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A New Paradigm for Learning the Fundamentals of Materials Science & Engineering

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Abstract

The learning and understanding of the fundamentals of materials science and engineering is difficult and nonengaging for many students. This paper discusses a new technique that incorporates two features not often incorporated in traditional introductory courses. One is the inclusion of assigned questions that require the students to explain in their own words materials concepts found in the course textbook. The other involves the paradigm of materials science and engineering, which consists of the four components: material performance, properties, structure, and processing. Assignments are made wherein the student is required to explain, for a specific material or phenomenon, how one paradigm component relates to another component. For example, provide an explanation as to why and how the mechanical properties (strength and ductility) of an iron-carbon alloy are related to its microstructure.

Introduction

Materials are very important and extremely interesting! Everything physical is made of materials and many of them and their characteristics are fascinating. Yet, some engineering students from other disciplines complain that their materials courses were dreadful and a waste of time.

Numerous factors influence level of interest and commitment as well as the understanding and knowledge a student takes away from a course at the end of the term. Factors that influence the quality of take aways include the following:

- For the student—self-discipline, motivation, commitment to studying/learning, and course preparation (prerequisites)
- For the instructor—personality, expectations of students, recognition of student limitations, pace of course, commitment to quality instruction, empathy for students
- Course/classroom conditions—class size, classroom size and arrangement, meeting time
- Mode of teaching—lecture, active learning [1], problem-based learning [2], "flipped classroom" [3], Process Oriented Guided Inquiry Learning (POGIL) [4]

Of course, each of these modes of teaching has its advantages and disadvantages. In addition, many of the factors listed are outside the instructors' jurisdictions.

The authors of this paper have been involved with the discipline of materials science and engineering for many years—as students and instructors. Most of their experiences in these contexts have been with the lecture mode of teaching, probably because their instructors taught using this mode, it is relatively easy to implement, and, as instructors, they were in control of the classroom experience.

The Typical Course

Often lecture-mode courses have large class sizes and are service courses for students in other departments. A typical class period may begin with a brief review of the previous lecture and perhaps a short discussion of homework problems that had been assigned. The instructor then presents the lecture, which consumes most of the remaining class time. At the end, students may be assigned text readings and more homework problems to be solved and submitted at the next class period. Exams may be composed largely of mathematical problems, which are variations of those from the homework. Student learning from this mode of teaching is primarily to solve problems (most often using equations) for numerical solutions and not to develop a deeper understanding of the underlying concepts of materials science and engineering.

For modes of teaching other than pure lecture, again the emphasis is often placed on developing problem-solving skills, which are conducted during the class period and under the direction of the instructor and/or teaching assistants.

Over time, the authors came to realize these approaches lacked several important types of learning opportunities for students of materials science and engineering. Most of the fundamental principles of this discipline are descriptive in nature (subject to being described), and do not involve using equations to solve mathematical problems. Likewise, most of the content contained in classroom lectures (notes), readings from textbooks and other written sources, instructor-prepared video lectures, etc. is descriptive. Yet, in most courses, students are not exposed to activities that provoke understanding of this descriptive material. That is, there is no student accountability for the reading/studying assignments.

The Concept of Concepts

The authors struggled for quite some time searching for a pedagogical approach to facilitate the understanding of materials principles. A strategy was eventually formulated that involves the understanding of *concepts*. A concept is an abstract mental idea, notion, or something one thinks about; and most of the subject matter in materials science and engineering is conceptual. There is an incredible number of concepts in this discipline: atomic bonding, crystal structure, dislocation, microstructure, stress, fracture, phase and phase transformations, corrosion, and magnetism to name a few. Concept understanding is different than memorizing equations and using these equations to solve problems. Unfortunately, the development of student concept understanding is highly neglected in many materials science and engineering courses, which, in the opinion of the authors, is a serious deficiency. The process of learning to understand concepts requires some mental activity such as pondering ideas and reflective thought. It involves a higher level of comprehension than mere memorization and is more demanding of the student. Furthermore, teaching (having students learn) concepts is difficult.

To illustrate concept understanding versus equation memorization, consider Fick's first law for diffusion, as follows:

$$J = -D\frac{\Delta C}{\Delta x}.$$

Here J is the diffusion flux, D the diffusion coefficient, and $\Delta C/\Delta x$ the concentration gradient. To solve a problem, say for the diffusion flux, it is necessary to have the equation memorized (or have the written form available), know the names for D and $\Delta C/\Delta x$ (or ΔC and Δx), be provided values for these respective parameters, do some algebra, and punch the values into a calculator.

