of McDermott et al., 2002) results in consistent gains for instructors with a variety of backgrounds and experience (Pollock & Finkelstein, 2008). Finkelstein and Pollock (2005) have also identified and investigated key conditions of implementation.

Development of Tutorial Materials and Methods

The development of tutorial materials and methods is an iterative and often parallel rather than serial process consisting of four tasks, outlined in Table 1. The outline of the development of tutorial materials and methods is simple and straightforward, however, several of the tasks often require significant time and effort, and there is significant overlap among tasks. The outline describes key features of the tutorial design process and is based on the work mentioned above and summarized in articles such as McDermott (1991) and McDermott (2001).

The first task is to identify a target content topic and instructional goals. Prevalent and widely accepted goals for standard introductory courses can be identified, for example, via interviews of course instructors and analysis of the syllabus and textbooks. It should be noted that tutorials usually focus on conceptual understanding and scientific reasoning rather than, for example quantitative problem solving or memorization.

The second task is to identify and characterize *specific* student difficulties with the target topic. This task is considered a fundamental component of the tutorial design process, and typically involves student interviews and testing over a period of a year or more. This task is critical for providing specific and useful information for the iterative development of materials, methods and assessments. Furthermore, the careful identification of specific student difficulties often results in a modification of instructional goals.

The third task is to construct specific material and methods aimed at addressing student difficulties. The typical strategy is to present questions that will reliably elicit specific student difficulties, engage the students in confronting the difficulty, and providing activities and exercises that help them to resolve the difficulty. It is common to use multiple representations including graphs, diagrams, equations, and an emphasis on clear, logical explanations. The exercises often stem from the interview questions posed to students in the previous task to discover student difficulties.

The fourth task is field testing and assessment of effectiveness. Field testing typically requires several iterations of material and methods revisions over several semesters. Assessment of the

Task	Resources
1. Identification of target content topic and instructional goals	Instructor interviews, syllabus, and textbook.
2. Identification and characterization of student difficulties with target topic.	Student interviews, instructor interviews, test performance, existing Education Research.
3. Construction of interactive small-group tasks aimed at the instructional goals and addressing specific student difficulties.	Findings from Task 2, findings from education research, existing materials from instructors, textbooks.
4. Field-testing and assessment of effectiveness.	Test and homework performance, in-class interaction, feedback from TA's and course instructors

Table 1. Outline of the iterative development of tutorial materials and methods.

effectiveness typically emerges as part of the process of instructor/teaching assistant (TA) feedback and construction of key questions and problems that diagnose student understanding. A

distinct advantage of this process is that the materials are empirically tested in classrooms so they are known to function in a real classroom environment.

Implementation of Tutorials

The development and the implementation of tutorials are closely related, since the development includes several iterations of implementation. However, there are a number of important issues and factors in implementation that are separate from development of materials and methods. Finkelstein and Pollock (2005) discuss critical features of implementation at several levels, including at the level of the task, the classroom environment, the course structure and the support at the departmental and university level. Here we will briefly describe some of the key conditions of implementation, as outlined in Table 2. The extent to which each condition alone is important has not been rigorously investigated. However, the conditions described here are common to most tutorial implementations that have demonstrated success in student learning. The first condition is the use of well-developed tutorial materials, using the tutorial design process described above.

The second and third conditions describe the format of the tutorial class activity. Students are placed in groups of 3 or 4, and they actively participate in the tutorial activity. The TA's facilitate student participation and elicit more complete and correct student explanations by asking the students well-posed questions that respond to the immediate student difficulties. The role of the TA is not to provide explanations, but to have *students* provide explanations.

The fourth condition is TA preparation. There are two components to this. First, the TA's must learn the skills of facilitating student explanations and handling the group-work environment. Second, the TAs must be fully prepared for the specific issues of each week's tutorial. Particularly, the TAs must be aware of common, specific student difficulties that will arise that week and be prepared with key questions that can help students to progress.

1. Well-developed tutorial tasks which challenge students, illicit difficulties, and provide pathways for resolution.
2. Class is structured in group-work, active participation format.
3. TA's continually emphasize and facilitate complete explanations *from students*. TA's do not simply give explanations and answers.
4. TA's are prepared weekly for specific student difficulties that go with each tutorial and general skills in group facilitation.
5. Tutorial material is explicitly tested on course exams.

Table 2. Critical conditions for tutorial implementation.

Finally the fifth condition is to support the importance of the tutorial material by placing questions on exams that are explicitly based on tutorial materials.

Relevant previous work in material science engineering

Several previous studies have identified and described a number of student difficulties with concepts in introductory materials science (Krause, Decker & Griffin, 2003; Krause, Tasooji & Griffin, 2004; Kitto 2008; Krause et al, 2010). In addition, a "Materials Concept Inventory" has been developed to assess a very basic conceptual understanding for some of the topics in materials science (Krause, Decker & Griffin, 2003; Krause et al., 2010a). Krause and collaborators (Krause et al., 2010b) have also categorized some materials science "misconceptions" and investigated how different methods of instruction affect these categories of misconceptions. They found that interactive concept sketching activities were the most effective at raising scores on the Materials Concept Inventory, followed by interactive concept card sorting activities, interactive discussions and passive lecture (in order of decreasing effectiveness).

In this study, we have used some of the these previous findings on student difficulties as a starting point to characterize and investigate in more detail identified difficulties as well as investigate a wide range of additional student difficulties with basic materials science concepts. Therefore some of the information from previous studies about student difficulties has in a sense become a part of the tutorial design process.

In this paper we use the term student difficulty instead of the term misconception. This is done because much of the literature uses the term misconception to mean an elaborate and coherent student belief. Here we are usually measuring and defining an area of difficulty as difficulty correctly answering test like conceptual questions. We therefore have made an effort to avoid the term misconception. Some of the student difficulties we report are most likely misconceptions and some are most likely not.

APPLICATION TO AN INTRODUCTORY MATERIALS SCIENCE COURSE

In the remainder of this paper we will describe the application of the tutorial design process to an introductory materials science and engineering course. This includes iterative designing and field-testing tutorial materials and methods, implementing tutorials in the classroom, and assessing the effectiveness. We begin with a description of the identification of the instructional goals of the course, and we also present important information regarding the general aspects of the design and implementation of the tutorials as well as data accumulation methods.

Initial Exploration of Course Goals

The course is a standard course in introductory materials science and engineering at the college level. The course is required by many engineering majors at Ohio State University. The topics covered are well-represented by the textbook of the course, which is the common textbook by Callister (2007).

At the beginning of the project, we interviewed 5 faculty who had recently taught the course and asked them what they saw as the goals of instruction of the course. Perhaps as to be expected, there were common themes to the responses. First, specific topics were mentioned, such as material properties, diffusion, defects, fatigue etc. – topics that were usually chapters in the text. Second, the instructors also described more general goals, and we found five general goals commonly stated. The goals are listed in Table 3.

The overwhelming message from the instructors was that basic conceptual understanding of basic materials science ideas was the most important goal. This goal lends itself well to the tutorial design process, which is typically aimed at conceptual understanding and basic reasoning. Therefore the content topics chosen for the tutorials were closely aligned with lecture topics and chapters in the textbook and we focused on conceptual understanding, keeping in mind the general goals in Table 3.

Recitation Format

The course consisted of three lecture and one recitation class per week. Recitations were 48 minutes in duration, and recitation attendance was voluntary. The number of the students per class varied but was on average 20 to 25 students. A senior experienced instructor, usually a faculty member, and two teaching assistants, typically graduate or undergraduate students, were present for each recitation. Students worked in groups of 3 or 4 to complete the tutorials and instructors circulated to answer questions, ask questions of the groups, and in general facilitate the activities. About 37% percent of students typically attended recitations, or every student attends on

1. Understanding of basic definitions, e.g., yield strength.
2. Basic understanding of major concepts, e.g., fatigue, diffusion.
3. Basic understanding of the relation between structure, processing, and properties.
4. Conceptual intuition for basic properties of common materials and material classes.
5. Basic conceptual understanding of material selection, e.g. necessity of tradeoffs.
6.* Ability to interpret and use basic materials science graphs and diagrams

Note. The sixth goal was identified in the course of this study, as a result of discovering pervasive student difficulties with graphs and diagrams.

Table 3. General goals of the introductory materials science course identified by instructors

average 3.4 recitations out of nine total. This attendance rate is similar to the attendance rate of the traditional recitations used before the tutorials, which typically consisted of mini-lectures and discussion of solutions to homework problems. Therefore the tutorials themselves did not appear to significantly affect attendance. Data from the most recent quarter of tutorial implementation had an attendance of 62% or about every student going to 5 recitations out of the eight available that quarter. This suggests that the tutorials *might* have a small, positive effect on attendance. However, other factors such as instructor encouragement, student population, etc. might have contributed to and/or be the cause for this increase.

