Identifying Student Misconceptions in Introductory Materials Engineering Classes

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Abstract

Numerous student misconceptions in an introductory materials engineering class have been identified in order to create a Materials Concept Inventory (MCI) to test for the level of conceptual knowledge of the subject matter before and after the course. The misconceptions have been utilized as question responses, or "distracters", in the multiple-choice MCI test. They have been generated from a literature survey of assessment research in science and engineering in conjunction with extensive student interactions. Student input consisted of: weekly short-answer, open-ended questions; multiple-choice quizzes; and weekly interviews and discussions. In a simplified way, the questions tied fundamental concepts in primary topical areas of atomic structure and bonding, band structure, crystal geometry, defects, microstructure, and phase diagrams to the properties of materials in the families of metals, polymers, ceramics, and semiconductors. An early version of the MCI test was given to students in introductory materials courses at Arizona State University (ASU) and Texas A&M University (TAMU). Results showed conceptual knowledge gains between 15% and 37% between course pre-test and post-test scores. Lower scores, specified as less than 30% gain by Force Concept Inventory work, are typical of traditionally delivered, lecture-base instruction. Scores from 30% to 60% are moderate gains and are often evidenced in courses using active learning methods. Early results of the MCI showed differences between ASU and TAMU on some questions. It appears that they may be due to curricular and course content differences at the two schools.

Introduction

Over the last two decades new theories of learning and associated methods of teaching have been emerging in the technical disciplines. In engineering education there have been a number of innovations in teaching such as internet courses, virtual experiments, computer classrooms, and team based active learning. However, development and use of well-accepted tools for assessment has lagged behind the innovations. The physics community has been using a well-regarded tool known as the Force Concept Inventory (FCI) created by Hestenes et.al.[1,2], and tested broadly by Hake[3] for students in high school and college physics classes. The FCI questionnaire utilizes a series of multiple-choice questions based on qualitative, concept-oriented problems on a particular topic. It measures deep understanding and conceptual knowledge of a topic rather than the memorization of facts or routine algorithmic equation solving. FCI results, which are being used to measure the performance of students in physics classes with different teaching methods, has initiated changes in teaching methodology and stimulated healthy debate on best teaching practices.

In the past three years, a project to develop and test assessment tools for engineering science courses called "Engineering Concept Inventories" has been initiated by Evans[4] through the NSF-sponsored Foundation Coalition. Under this program an early version of a Materials Concept Inventory (MCI) has been developed and tested on introductory materials engineering classes at ASU and TAMU. The 30-question, multiple-choice MCI test was developed from a literature survey of assessment research in science and engineering in conjunction with extensive student interactions. A key aspect of the MCI is discovering the student misconceptions that can be used as the incorrect answers for each question. Hestenes et.al.[1] refers to these appealing, but incorrect, choices as "distracters", a term which has been adapted in the literature. The subject of this paper is the description, approach, methodology, and techniques used to develop the MCI and also a discussion of early results on the nature of the broadly held student misconceptions revealed by the MCI.

Selection of Topical Areas and Design of the Test for the Materials Concept Inventory

The development of the Materials Concept Inventory followed the approach of Hestene's FCI, which identified a limited number of broad, fundamental topical areas that are taught in an introductory physics courses. In introductory materials engineering classes, the overall goal is to analytically link relationships of scientific fundamentals to macroscopic materials behavior. In particular this refers to linking relationships of atomic structure and bonding, band structure, crystal geometry, defects, microstructure, and phase diagrams to the properties and performance of materials in the families of metals, polymers, ceramics, and semiconductors. As such, the delineation of a set of key conceptual areas from course syllabi and textbooks was reported in an earlier paper by Krause et.al[5]. An updated set of fundamental areas has been delineated as; 1) units and conversions; 2) atomic bonding; 3) electronic structure; 4) atomic arrangements and crystal structure; 5) defects, diffusion, and deformation; 6) solubility and phase diagrams; 7) processing and microstructure; 8) relationships between mechanical properties and structure and processing, and; 9) relationships between electrical properties and structure and processing. The delineation of these areas may change somewhat in the future since broader participation by materials engineering educators is being solicited as part of the research in MCI development.