Understanding this equation is more complicated. Memorization is necessary, but, in addition, what each parameter in the equation means or represents is required (for example, providing a written definition or explanation for each parameter).[1]

Question-Based Understanding

How are concept-understanding exercises implemented in an introductory materials science and engineering course? What kind(s) of assignments can an instructor provide to help students come to understandings of important concepts? To reiterate, for the student, developing understandings of concepts (i.e., thinking and pondering) are toilsome activities for the learner. Whereas, for the instructor, formulating questions that elicit appropriate mental processing on the part of students is undoubtedly also difficult.

The authors wrestled with finding a mechanism to motivate students to concept understanding, and eventually they came up with some ideas. First, it was decided to design assignments for students requiring them to provide answers to concept-related questions. Answers would be in the form of written descriptions, explanations, and definitions, and could be recorded/reported on digital devices such as a laptop, iPad, smartphone, etc. Generating answers would require some mental activity for the student; some reflective thinking and pondering, more than just memorization. Grading of answers would be based on content and quality of written statements.

The next issue that needed resolution was finding sources of concept questions and their answers. It was decided to use the textbook as a source for both questions and answers. Each question would ask for a definition/explanation/description that relates to some concept discussed in the text. For example, "define diffusion flux and cite its units." For an answer, the student first needs to do a search of the textbook, find and peruse the associated material, and, finally, think about and formulate a written-statement answer in his/her own words. Hopefully, this thinking about and writing the answer will evoke some level of understanding of the concept. We propose "question-based understanding" (acronym "QBU") as an apt title for this approach of teaching.

Regarding sources of questions, the authors plan on preparing one workbook for students and another for instructors; both will contain an exhaustive list of concept questions for all topics in the textbook.

The Paradigm of Materials Science and Engineering

Another compelling problem in many introductory materials courses is that many seemingly disparate concepts are discussed with virtually no rationale of how they are related to

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[1] With regard to Bloom's taxonomy of cognitive skills [5], memorization of equations fits into the lowest category (remembering), whereas developing concept understanding corresponds to the second hierarchical level (understanding). Practicing engineers should develop mastery of the four higher levels (applying, analyzing, evaluating, and creating) which, hopefully, will be achieved in more advanced courses (e.g, senior capstone project).

one another. For example, what kinds of relationships exist among atomic bonding, crystal structure, imperfections, diffusion, phase diagrams, phase transformations, and mechanical properties? How do they fit together? Why is it necessary to study and understand these topics? For most students (including materials majors) this disorganization of topics proves to be very confusing and mind boggling. Consequently, student interest and motivation begin to wane, and by the semester's end many (most) students have developed a dislike for the course and have become disinterested in the science and engineering of materials. This situation is unfortunate since engineers design devices and products that are constructed of materials.

After considerable thought on this matter, the authors decided that developing student understanding between/among concept relationships is one solution—that is, to organize the topics in such a way as to provide some perspective of the directions in which topic discussion are proceeding. The next dilemma was to find a way to accomplish this task. A "Eureka" moment occurred upon the realization that the *Paradigm of Materials Science and Engineering* could be used as a framework to fit these concept relationships together. The Paradigm may be stated as follows: The performance of a material depends on its properties, properties depend upon structural elements of the material, and structure is dependent on how a material is processed.[2] On occasion the Paradigm is abbreviated as "PSPP."

Often components of the Paradigm are presented pictorially at the corners of a tetrahedron, as in Figure 1*a*. Functionally, a linear representation of these four components, as in Figure 1*b,* is more accurate; arrows indicate dependencies (i.e., relationships) between components.

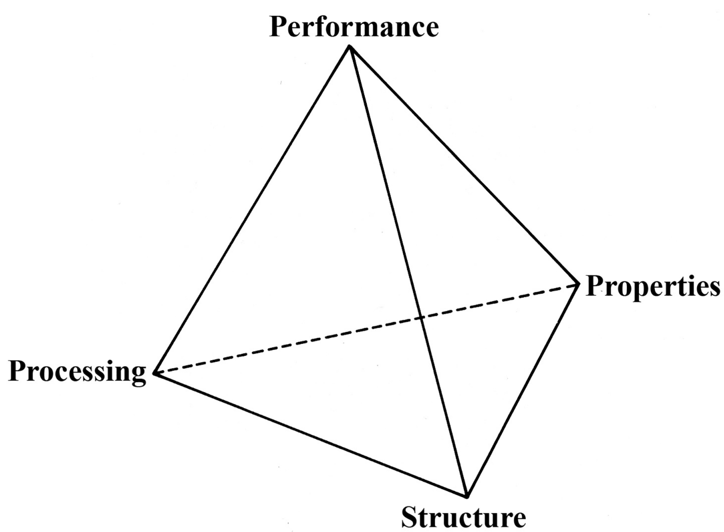

Figure 1*a* Representation of the Paradigm of Materials Science and Engineering—components at corners of a tetrahedron.