The Importance of TAs to Facilitate the Tutorials

Instructor preparation for the tutorials is a critical component of the implementation. While the tutorials consist of carefully constructed questions, they are designed to be complemented by questions and dialog between the students and the teaching assistants (TAs). Every week the TAs have an hour long training session in which they discuss the correct answers to the tutorials, difficulties they can expect students to have, how to assess what difficulties the students are having, and how to guide students to overcome their difficulties by asking thoughtful and responsive questions instead of simply telling the student the correct answer. As a result of TA training, the TAs are prepared for potential issue and have prepared ways to help students. Effective dialog between the students and TAs is critical for the tutorials to be successful and preparation of methods to overcome known common difficulties is an important part of effective dialog.

Participants and Data Collection Methods

Data was collected in this study in order to (a) identify and characterize specific student difficulties and (b) implement tutorials and assess student learning from the tutorials. In this section we describe details of the participants and how the data was collected.

The participants in this study were enrolled in the introductory materials science course for engineers, which is a required core course for many of the engineering major programs at The Ohio State University, a large public research university. The students ranged from 1st to 5th-year engineering students. About 10-15% of the students intended on becoming materials science engineering majors, and about 35% of the students were mechanical engineering majors, the most common major in the course.

Data was collected over a period of 7 quarters, for a total of approximately 1000 participants. The data was collected in five ways. First, we conducted individual or group interviews on over 200 students. These interviews consisted of asking a wide range of open ended and multiple choice questions, such as those presented in this paper. Several dozen interviews were videotaped, and the rest were recorded via interview notes. The interviews were used to first explore areas of difficulty, then to focus on specific difficulties identified in the initial interviews and free response tests. Most interviews were conducted individually, but some were given in groups of 3 or 4.

The second method of data collection was via free response and multiple choice tests. In addition to the standard homework, students were given a "flexible homework" assignment with credit for participation as part of the course grade. The flexible homework assignment consisted of participation in a one-hour session where students completed some combination of testing and interviewing. Throughout the quarter, students were randomly selected to participate in the flexible homework. Typically, about 95% of students participated in the flexible homework. The tests items were in either multiple-choice, free-response, or a multiple-choice-with-explanation format. Students completed the material at their own pace at individual stations in a quiet room. Afterwards we would informally ask students whether they had any questions and/or to explain their answers. We observed during these sessions that students made a good faith effort to answer the questions to the best of their ability.

The third method for collecting data was again via flexible homework. However, the sessions were conducted in a more regular classroom environment during the 7, 8 or 9th week of the quarter only. Students were given 30 to 35 minutes to complete a set of about 30 multiple choice items. (Students were aware that their score on the "quiz" would not affect their course grade, but again we observed the majority of students making a good faith effort to answer the questions.) Students were then asked to spend approximately 10 minutes discussing the correct answers to the items in small groups with TA assistance which allowed for some informal interview data on the validity of the multiple choice items.

The fourth method for collecting data was via observations of small group work and collected tutorial responses in recitations. The authors participated in some of the recitations which were conducted in small group format. This method was used to further verify and/or clarify student difficulties found via interviews and tests, to evaluate student understanding and interaction with the tutorial questions, and to assess student ability to correctly complete the tutorial questions.

Finally, the fifth method for collecting data was via the official exams administered as part of the course. The exams were in multiple choice format, and some of the items (about 10-20%) were designed by us in collaboration with the instructor. This method helped to assure that student answering was not simply an artifact of the testing context, i.e., whether performance would dramatically improve for high–stakes testing contexts.

Most tests and interviews were at least one week *after* the relevant instruction, however some were administered before relevant instruction. The data reported here is all post instruction.

Most of the difficulties reported here were first found in interviews. We subsequently devised questions to demonstrate the relative frequency of these difficulties in the student population. Thus incorrect answers to the questions should not be viewed as uninteresting artifacts of the particular questions, but rather indicative of student difficulties with understanding the materials science concepts underlying the questions, or possibly, as in the case with questions in graph or diagram format, some of the difficulty arises from the format itself.

Iterative Construction of the Tutorial Materials

The writing of tutorial materials began after the initial identification of course goals and student difficulties with specific topics. In collaboration with the instructor, high-priority student difficulties were chosen for the tutorials among the many student difficulties discovered in the initial interviews and testing. An initial version of the tutorials was drafted based on interview and test questions used in the initial difficulty-identification stage. One quarter (i.e. course term) of small mock recitation sections (with students attending as part of a homework assignment) was used to field-test the first version of the tutorials. Feedback from the written material produced by the students and comments from the instructors implementing the sections was used to improve on the materials. After this, the tutorials were implemented in the regular recitation sections for three quarters. For each quarter, were redesigned based on in-class observations, assessments of submitted group responses to the activities, instructor feedback, and assessments of the tutorial's effectiveness based on exam scores.

Quarter	Number of Students	Description of Experiments done
Sp 2008 &Au 2008	N ≈ 45 & N ≈ 45	Exploratory interviews and testing data collected via student volunteers.
Wi 2009	N ≈ 150	Pilot Testing of Tutorial activities with Mechanical Properties during special 48 minute homework sessions held in our lab, i.e. "flex homework".
Au 2009	N ≈ 175	Tutorials used in weekly recitations. Questions pertaining to recitation were given on exams. Short answer and multiple choice data on student difficulties collected in 48 minute homework sessions held in our lab, i.e. "flex homework".
Sp 2010	N ≈ 175	Short answer and multiple choice data on student difficulties collected in 48 minute homework sessions held in our lab, i.e. "flex homework".
Au 2010 &Wi 2011	N ≈ 120 & N ≈ 220	Reworked tutorials used in weekly recitations. Questions pertaining to recitation were given on exams. Multiple choice data on student difficulties collected in 48 minute homework sessions held in our lab, i.e. "flex homework".
Sp 2011	N ≈ 150	No tutorials used in recitations. Questions pertaining to usual recitation material given on final exam. Multiple choice data on student difficulties collected in 48 minute homework sessions held in our lab, i.e. "flex homework".

Table 4. Summary of different data collection methods used and numbers of participants.

The following sections will describe the important student difficulties identified in this study and the tutorials used to address these difficulties for four example topics.

STUDENT DIFFICULTIES AND TUTORIAL MATERIALS: 4 EXAMPLE TOPICS

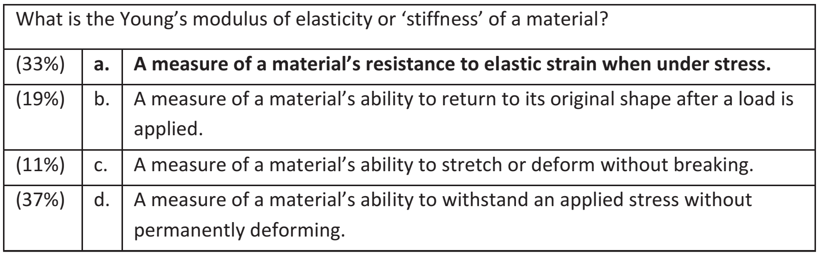
While tutorial topics covered included include the nature of **atomic bonds**, crystal structure, **diffusion**, the **mechanical properties of metals**, stress-strain curves, the effects of processing on properties, failure, **phase diagrams**, phase transitions, TTT plots, properties of ceramics, and properties of polymers, we will only be showing examples from the four tutorials addressing the bolded topics.

Mechanical Properties

Student difficulties with mechanical properties. We have identified two general and inter-related kinds of student difficulties with mechanical properties, which we discuss in this section and the next section (see also Kitto, 2008; Krause et al., 2010; Rosenblatt & Heckler, 2010; Heckler & Rosenblatt, 2011). First, we found that even after instruction students often equated mechanical properties concepts and terms, used them interchangeably, or at very least thought the properties were necessarily correlated or anti-correlated. Perhaps the most prevalent and fundamentally important confusion was between the concepts of material strength and elasticity. Even if some of the students did understand the difference in the definitions, they often believed that the two properties must be correlated. That is, they believed a stiff material must also be strong and vice versa. This is highlighted by the questions in Figure 1 and 2. The first question concerns a conceptual definition of modulus of elasticity. Only one-third of the students answered correctly, with most students confusing the concept of yield strength with elasticity. This question requires a careful reading of the answer choices and is somewhat subtle, yet interviews revealed that student understood the options and chose purposefully.

The next question (Figure 2) is somewhat more straightforward, yet only 13% of the students answered correctly. Approximately 40% of students believed that the material with a higher yield strength will also have a higher tensile strength, which is not unreasonable, and over 40% (the majority) of students answered that the material with a higher yield strength, also has a higher tensile strength and higher modulus of elasticity.

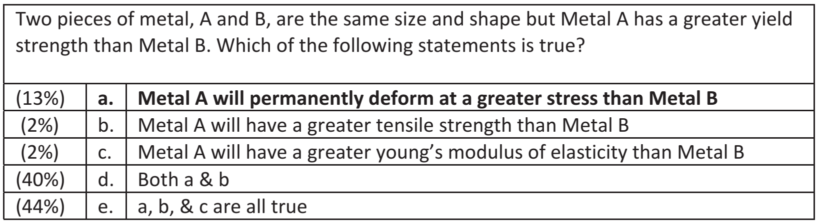
It was also somewhat common for students to believe that there is a strict anti-correlation between yield strength and ductility, namely that a highly ductile material has low strength, as shown in Figure 3.