After the selection of the key conceptual areas, the general distribution of questions was considered. A decision on the fraction of prior knowledge versus new course content knowledge was partially based on students' prior course work experience. At ASU and TAMU a student in a materials course is typically a college sophomore with one or two semesters of college chemistry, one to two semesters of physics, one to three engineering-oriented math courses, and a multitude of high school level math and science courses. It was decided that about one-third of the MCI would test prior knowledge, since some materials course content is based upon the assumption that students would build upon prior course knowledge. In examining course syllabi and content, it was found that prior course knowledge was based mainly on chemistry and, to a more limited extent, on geometry (especially for crystal lattice characterization and calculations).

As such, one third of the questions were designed to explore relevant topics in these areas. For the remaining two-thirds of the MCI there were new, materials-course content questions, designed for each of the key conceptual areas. The current version of the MCI has following distribution of questions; two are geometry based, eight are chemistry based, and 20 are based on new course content.

Development of Materials Concept Inventory Questions and Responses

As a starting point in the development of the MCI, the general principles described by Hestenes et.al.[1], and embodied by the FCI, were utilized. Additional information and content from concept inventories on thermodynamics, chemistry, and mechanics from the literature was utilized. In particular, there was considerable information in chemical education journals on student misconceptions that proved to be helpful in understanding concept inventory development, as well as providing some content for chemistry-based questions for the MCI.

A number of general guidelines were followed in the development of the MCI that are described here. When developing a given question, it should only have a single correct response since multiple correct responses make analysis of results difficult. The questions and responses should be basic, simple and as short as possible since this shortens test-taking time and helps reduce ambiguity. The questions should use everyday lay terminology, and not use terminology specific to the course since this allows more effective pre-test and post-test evaluation of results. When appropriate, the use of diagrams, schematics, and graphs helps shorten questions, simplify responses, and reduce time. It is helpful, maybe even critical, to work with students and/or focus groups to help identify problems with questions and responses. Some of the problems found in the development of the MCI were; ambiguous questions and/or answers, multiple correct answers, misworded and misinterpreted questions and answers, and questions or answers that addressed more than a single concept. In the first pass at the creation of a given question, a trial set of responses was generated that included the correct answer as well as the incorrect responses, or "distracters". These distracters were principally based on faculty insight of difficulties with course content that evolved from teaching introductory materials courses over a length of time. For many questions, these faculty-generated distracters were intended as a starting point for developing more authentic and useful student-generated distracters that were extracted from individual student misconceptions.

Authentic student distracters for a number of questions were generated from weekly interviews and "intuition quizzes" during the introductory materials courses. "Intuition quizzes" were created by a faculty-student team that generated weekly short-answer, open-ended questions or multiple-choice questions on content to be covered during the lecture. The questions were given at the beginning of class and the answers evaluated after class by compiling and summarizing the results. The other method used to identify misconceptions was weekly volunteer interviews performed by the class instructor and a student assistant. In the interviews students would discuss current content, prior content, and the nature of misconceptions. The interviews were not particularly useful since students were hesitant to talk, possibly because they felt self-conscious or because they had little experience with reflective thinking. On the other hand, the "intuition quizzes" were quite useful in identifying creative and original student misconceptions which were often used as effective distracters. Larger scale testing during the following semester was used to determine which misconceptions were most broadly held.

Identification of Some Broadly Held Student Misconceptions

The 30-question MCI test was administered at the beginning and ending of a limited number of classes ranging in size from 16 to 90 students at ASU and TAMU in summer and fall of 2002. These early results revealed some interesting points as follows. The incoming test revealed the presence of both "prior misconceptions" and knowledge gaps resulting from earlier coursework. The exiting test showed both that some "prior misconceptions" persisted and also that new "spontaneous misconceptions" had been created during the course of the class. The results also showed that a few questions needed rewording, reworking, or replacement to avoid ambiguity and/or misinterpretation. Most classes showed a limited, 15% to 20%, gain in knowledge between course pre-test and post-test scores, but one class, which used some active learning, showed a gain of 38%. Examples of results showing broadly held misconceptions in some of the key conceptual areas will now be presented and discussed.