What is the Young's modulus of elasticity or 'stiffness' of a material?

(33%)	**a.**	**A measure of a material's resistance to elastic strain when under stress.**
(19%)	b.	A measure of a material's ability to return to its original shape after a load is applied.
(11%)	c.	A measure of a material's ability to stretch or deform without breaking.
(37%)	d.	A measure of a material's ability to withstand an applied stress without permanently deforming.

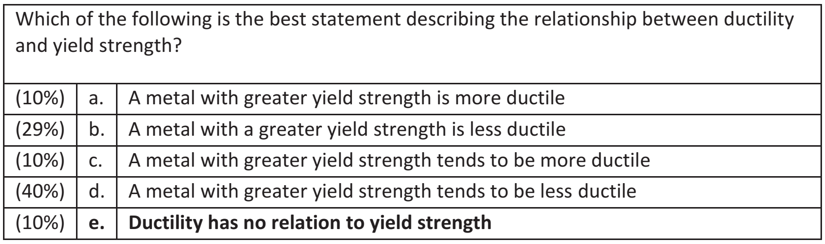
Figure 1. Example question demonstrating student difficulty with the concept of elasticity. Student response percentages in parentheses, and correct answer in bold. (N = 62, SE = 6%)



Two pieces of metal, A and B, are the same size and shape but Metal A has a greater yield strength than Metal B. Which of the following statements is true?

(13%)	**a.**	**Metal A will permanently deform at a greater stress than Metal B**
(2%)	b.	Metal A will have a greater tensile strength than Metal B
(2%)	c.	Metal A will have a greater young's modulus of elasticity than Metal B
(40%)	d.	Both a & b
(44%)	e.	a, b, & c are all true

Figure 2. Example question demonstrating student confusion of the concepts of yield strength, tensile strength and elasticity. Student response percentages in parentheses, and correct answer in bold. (N = 67, SE = 6%.)



Which of the following is the best statement describing the relationship between ductility and yield strength?

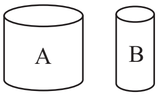
(10%)	a.	A metal with greater yield strength is more ductile
(29%)	b.	A metal with a greater yield strength is less ductile
(10%)	c.	A metal with greater yield strength tends to be more ductile
(40%)	d.	A metal with greater yield strength tends to be less ductile
(10%)	**e.**	**Ductility has no relation to yield strength**

Figure 3. Example question demonstrating student confusion of the concepts of yield strength and ductility. Student response percentages in parentheses, and correct answer in bold. (N = 67, SE = 6%.)

In addition to difficulties with confusion of mechanical properties, we found that students had difficulty with understanding and applying the basic concepts and quantities necessary for defining mechanical properties. One place where this is manifest is in the common incorrect reasoning

The following metal pieces are cut from the same plate. Compare the yield strength of the pieces.

(60%) a. A has a higher yield strength than B
(8%) b. B has a higher yield strength than A
(32%) **c. A and B have the same yield strength**



(A and B have equal heights)

Figure 4. Example question demonstrating difficulty with the definition of yield strength. Student response percentages in parentheses, and correct answer in bold. (N = 114, SE = 4%.)

with questions involving yield strength, force and stress. In particular, students usually associate yield strength with force rather than stress. A dramatic example of this is demonstrated by student post instruction responses to the question in Figure 4. In this simple question, it seems that the majority of students believed that yield strength depended on cross sectional area, or put another way, that yield strength was defined in terms of force rather than force per unit area. In interviews, student responses were consistent with this: we found most incorrect students had considered only that the larger piece could withstand a greater force (rather than stress) without deforming. Furthermore, interviews and classroom observations revealed that many students used the terms force and stress interchangeably. When questioned further, most students did recognize the formal difference between the concepts stress and force. Nonetheless, they often failed to recognize that the two terms must be used carefully.

Difficulties relating stress-strain graphs and mechanical properties. The second kind of student difficulty with mechanical properties was in relating mechanical properties to a stress-strain plot. For example, Figure 5 presents results from a simple question comparing modulus of elasticity of two materials represented in two stress-strain curves. Over half of the students chose the curve that had the higher maximum value, rather than the curve with the steepest linear slope. This explanation that “higher position on graphs means more” was commonly found in interviews, and is similar to findings for kinematic graphs in physics courses (McDermott, Rosenquist & van Zee, 1987). Interestingly, some students thought that since the higher curve also had higher elongation until breaking, this was seen as additional evidence of higher elasticity. This example highlights the fact, as discussed earlier, that many students conflate concepts such as ductility, strength and elasticity, and this difficultly is manifest in (and confounded by) the reading of graphs.

Tutorials for mechanical properties. A portion of the tutorial designed to address difficulties with material properties is shown in Appendix A. The tutorial provides various ways in which to apply and practice definitions and explanations of elastic deformation, Young’s modulus, yield strength, and tensile strength. Special attention is given to terms students frequently confuse such as stiffness and strength or yield and tensile strength, and students were asked to explain the differences

Consider the stress-strain curves of two metals above. Which metal has a higher modulus of elasticity?

(46%) **a. A has a higher modulus**
(54%) b. B has a higher modulus
(0%) c. The modulus of A is equal to that of B

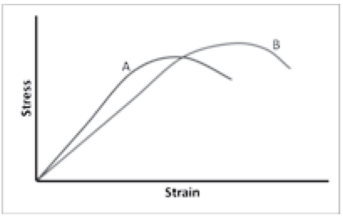


Figure 5. Example question demonstrating difficulty with interpreting stress strain plots. Student response percentages in parentheses, and correct answer in bold. (N = 116, SE = 6%.)

between these terms. Following a technique used in other tutorials (McDermott et al., 2002), The tutorial also provides a set of quotes commonly made by students during interviews. Students are asked to comment on the correctness of the quotes. These “student dialog” questions are designed to demonstrate the necessity of precision in language and raise student awareness of common incorrectly stated definitions or generalizations, such as, “A tougher material is stronger,” or, “A stiffer material is harder to break.”

The mechanical properties tutorial also asks students to apply their mechanical properties definitions to stress-strain plots. This serves several purposes. It gives students experience deriving information from, and plotting information on, graphs which is itself a goal of instruction. It also provides a second way to think about the definitions and thus acts as both a check to students understanding and an additional way for students to distinguish exactly what

parts of their written definitions were of importance. The easily separable dimensions of the graph (i.e. slope, height, peak, and line length) provide a clear visual aid for discussion, as a group or with a TA, of the exact differences in the properties and how one property does not necessarily affect another property.

Diffusion

Student difficulties with diffusion. We have found that from the perspective of introductory materials science, virtually every aspect of diffusion is difficult for students to understand. It has been recognized that the process of diffusion is difficult to understand by a number of researchers (Streveler et al., 2008; Chi, 2005). Chi, for example has discussed this difficulty in term of the perspective that diffusion is an emergent process, and the cause of diffusion is often confused. In our studies, we also found these issues. However, we also found other significant post-instruction student difficulties with diffusion that are important to materials science, including a lack of understanding of the terminology, mathematical equations, and graphs characterizing diffusion and a lack of a consistent microscopic model and physical intuition of the process of diffusion in solids.

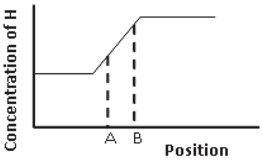
For example, students have difficulty with the concepts underlying Fick's first law, which states that the diffusion flux is proportional to the (negative of the) concentration gradient. Specifically, students often confuse higher concentration with higher diffusion flux rather than higher concentration *gradient*, and they do not have a physical understanding why a gradient is necessary to obtain a non-zero net diffusion flux. Furthermore, they have difficulty in understanding the meaning of concentration versus position graphs and making meaningful inferences about diffusion from such graphs. Figure 6 provides an example of these difficulties, with about 30% of students considering the height rather than slope, and more importantly, only

36% are able to determine the direction of the net diffusion flux from the graph. This indicates that either students do not have any understanding of the relation between diffusion and concentration gradient or that they have a significant lack of understanding of the meaning of the position versus concentration graphs. Further interviews indicate that some students do have some physical understanding of the relation between concentration gradient and diffusion flux, but they are unable to connect this understanding with the graphic representation of position versus concentration.

Another example of student difficulty with diffusion is with Fick's second law, which relates the rate of change in concentration with the second derivative of concentration with respect to position.

The figure to the right shows the concentration of Aluminum as a function of position. How does the diffusion flux of Aluminum at point A compare to that at point B?

(8%) a. A > B
(29%) b. A < B
(63%) **c. A = B**



In the figure to the left, in which direction is there a net diffusion of Hydrogen at point A?

(51%) a. To the right (+ x direction)
(36%) **b. To the left (- x direction)**
(7%) c. The concentration profile is in steady state, so the net diffusion is zero.
(7%) d. There is no direction to the diffusion.

Figure 6. Example questions demonstrating student difficulty with diffusion and concentration vs. position graphs. Student response percentages in parentheses, and correct answer in bold.

(N = 62, SE = 6%.) Note: To save space the graph which is common to the two questions is shown only once and placed between the two questions. This was not the case when students saw the questions.

For Fick's second law, the scope of students' difficulties becomes more pronounced. For example, as shown in Figure 7, only about 25% of students recognized that the

physical understanding of the relation between concentration gradient and diffusion flux, concentration would increase with time at a local minimum in concentration, and only about 15% recognized that concentration would change the fastest at points of "high curvature" in concentration. Instead, when asked about the graph in Figure 7, most students chose according to the slope, presumably since we are asking how concentration is changing with time, and rates of change are often associated with slope. Unlike with questions regarding Fick's first law, students did not do better on these questions when pressed in interviews. This suggests a more serious lack of understanding of the graphs and the physical processes underlying Fick's second law.

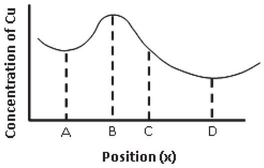
For a final example, we consider student responses to a question that probes student understanding of the nature of diffusion in metal on an atomic level, shown in Figure 8. Only 36% of students correctly responded that a copper atom will diffuse through a sample of copper. From these responses and from interviews, it was clear that students do not have strong consistent models for diffusion in metals on an atomic level.

Tutorials for diffusion. A portion of the tutorial designed to address these difficulties is shown in Appendix B. The tutorial starts by providing students with a series of conceptual questions about diffusion, such as questions concerning diffusion flux, concentration, and steady state diffusion. These questions highlight not only basic definitions and units of critical terms, but also how and why these terms are interrelated. Students then work through a series of questions related to Fick's equations, physical descriptions of diffusion, and the drawing of concentration vs. position graphs

The figure below shows the concentration of Copper as a function of position in a sample at 200^0C. At point A, how is the concentration of Copper changing with time?

(24%) **a. It is increasing with time.**
(4%) b. It is decreasing with time.
(45%) c. It remains constant with time.
(27%) d. It could be increasing or decreasing with time.

The figure below shows the concentration of Copper as a function of position. At which point is the concentration of Copper changing the fastest with time?



(1%) a. A
(16%) **b. B**
(67%) c. C
(16%) d. D

Figure 7. Example questions demonstrating student difficulty diffusion and concentration as a function of time. Student response percentages in parentheses, and correct answer in bold. (N = 376, SE= 3%.) Note: To save space the graph which is common to the two questions is shown only once and placed between the two questions. This was not the case when students saw the questions.

for the special case of steady state diffusion. These activities are designed to help students connect the concepts of the mathematical equations of Fick's laws with that of graphical concentration information. In addition, students work through an activity designed to help them connect the macroscopic properties of concentration and diffusion flux with what is happening at the atomic level through drawing of a very simplified atoms-in-a-bin picture of concentration and connecting this with a concentration vs. position graph and a diffusion flux graph (see Appendix B).

As a final activity, (not shown in Appendix B.) the tutorial guides students through a non-steady state concentration graph very much like the one in Figure 7. Students are asked several questions like, "Where is the diffusion flux greatest, where is the concentration greatest, …" These questions are designed to help students evaluate their understanding and catch students who fall back on naive responses to give them a last chance to correct their reasoning.

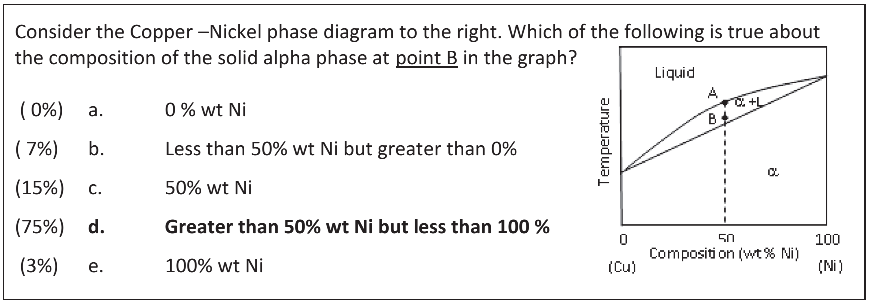
Phase Diagrams

Student difficulties with phase diagrams. Perhaps not unexpectedly, students have a number of difficulties with phase diagrams. These difficulties appear to arise from both an inability to understand the nature of the diagrammatic representation of phases and a lack of understanding of the nature of phases and concepts relating to phases such as the difference between composition of a phase and the phase fraction of an alloy.

In general, many students have significant difficulty extracting relevant information from phase diagrams, and performance decreases rapidly with increasing complexity of the diagram. For example, as shown in Figure 9, post instruction, over 75% of students can typically answer simple questions about binary phase diagrams involving solid solutions, i.e. only one solid phase. However, as shown in Figure 10, student performance dramatically decreases for questions about binary eutectic diagrams.

Consider a single particular Copper atom in a sample that is 100% Copper at 300^{0}C. Which of the following is correct?		
(17%)	a.	The Copper atom will not diffuse through the sample because the atoms are fixed in a crystal lattice.
(43%)	b.	The Copper atom will not diffuse through the sample because the sample is 100% Cu and therefore movement of atoms is not energetically preferred.
(4%)	c.	The Copper atom will diffuse through the sample because Copper atoms are not in a crystal lattice.
(36%)	**d.**	**The Copper atom will diffuse through the sample because of thermal energy.**

Figure 8. Example question demonstrating student difficulty the concept of atomic diffusion in a metal. Student response percentages in parentheses, and correct answer in bold. (N = 376, SE = 3%.)



Consider the Copper –Nickel phase diagram to the right. Which of the following is true about the composition of the solid alpha phase at point B in the graph?

(0%) a. 0 % wt Ni

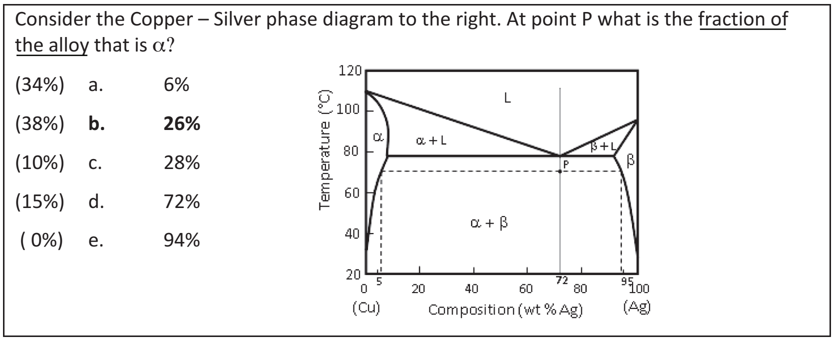
(7%) b. Less than 50% wt Ni but greater than 0%

(15%) c. 50% wt Ni

(75%) d. Greater than 50% wt Ni but less than 100 %

(3%) e. 100% wt Ni

Figure 9. Example question demonstrating student difficulty with phase diagrams for a single solid phase. Student response percentages in parentheses, and correct answer in bold. (N = 64, SE = 6%.)



Consider the Copper – Silver phase diagram to the right. At point P what is the fraction of the alloy that is α?

(34%) a. 6%

(38%) b. 26%

(10%) c. 28%

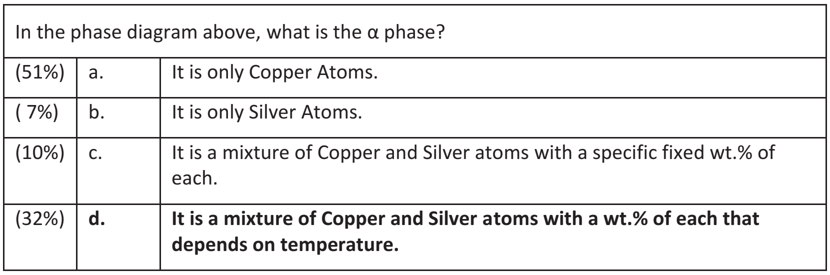
(15%) d. 72%

(0%) e. 94%

Figure 10. Example question demonstrating student difficulty interpreting phase diagrams. Student response percentages in parentheses, and correct answer in bold. (N = 212, SE = 3%.)

Only 38% of students correctly picked *fraction* of α with almost as many choosing the *composition* of the α. The rest of the students were divided between the composition amounts for the solution as a whole. In interviews and classroom discussions with students it was clear that much of the difficulty with this question arises from the complex nature of the graph itself and thus from students not knowing what to attend to. However, there are also a significant number of students who have difficulty either understanding the differences between the concepts of fraction and composition as well as the meaning of *phase*.

Student difficulties with understanding the meaning of phase is also demonstrated in the question in Figure 11, in which most student identified the phase as being comprised solely of one of the two elements in the alloy. Interestingly, many students who incorrectly believed in "pure phases" still successfully performed lever rule calculations, which inherently assume that the composition



In the phase diagram above, what is the α phase?