An important topic in the geometry area, which students often find difficult is the characterization of points, lines and planes (Miller indices) in crystal structures. A solid knowledge of this topic is required to understand a variety of other topics in the course, which include deformation behavior and mechanical properties of metallic systems. It is assumed by most faculty that, as a starting point from prior work in geometry and trigonometry, students understand what are the general nature and characteristics of features of solid geometrical objects and, in particular, those of a cube. This did not prove to be a good assumption. This knowledge was tested with the MCI questions, one of which is shown below. Mistakes on this question could be classified as "prior misconceptions".

In a cube there are <u>***</u> sides and <u>***</u> edges.

a) 4 and 6
b) 4 and 8
c) 6 and 8
d) 6 and 12
e) 8 and 12

The percentage of entering students that chose the correct answer, d), was 61% at ASU and 79% at TAMU. The most frequent incorrect answer was c). This misconception is probably due to the fact that students forget to count the four edges, which connect opposite faces of the cube. The underlying origin of the misconception is probably a limited ability to visualize 3-dimensional solid objects. A possible explanation for the lower ASU score may be the fact that there is no introductory design class at ASU, which emphasizes technical drawing or computer aided design (CAD). On the other hand, TAMU has a major CAD component in their introductory, yearlong design class, which would help in 3-D visualization of the features of the cube. An interesting outcome of the results of this question is that concept inventory questions may reflect differences in curricula in different engineering programs.

The percentage of exiting students that chose the correct answer was 81% at ASU and 88% at TAMU. The difference in correct percentage was reduced but persisted. An interesting physical aspect of tests given at ASU is that, about half of the 50 students who chose the correct answer drew wire frame cubes next to this question. This indicates that the content and exercises in the course had improved 3-D visualization skills. On the other hand, 40% of the students that did not draw the figure chose the wrong answer. Overall, this example shows that student difficulties with indexing planes may have, in part, a more fundamental origin in the 3-D visualization and manipulation of simple geometrical figures.

Another important topical area which students often find difficult is phase diagrams. A solid knowledge of this topic is required to understand the origin of microstructures in materials. This, in turn, is critical in understanding the associated processing and property relationships of materials. It is probably assumed by most faculty that, as a starting point from prior work in chemistry, students understand the concepts of solubility and solubility limit. This may not be a good assumption, as demonstrated by the results of this MCI question as discussed below.

> When three tablespoons of salt are mixed into a glass of water and stirred, about a teaspoon of water-saturated salt remains on the bottom. If a small amount of salt is slowly added to the glass while stirring the solution, the concentration of the salt in the solution will:
>
> a) increase
> b) stay the same
> c) decrease

The percentage of entering students that chose the correct answer, b), was 39% at ASU and 50% at TAMU. The most frequent incorrect answer was a). This misconception shows that that students do not understand the concepts of solubility and solubility limit. The underlying reason may originate from prior chemistry course work, where students may not develop a working knowledge of equilibrium phenomena. It is uncertain as to why the scores differ between ASU and TAMU, but additional data collection will provide better statistics to which will help determine if the difference is real.

The percentage of exiting students that chose the correct answer was 67% at ASU and 66% at TAMU. The small knowledge gap disappeared, but still one-third of the students at both schools do not understand the concept of solubility limit. This is an example where students do not have a good understanding of a topic introduced in chemistry and also that, although there is some improvement, the concept is still not well understood at the end of the materials course. Thus, this example shows a question that reveals a "prior misconception" from the entering MCI test, as well as an exiting MCI "persistent misconception" that is not well addressed in the materials class.

Some topical areas may receive emphasis in the introductory materials course at different schools depending on the needs of their students. At ASU there is a stronger curricular emphasis on electrical properties of materials compared to the TAMU's stronger emphasis on mechanical properties. Such differences may be revealed by MCI questions that query student conceptual knowledge of electrical versus mechanical properties of materials as discussed below.