(51%)	a.	It is only Copper Atoms.
(7%)	b.	It is only Silver Atoms.
(10%)	c.	It is a mixture of Copper and Silver atoms with a specific fixed wt.% of each.
(32%)	**d.**	**It is a mixture of Copper and Silver atoms with a wt.% of each that depends on temperature.**

Figure 11. Example question demonstrating student difficulty with the nature of a phase in binary phase diagrams. Student response percentages in parentheses, and correct answer in bold. (N= 155, SE = 4%.)

of phases is mixed. (This is consistent with previous finding by Demetry (2006).) Thus, it becomes clearer that part of the difficulty students have with phase fraction and phase compositions terminology is that they do not have a correct understanding of the nature of the α and β phases and thus what the graph itself is representing.

Tutorials for phase diagrams. The tutorial on phase diagrams is aimed at addressing student difficulties with the diagrams, including those described above, by guiding the students through a series of general questions about the nature of phases, the meaning of solubility for metallic alloys, and the meaning of the regions of the phase diagram. The tutorial also guides the students to describe the phases on both an atomic and macroscopic level at various temperatures and compositions as well as transformations that occur as an alloy of a given composition changes temperature. Exercises include drawing pictures of microstructure and calculations of composition and fraction. A sample of the tutorial's questions is shown in Appendix C.

Atomic Bonding

Student difficulties with atomic bonding. We found a number of deep and fundamental student misunderstandings of very basic concepts of atomic bonding. We found that such basic misunderstandings were not addressed in the text or in the course curriculum, yet these misunderstandings may significantly contribute to barriers in understanding materials at an atomic level, and how the atomic level physics effects macroscopic properties. We will discuss four major difficulties of basic concepts.

First, we found that students often believe that atomic bonds can be modified, such as becoming permanently stretched, much like the phenomenon of a permanently stretched spring. Evidence of the stretched-bond model is shown in Figure 12, and was verified in numerous interviews. Students were asked post instruction to compare the atomic separation in a metal before and after plastic

A metal is permanently elongated by a load, then the load is removed. Which of the following is true?		
(29%)	**a.**	**Atoms will be rearranged compared to before the elongation.**
(11%)	b.	The atomic bonds will be stretched compared to before the elongation.
(60%)	c.	Both a) and b) will occur.

Figure 12. Example question demonstrating student difficulty with the concept of plastic deformation. Student response percentages in parentheses, and correct answer in bold. (N = 64. SE = 6%.)

deformation, and 71% of them indicated that the bonds would be stretched after plastic deformation. Note that this idea of stretched bonds is similar to the results found previously regarding a question in the Materials Concept Inventory, in which many students answered (pre-instruction) that when a wire is drawn through a tapered hole, the bonds have been compressed (Krause, Decker & Griffin, 2003).

This incorrect model of atomic bonding and plastic deformation reveals that students do not understand the process of plastic deformation at a microscopic level, and this may in turn contribute to difficulties in understanding how yield strength is determined by the propagation of dislocations, rather than the permanent stretching of atomic bonds. In addition to the idea of stretched bonds, many students also believe that bonds can be weakened. Consistent with previous findings (Krause, Tasooji & Griffin, 2004), we also found that about 40% of interviewed students believed that when a metal is heated, atomic bonds become weakened and they believed this explains, for example, why a heated metal expands.

Second, we found that an overwhelming majority of students assumed that high mass density necessarily implied small atomic separation. In this case, students ignored the fact that mass density depends on both atomic separation and atomic mass. When pressed in interviews, most students quickly recognized that atomic mass is a factor. However the neglect of atomic mass when considering mass density was quite pervasive, as shown in Figure 13, response *a*.

The assumption that mass density necessarily determines atomic separation and vice versa may seem like a minor and innocuous oversight. Students may have simply interpreted (implicitly or explicitly) that “density” means “number density” rather than the more commonly assumed “mass density” (even if “mass” is explicitly stated), and the focus on number density might be expected, since the lessons on crystal structure focus on numbers of atoms, for example when calculating the atomic packing factor, rather that the mass of the atoms. However, Figure 14 provides evidence that this assumption is a symptom of a much deeper misunderstanding of microscopic and macroscopic

Material A has a greater (average) atomic separation than Material B. Which of the following must also be true given this information? (You may choose more than one.)

(72%)	a.	Material B has a greater mass density.
(75%)	b.	Material B has a great atomic bond strength
(44%)	c.	Material B has a greater yield strength
(40%)	d.	Material B has a greater melting temperature.

Figure 13. Example question demonstrating student difficulty with the concept of plastic deformation. Student response percentages in parentheses, and correct answer in bold. Question regarding atomic separation and material properties. (N= 67, SE = 6%.)

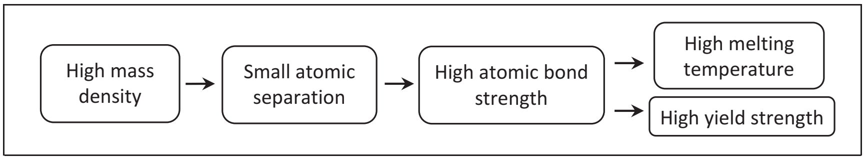


Figure 14. Common incorrect line of reasoning about the relation between density, melting temperature, and yield strength. Note that all but one of the steps is incorrect.

properties which may lead to common errors in multi-step reasoning involving density. Responses to the question in Figure 13 and interview responses reveal that many students use a train of incorrect steps to argue that density predicts strength and melting temperature. First, most students assume that relatively high mass density implies relatively small average atomic separation. Second, most students also believe that relatively small average atomic separation necessarily implies relatively large atomic bond strength. Finally, most students believe (correctly)[1] that high atomic bond strength necessarily implies high melting temperature and (incorrectly) that high atomic bond strength necessarily implies high yield strength. Therefore, the idea that high density implies high melting temperature and high yield strength is compelling to students because there is a natural and plausible (yet incorrect) mechanism: stronger atomic bonding due to smaller atomic separation. This is the common student reasoning for equating the properties of mass density with the macroscopic properties of melting temperature and yield strength. (See Figure 14 for a summary of this reasoning pattern.)

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[1] This is marked as correct but again many students do not distinguish between force of the bond and energy of the bond. High bond strength correctly implies high melting temperature only if energy is being considered which, when a student is discussing their reasoning, is often not true.

The third basic student difficulty with understanding atomic bonding is that students often confuse the concepts of force and energy when referring to the strength of atomic bonds and use the two terms interchangeably in their explanations (see also Heckler & Rosenblatt, 2010). Atomic bonds are often described by instructors as being either “strong” or “weak”. Unfortunately this can be misleading or confusing to the students because sometimes the word “strong” refers to the force of the bond and sometimes it refers to the bond energy. Like many misconceptions, the use of a common word can lead to difficulties in understanding the proper scientific concept. In everyday usage, “strength” usually refers to force, whereas normally when an expert speaks of a strong atomic bond, it is meant in terms of a large binding energy. In general we observed that it was common for students to use the terms force or energy when discussing the origins of macroscopic properties such as elasticity, strength and melting temperature, with little regard for the scientific accuracy of their own usage of the words. The failure to distinguish between energy and force in atomic bonds may be contributing to student difficulty in understanding how the properties of atomic bonds are related to macroscopic properties such as strength and elasticity.

Finally, we found that students have considerable difficulties using a (Lennard-Jones) bonding potential energy graph to answer common questions about melting temperature, Young’s modulus, and atomic separations. Comparing student’s responses for the two questions shown in Figure 15; it is evident, from the almost identical responses for the two separate questions, that students do not understand what parts of the graph are related to the requested properties of the bond. In

Shown below are the Potential Energy curves for three different materials. Circle the answer with the correct rankings of the three materials’ melting temperatures.

(13%)	A > B > C
(33%)	**C > B = A**
(11%)	C < B = A
(42%)	C > B > A

Shown below are the Potential Energy curves for three different materials. Circle the answer with the correct rankings of the three materials’ stiffness (i.e. their Young’s moduli, E).

(18%)	**A > B > C**
(30%)	C > B = A
(11%)	C < B = A
(41%)	C > B > A

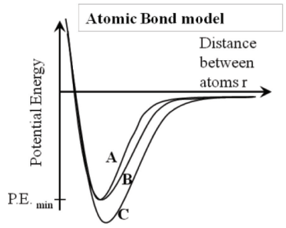

Figure 15: Example questions demonstrating student difficulties interpreting a graphs of the Lenard-Jones potential. Student response percentages in parentheses, and correct answer in bold. (N = 61, SE = 6%.) Note: To save space the graph which is common to the two questions is shown only once and placed between the two questions. This was not the case when students saw the questions.

If the total energy of the system is $E_{N,}$ what is the smallest possible separation between the two atoms?

(3%) a. The smallest separation is zero.

(26%) b. The smallest separation is very small but must be greater than zero.

(54%) **c. The smallest separation is r1.**

(16%) d. The smallest separation is ro.

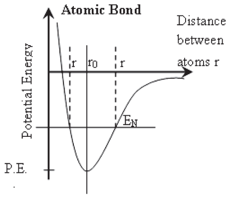

Figure 16: Example questions demonstrating student difficulties interpreting a graphs of the Lenard-Jones potential. Student response percentages in parentheses, and correct answer in bold. (N= 61, std error = 6%)

addition, students' responses to the even simpler question in Figure 16 illustrates that many students do not have even a basic understanding of the meaning of the graph.

Tutorials for atomic bonding concepts. Student difficulties with understanding atomic bonding are addressed in a number of the tutorials to some extent, since the concepts are so basic and pervasive. Nonetheless, we developed a specific tutorial, some of which is presented in Appendix D, which focuses on the Lennard-Jones potential energy of two metal atoms as a function of separation. First the tutorial provides a brief explanation of two common models for atomic bonding – the Lennard-Jones model and the spring model. Then students are prompted to compare the two models. This includes describing and comparing the motion of the atoms in the two cases, and how the average separation between the atoms changes when the average energy increases. We found that even though these concepts were mentioned in the textbook and in lecture, most students were not at all familiar with the Lennard-Jones potential or how it is related to the behavior of the atoms. Thus such simple questions were useful to familiarize students with the two models and their graphs. There are also a number of questions prompting students to use the potentials to address macroscopic properties of materials such as its melting temperature, Young's modulus, coefficient of thermal expansion, and the energy necessary to break bonds as a function of temperature.

We chose this tutorial activity for several reasons. First, a basic (and we stress basic) conceptual understanding of the major features of the potential is fundamental to understanding the nature of atomic bonds, and this understanding can be used throughout the course to help students think about the microscopic structure of a material. (This is discussed further in the section "Addressing the Relation between Structure, Processing, Properties.") Second, students difficulties using the Lennard-Jones potential to answer simple questions, which was already, pre-tutorial, a part of the expected atomic bonding curricula for the course, would have suggested some instruction with the Lennard-Jones potential anyway. Third, the graph, is a convenient visual representation that facilitates understanding of the independence of the fundamental dimensions of bond energy, average separation, and curvature that can be conceptually linked to the independent macroscopic properties of melting temperature, number density, and Young's modulus. This can help students to more clearly distinguish between, and understand the independence of, atomic separation, bond energy, yield strength (related in part to depth of well), and elasticity (related to curvature of well). Finally, comparisons of the two models can assist in illustrating for the students when a spring model is not a good model to use for bonding, for example that it does not explain thermal expansion, which can be built upon later when students are learning plastic deformation.

THE TUTORIALS AND GENERAL INSTRUCTIONAL GOALS

So far, we discussed how the tutorials address specific content topics, such as mechanical properties or phase diagrams. However, there are also several general themes that run through the tutorials; these themes are aimed at goals the faculty and instructors identified for the course as a whole, as outlined in Table 4. In this section, we describe how the tutorials address these general course goals.

Addressing General Concepts, Basic Definitions, and Terminology

The main difficulty that students have in this area is that they commonly conflated similar terms and concepts. Examples discussed in the previous sections include confusion between force and energy of a bond, strength and elasticity of a material, and phase composition and phase fraction. Interestingly, after finding initial evidence of confusion between two given concepts or terms such as force and stress, we found that following further conversation many students *could* distinguish between the two concepts in question. Therefore in some cases, rather than finding that students *could not* make the distinction between the concepts in question, we found instead that students often simply *did not* distinguish between them. For example, after brief conversation, students would often easily grasp (or recall) the distinction between stress and force. While these are precise terms in the domain of engineering, students nonetheless often appeared to equate the concepts, or they often used the terms interchangeably.

Furthermore, in some cases it appeared that the confusion of terms was partially due to common language usage. For example, when referring to a property of a material in everyday language, *stiff* is often synonymous with *strong* or *tough*. However, these terms are not synonymous in materials science and have precise and critically different meanings.

Therefore, there appears to be two issues associated with student incorrect usage or application (interpreted as confusion) of similar terms and concepts. First, the students must *learn the distinction* between the concepts in question. This may or may not be difficult depending on for example whether the differences are subtle or whether both concepts are complicated. Second, it may be the case that in everyday experience the two concepts or terms in question are habitually used interchangeably, and even if a distinction is understood by the students, they may not recognize the need to distinguish between the concepts or terms. This second issue then involves the student learning that the *distinction is important* in some circumstances, especially in matters concerning material science.

The tutorials were designed to address these issues in a number of ways. Some tutorials explicitly ask students to provide a definition of a term in non-technical words. For example, the phase diagram tutorial starts with the question, "What is a phase?" For some students, this is a challenging question because they often use the everyday meaning of the word. In addition, commonly confounded terms were often directly confronted by asking students to describe the difference between, for example, stiffness and strength or stress and force. Another methods used was to provide quotes from students that used terms incorrectly (such as the student quote in exercise 10 in the mechanical properties tutorial examples in Appendix A), and student were asked to discuss the validity of the quote. Finally, many terms, such as *strength*, were often used over multiple tutorials. As part of the intervention, TAs were instructed to be aware these oft-confused terms, and assist students in recalling and defining these terms when students were stuck on a question. For example, a student might say, "We are stuck on #4, how does cold working strengthen a material?" The TA might respond by asking the student, "Last week we talked about tensile strength. What is tensile strength? Can you recall how it differed from yield strength?"

Addressing the Relation between Structure, Processing, Properties

Achieving the understanding of the relation between structure processing and properties even at a basic level is complicated because it relies on multiple areas of student knowledge and the knowledge that bridges these different areas. While more tutorial development is needed on this topic, the tutorials in their current form do address important aspects. We found that many student difficulties in this area are rooted in either a lack of a conceptual (or visual) model or an incorrect model of the structure of materials on sub-macroscopic scales. This is true even after they finish the course. For example, as mentioned earlier, students often believe that bonds can be permanently stretched, and this interferes with learning of the proper description of plastic deformation (and yield strength).

In addition, students have difficulty producing visual models of the crystal structure nature of metals, the grains and dislocations (and how these differ), and the phases of metals at the microscopic level. This lack of correct visual models of materials on smaller scales hinders students' abilities to understand how processing, such as drawing a wire through an aperture, changes microstructure and thus effects material properties.

To help address these difficulties, most tutorials include a section which requires students to draw pictures representing important atomic or microstructure-sized features and often has questions requiring students to analyze or use their picture. Examples of this can be seen in each of the tutorial exercises presented in previous sections. For example, in the mechanical properties tutorial students are asked to sketch what the atoms are doing before, during, and after elastic and plastic deformation. Then they are asked to use their picture to infer how density or atomic separation changes. Another example of this can be seen in the tutorial aimed at difficulties with crystal structure and defects where students are required to both draw a dislocation and give a written description for it, or in the failure tutorial where students are required to identify the types of failure seen in magnified fracture surfaces and then to describe the identifying features of the failure. This kind of exercise is consistent with work by Krause et al., which indicates that drawing exercises may generally be an effective teaching tool for addressing conceptual difficulties with materials science (Krause et al., 2010).

Addressing the Interpretation and Use of Graphs and Diagrams

A wide variety of graphs and diagrams are used in the many topics covered in introductory materials science, and we have found that there are significant student difficulties with all of them. This includes stress-strain plots, concentration versus position plots used to describe diffusion, the Lennard-Jones potential graph and phase diagrams discussed in previous sections. Difficulty with at least some of these diagrams, such as phase diagrams and TTT plots is to be expected, since most students are not familiar with the “rules” of these unique diagrams, in addition to struggling with the underlying concepts represented by TTT plots. Nonetheless, the graphic representations are critical to materials science, and understanding them is an important goal.

Therefore, to address these issues with graphs and plots, each tutorial includes at least one activity in which students derive information from or plot information on a graph or diagram. These activities often include a series of questions regarding the chart or graph which address common specific difficulties with a particular diagram. Often the task is designed to elicit and resolve a specific difficulty. The TA’s are instructed on assist students with such difficulties. Questions #2 and 3 in the atomic bonding tutorial or #11 and 12 on the mechanical properties tutorial are examples.

RESULTS OF IMPLEMENTATION

Nine tutorial worksheets were implemented in weekly recitations (as outlined earlier) in three separate lecture sections in three separate quarters. Two of the sections (Autumn 2010 and 2011) were taught by an experienced materials Science Engineering faculty member who taught the course for a number of years, and one of the sections was taught by a faculty member who taught the course for the first time. All lectures were mainly traditional format, with the exception that electronic voting machine questions were presented and discussed for a portion of most of the lectures.

Regarding assessment, as mentioned earlier, a Materials Concept Inventory is available (Krause et al., 2010b), but we found that this instrument was not adequate for the purposes of our study because, for example, the instrument has several items assessing topics that were not covered in the course.

Therefore, we evaluated the effectiveness of the tutorials by analyzing final exam scores. The final exams were constructed in multiple choice format by the instructors and were similar in nature in all three sections, yet each exam was different. The metrics of the exams were within a reasonable range, for example the Cronbach's alpha measures were in the range of 0.7-0.75 and average scores in the 70-75% range.