Aluminum is a better electrical conductor than is glass because aluminum:

a) has more total electrons per volume
b) has more conducting electrons per volume
c) has electrons which move faster
d) has more electrons which move slower
e) has more conducting electrons per volume that move faster than those in glass

The percentage of entering students that chose the correct answer, b), was 20% in classes at ASU and 36% in classes at TAMU. The most frequent incorrect answer was e). The misconception here is that electrons move faster in aluminum than glass. The reason for the difference in ASU and TAMU scores is uncertain.

The percentage of exiting students that chose the correct answer was 76% at ASU and 51% at TAMU. A possible explanation for the higher ASU score may be the fact that there is more emphasis on electrical properties of materials in ASU materials courses compared to the stronger mechanical properties emphasis in TAMU materials courses. The results of this MCI question show an example of how MCI questions can show differences in topical emphasis in course content.

A topical area which students often find difficult is the mechanism of plastic deformation of metallic materials. A solid understanding of this topic is required to understand the relationship between processing and mechanical properties of metals. Students entering the course could not be expected to understand the atomic level mechanism of deformation and, as such, quite creatively generate new "spontaneous misconceptions" on the topic based upon prior real-world experience or course work knowledge. The distracters in this MCI question were generated from student responses from an "intuition quiz".

If a rod of metal is pulled through a tapered hole smaller than the diameter of the rod, the strength of the metal in the rod increases. This is because:

a) the density has increased
b) there are more atomic level defects present
c) there are less atomic level defects present
d) the bonds have been strengthened
e) the bonds have been compressed

The percentage of entering students that chose the correct answer, b), was 8% at ASU and 7% at TAMU. The most frequent incorrect answer was e). The origin of this misconception is that students at both schools do not understand the atomic mechanism of deformation, which is controlled by the motion of linear defects called dislocations. Deformation of a metal occurs by dislocation motion and the greater impedance to the motion of dislocations, the greater the material's strength. Thus, dislocations that formed during deformation will block the motion of other dislocations, thereby increasing the strength of the metal. It is not surprising that entering students in a materials class do not choose the correct response, since it represents new content that is first encountered in the course, so it is acceptable to have lower incoming scores. It is also interesting to note that the scores of 7% or 8% are below random value of 20%, which demonstrates the appeal of student-generated distracters.

The percentage of exiting students that chose the correct answer was 23% at ASU and 38% at TAMU. A possible explanation for higher TAMU score may be the fact that there is more emphasis on mechanical properties of TAMU materials courses whereas there is greater emphasis on electrical properties of materials in the ASU materials courses. This suggestion is also supported by the results of the previous question where ASU students performed better on an electrical property related question. These results appear to show how MCI questions may reveal differences in course content emphasis. Another important point to be noted on this question is that the topic of atomic mechanism of deformation of metals and the relationship to strength is clearly a difficult topic for students to understand at both schools since three-quarters of ASU and two-thirds of TAMU students had incorrect answers. Another possibility is that the question, as written, does not properly capture the concept of the deformation mechanism. The questions arising from the results of this MCI question show the need for further investigation of the student's learning approach and understanding of the topic.

Summary and Conclusions

This paper has presented a brief justification, approach and methodology to the development of concept inventories and, in particular, the Materials Concept Inventory. Activities, guidelines, and possible problems in the development of the MCI have been described. Early results appear to demonstrate that the MCI can be a useful tool for assessing the level of prior conceptual knowledge of incoming students as well as knowledge gain when comparing the results of students exiting from an introductory materials engineering course. An interesting outcome of the early results is that the MCI may well reflect differences in curricula at two different engineering colleges, ASU and TAMU, as well as differences in topical emphasis in materials courses in the two colleges. The results raise a host of new questions on topics such as teaching methodologies, prior course preparation, approaches to enhance knowledge transfer, and teaching effectiveness. These and other questions offer many opportunities for research on topics of broader interest to engineering education as well as on topics specific to questions and distracters and misconceptions related to the MCI. The ultimate hope is that, in the future, broader participation in development and use of the MCI will lead to healthy debate and change in teaching in the materials education community and in engineering science courses in general, in the same way that the FCI has done for the physics education community.

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