While the use of final exam scores does not allow for a comparison between lecture sections, for example between a section using tutorials vs. a section that employs traditional recitation lecture and homework reviews, one still may make informative comparisons of exam performance *within* lecture sections. Specifically, as noted earlier, students attended on average only about 37% of the recitations. This variability in attendance allowed for a comparison of final exam scores of students who attended the voluntary recitations to scores of students who did not attend recitation. Figure 18 reveals a clear linear, increasing relation between the number of recitations attended and the final exam score. Students gained about 0.10 3 0.02 standard deviations on the final exam score for every recitation they attended. (See Figure 18 which shows similar trends in all three quarters.)

However, this increase performance with increased tutorial participation is necessary but not sufficient evidence for the added benefit of tutorials. Because the recitations were voluntary, it might be argued that the gain in score could be due to the fact that better students may have more often attended recitation. While this is a plausible contributing factor to the score-attendance relation measured, we argue that there is evidence of additional learning due to recitation participation. In particular, we made a within student comparison of performance on exam questions that were related to the recitation material vs. exam questions that were not related to recitation material. If one interprets the score on the non-recitation related questions as a measure of the mastery level of the student, then one can use this information to factor out the quality of the student and determine if there is any residual effect of recitation attendance alone.

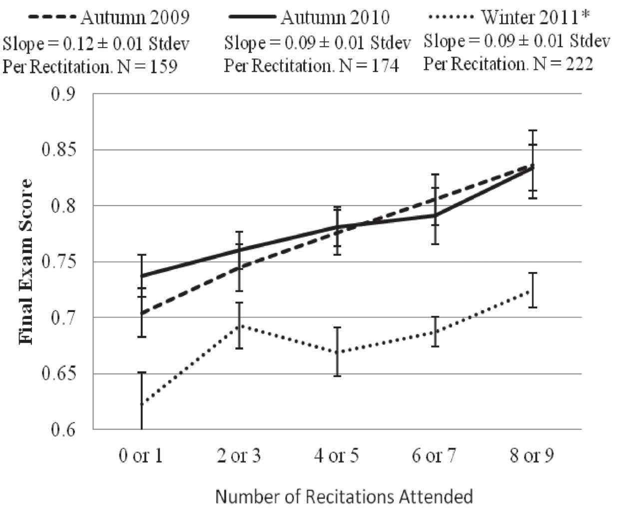

Figure 18. Final exam score vs. recitation attendance for three separate quarters. The slope for each quarter is also provided. The recitations are binned by two to reduce fluctuations from topic difficulty, tutorial strength, and the number of final exam questions on each topic. (*Wi 2011 had only 8 recitations)

In order to formally analyze this possibility, we performed a 2 x 2 repeated measures analysis of variance, with high/low attendance (greater or less than average attendance) as the between student factor, and question type (recitation related vs. not recitation related question) as the repeated (within student) factor. Figure 19 presents the data separated into these factors. Perhaps unsurprisingly, there was a main effect of attendance, with high attenders outscoring low attenders by 0.36 standard deviations on all questions on average ($F(1, 553) = 20.06$, $p < 0.001$). There was no main effect of question type, thus students performed on average equally well on recitation vs. non-recitation related questions, 74% vs. 73% ($F(1, 553) = 3.76$, $p = 0.053$). Most interestingly, as seen in Figure 19 there was a significant interaction between attendance and question type ($F(1, 553) = 19.55$, $p < 0.001$), with a clear value added on recitation related questions for those attending recitation. Thus, even accounting for the fact that slightly "better" students attended the recitations there was a valued-added effect of the recitations that improved relative student performance on recitation related questions by 0.35 standard deviations. This effect size is fairly impressive considering that difference in attendance between high and low attenders is about 4 recitations, which is less than 3.5 hours of tutorial participation.

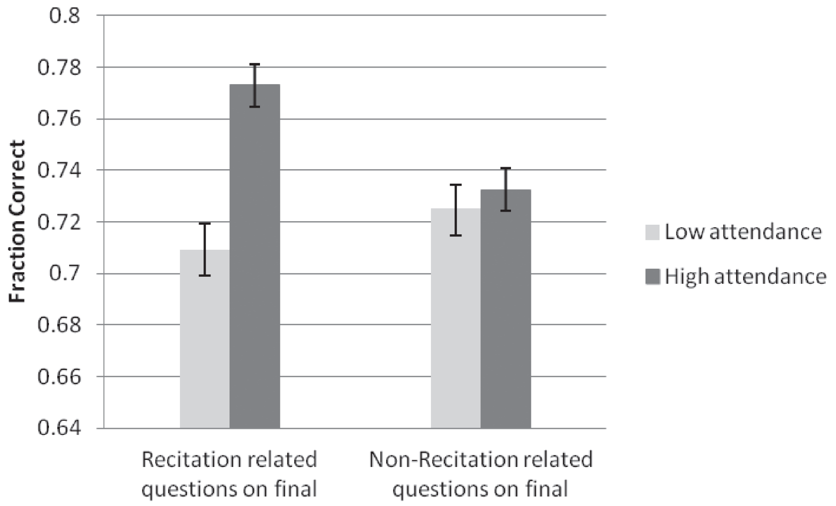

Figure 19. Interaction of recitation attendance and recitation related vs. non-recitation related questions (N=553). The final exams were on average 32 questions long with 14 questions not related to recitations and 18 questions related to recitations. Low attendance is less than average attendance 3, recitations or less, and high attendance is greater than average attendance, 4 or more.

DOES ANYTHING EXTRA HELP?

Here we address the possibility that any extra activity would produce learning gains like the ones seen above. Before the tutorials were implemented recitations were used for homework help and review sessions. Students came to get homework help, or if they had no homework questions, they were given alternative homework type questions to work on. Groups were 'encouraged' but not enforced, and several students worked alone. Attendance was unfortunately not taken but a rough estimate of 25% to 35% of students attended recitations later in the quarter (the first week usually has very high attendance 85% or 90% with a sharp drop to 40% or below by week 3. This close similarity of attendance in the tutorial and nontutorial recitations allowed for a small comparison of learning gains with activity. A set of the multiple choice questions which were created to identify and describe student difficulties was given to students as a posttest in both recitation styles. Table 4 reports this data. As can be seen, there were small but consistent learning gains for the tutorial class over the homework help and extra problem sessions class.

Over all the average difference in score is 5%, or 0.25 standard deviations. Thus, the tutorial activities were better than the homework help/extra problem sessions at creating correct understanding of these three important materials science concepts.

Topic	Atomic Bonding		Phase Diagrams			Mechanical Properties				
Question	Fig 15 (left)	Fig 12	Fig 9	Fig 10	Fig 11	Fig 1	Fig 2	Fig 4	Fig 5	Average
Nontutorial (N = 125)	60%	22%	31%	30%	70%	56%	48%	34%	86%	49%
Tutorial (N = 136)	67%	46%	38%	32%	74%	58%	50%	67%	59%	55%
Difference	7%	24%	7%	2%	4%	2%	2%	33%	–27%	6%

Table 5. A comparison of tutorial and homework help recitation activities. Attendance is believed to be comparable. The score for each question is shown and the question's Figure from the student difficulties section is noted. Students reported that diffusion was not emphasized in the Nontutorial course and Nontutorial diffusion scores were very low so that data is not shown.

GENERAL DISCUSSION AND CONCLUSION

What is somewhat remarkable is that there exists a fairly well-defined process for developing physics curricula that significantly improves student learning of important and difficult concepts in physics, and this study demonstrates that this same process can also work for an introductory materials science engineering course. The implication is that this process might work in other, possibly all, STEM topics and especially in stem topics more closely related to materials science such as chemistry and other engineering courses. While the process is fairly straightforward, it nonetheless requires significant and lengthy effort typically on the order of several years. This process includes the careful identification of specific student difficulties and the iterative process of developing interactive group activities facilitated by suitably-prepared TAs.

More specifically, we have reported here on the successful application of this tutorial design process to an introductory materials science engineering course. We have identified a number of prevalent student difficulties with fundamental concepts in materials science, and designed tutorials as group-work activities aimed at addressing these difficulties. The tutorials follow the a large extent many of the chapters of a common book used in the course (Callister, 2007), and include the topics of atomic bonding, crystal structure, diffusion, mechanical properties, plastic deformation, cold-working, creep, fatigue, failure, phase diagrams, TTT plots, ceramics, polymers and composites. The tutorials not only address specific topics but also more general instructional goals such as the interpretation of diagrams and graphs, and the relation between structure, processing, and properties. The tutorials guide student through a series of questions which are designed to elicit known student difficulties and encourage students to explicitly confront these difficulties via group discussions of posed questions and/or dialog with a TA. In addition, the tutorials address larger course goals - including understanding basic materials science terms, visualizing the microstructure of materials, and expertise with graphs and diagrams - through incorporating these skills in each of the tutorials. Analysis of final exam performance suggests that participation in the tutorial based recitations significantly improves student understanding. In all, these results suggest that these methods and materials are effective in teaching students the difficult and important conceptual materials which they were designed to address.

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AUTHORS

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Andrew F. Heckler is an Associate Professor of Physics at Ohio State University. His original area of research was in Cosmology and Astrophysics. In the past nine years, he has focused on Physics Education Research, studying fundamental learning mechanisms involved in learning physics, the effects of representation on learning and problem solving, and the evolution of physics understanding during and after a physics course. In addition, he is also leading a project to identify and address student difficulties in learning materials science. This effort is part of the education component of the OSU Center for Emergent Materials, an NSF MRSEC center.

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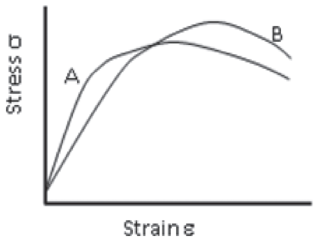
APPENDIX A

Mechanical Properties Tutorial (excerpt)

1. What is the difference between a material's strength and a material's stiffness?
2. What is elastic deformation? (Please give a description that a 2nd year engineering student who has not taken this class yet would understand.)
3. How is elastic deformation related to Young's modulus, E?
4. A tensile stress is applied to a metal bar such that is deforms **elastically**. Draw a sample of atoms in the bar.
    a) Before deformation
    b) During deformation while under stress
    c) After the stress is released
5. While the bar is under stress, is its volume different than before being deformed? Explain.
6. A tensile stress is applied to a metal bar such that is deforms **plastically**. Draw a sample of atoms in the bar.
    a) Before deformation
    b) During deformation while under stress
    c) After the stress is released
7. Does the density increase, decrease, or remain the same after plastic deformation? Explain.
8. How is the strength of a metal defined? (Please give description that a 2nd year engineering student who has not taken this class yet would understand.)
9. What is the difference between yield strength and tensile strength?
10. Student C says: "Steel has a yield strength of 180 MPa and Nickel only has a yield strength of 130 MPa. Steel is therefore stronger and more force is needed to break it." This student is: Correct, Partially Correct, Incorrect. Explain.
11. Indicate the features which would characterize the Young's modulus, yield strength, tensile strength, ductility, and toughness. [Stress strain plot given]
12. Rank the two curves:

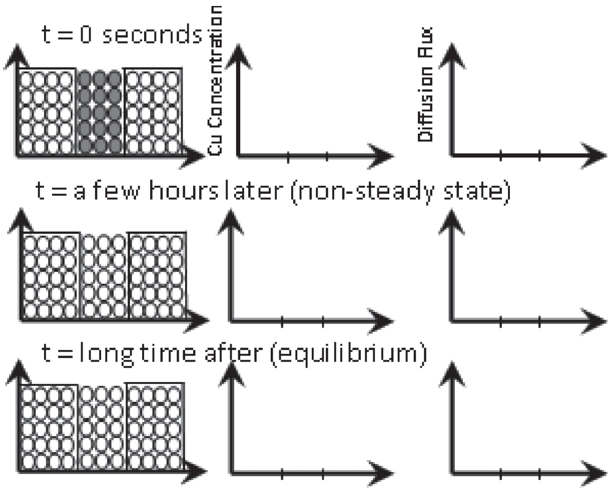
Modulus,E:	**A** (> , < , =) **B**
Yield strength:	**A** (> , < , =) **B**
Tensile strength:	**A** (> , < , =) **B**
Ductility:	**A** (> , < , =) **B**



APPENDIX B

Diffusion Tutorial (excerpt)

1. In Fick's First Law, why is J, the diffusion flux, proportional to the concentration gradient, rather than being proportional to the concentration, C?
2. What does the minus sign in Fick's First Law mean physically? What would happen if the minus were to become a plus sign?
3. In steady state diffusion, what quantity is "steady"? Is it "steady" with respect to position, time, or both?
4. Are atoms moving in steady state diffusion?
5. Is there anything that is changing in steady state diffusion?
6. How does the concentration of material change with position when diffusion is in steady state?
7. How does the diffusion flux, J, change with position when diffusion is in steady state?
8. Rewrite Fick's First and Second Laws for steady state diffusion.
9. A Slab of Ni atoms (gray) are perfectly sandwiched between two slabs of Cu atoms (white), as shown on the first graph marked "t = 0 seconds". Draw graphs for the Cu concentration and the magnitude of the Cu diffusion flux as a function of position at t = 0 seconds. Then, for t = a few hours later (non-steady state) and t = long time after (equilibrium), show how the atoms would be distributed (i.e. color in Ni atoms) and draw the graphs for the Cu concentration and the magnitude of the Cu diffusion flux as a function of position.



APPENDIX C

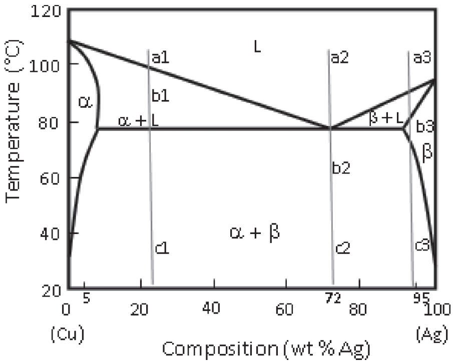
Phase Diagrams Tutorial (excerpt)

1. What is a phase? Write a definition that a 2nd year engineering student who has not taken this class yet would understand. Give 3 or 4 examples.
2. Some binary alloys (alloys with two species) have only one solid phase such as a Copper and Nickel system. Others have two solid phases such as a Lead and Tin system.
    a. Why is this?
    b. Under what conditions will a Lead Tin alloy have only one phase?
3. Draw pictures of the microstructure of this Copper-Silver alloy as you slowly cool the solution

    At 24% Ag: a1, b1, c1

    At 72% Ag: a2, b2, c2

    At 94% Ag: a3, b3, c3



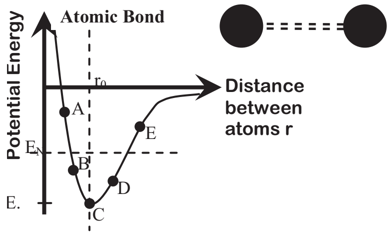
4. At point b1 in the diagram, estimate the composition of the α?
5. At point b1 in the diagram, estimate the composition of the Liquid?
6. At point b1 in the above diagram, use your estimates above to calculate the fraction of the microstructure that is α?
7. In the eutectic phase diagram, what is alpha? Draw a picture of alpha at the atomic level.

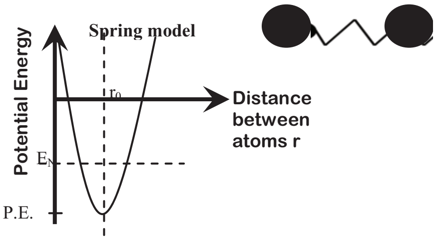
APPENDIX D

Atomic Bonding Tutorial (excerpt)

1. When a metal is heated it expands, why does this happen?

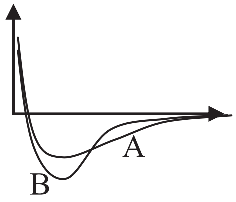
A model of atomic bonding: The symmetric spring potential vs. the real asymmetric potential.





2. For points A, C, and D draw pictures representing the two atoms and their atomic separations.
3. For the points A-E which points are allowed when the system has total energy E_N? Give an explanation for why points would be allowed or not allowed.
4. What is the average atomic separation in the spring model case? (Greater than, less than, or equal to r_0?)
5. What is the average atomic separation in the “atomic bond” case?(Greater than, less than, or equal to r_0?)
6. What happens to the average separation for the spring model and atomic bond model when the total energy increases?
7. When you heat up a material, what happens to the total energy between two adjacent atoms? When you heat up a material, what happens to the average separation between atoms for the spring model and atomic bond model? Why?
8. How would the potential energy curve for a material with a greater bond energy be different? (Either a written explanation or a comparison picture with two labeled curves is sufficient.)
9. What about a material with a higher coefficient of thermal expansion ($\alpha \sim \Delta r/\Delta T$)? (Either a written explanation or a comparison picture with two labeled curves is sufficient.)
10. What about a material with a higher modulus of elasticity? (Either a written explanation or a comparison picture with two labeled curves is sufficient.) Hint: A stiffer material, higher modulus, is a stiffer spring. $P.E._{spring} = \frac{1}{2} * k * x^2$ try graphing a few different k to see what happens.

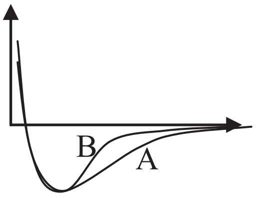
11. Concept check: For each situation rank (<, >, or =) the two curves A & B by the requested properties.



B.E.:

Modulus:

α:



B.E:

Modulus:

α

12. Material A is denser than Material B. How does Material A's melting temperature compare to material B's? Explain.