[2] The first articulation of the *Paradigm of Materials Science and Engineering* is found in *Materials Science and Engineering for the 1990s—Maintaining Competitiveness in the Age of Materials*, National Academy Press, Washington, DC, 1989, pp. 27-29.

Performance ⟵ Properties ⟵ Structure ⟵ Processing

Figure 1*b* Linear depiction of the Paradigm of Materials Science and Engineering—components at corners of a tetrahedron.

Concept Relationships According to the Paradigm

In very simple terms, the field of materials science and engineering functions according to the Paradigm. Therefore, we propose using the Paradigm to teach materials concept relationships—that is, for a specific situation how does one component depends on an adjacent component per Figure 1*b*. In this regard three possibilities are as follows:

- How structure depends on processing
- How properties depend on structure
- How performance depends on properties

Implementation of the exploration of concept relationships is by homework assignments similar to those for concept understanding as outlined above. In this case, assignments are in the form of questions that ask for explanations for a set of concept relationships (e.g., properties and structure) for a specific situation. Students locate related content in the textbook, and then provide written-statement answers in their own words. Formulating and writing answers require pondering and thought processes that, hopefully, stimulate student understandings of relationships and realizations of why the discussion topics are relevant and important. In addition, the sequence of the elements of an answer need not follow the flow of the textbook and may come from more than one chapter. Concept-understanding questions can also be included on tests. This approach to teaching/learning is termed Concept-Related Learning (CRL).

For example, consider the structure-property relationship for the phenomenon of solid-solution strengthening: for a single-phase metal alloy an increase in strength occurs as a consequence of adding impurities that form a solid solution. Structural elements are dislocations and impurity point defects (substitutional and interstitial), whereas the properties are yield and tensile strengths. The answer would describe concepts of dislocation structure (on the atomic level), lattice strains fields in the vicinities of dislocations and impurity atoms, strain field interactions between dislocations and nearby solid-solution impurity atoms, and the resultant impedance of dislocation motion and increased alloy strength.

A multitude of concept-relationship questions covering virtually all topics discussed in an introductory course and consistent with the four paradigm components will be generated by the authors. These will be included in the student and instructor workbooks mentioned above.

Another device available to promote student understanding of concept relationships is the *concept map*, a visual or pictorial diagram that represents concept connections. Students can be assigned to create maps for specific situations. One type of map displays hierarchical relationships using a vertical organization or ranking scheme. For example, a map for different types of magnetization might appear as in Figure 2. Furthermore, other concept maps that demonstrate concept performance-property, property-structure, and structure-processing relationships are also possible. The lay-out for this map type is horizontal, as with the representation of components of the Paradigm in Figure 1*b*.

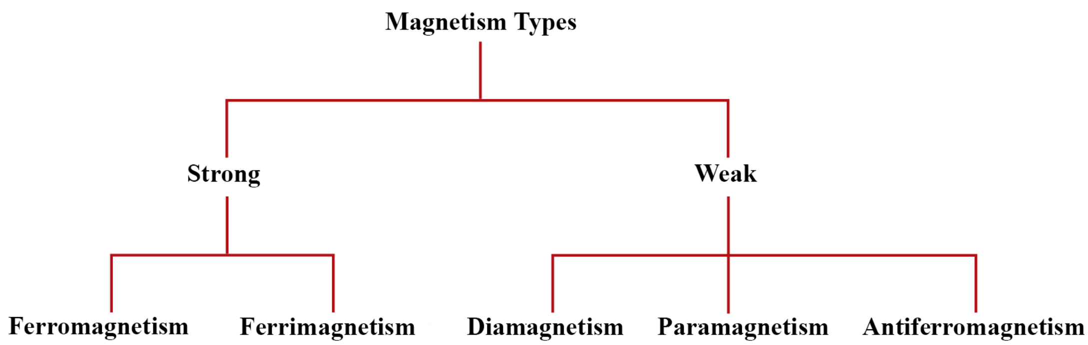

Figure 2 Hierarchical concept map for the several types of magnetism.

Implementation of Question-Based Understanding and Concept-Related Learning

Significant course reconstruction will be necessary for the adoption of this mode of teaching. The instructor must first decide, in general, what portion of class periods is to be devoted to discussions of answers to QBU and CRL questions and solutions to assigned homework problems, and if some time is to be allocated to traditional lecture. In addition, the mix of QBU and CRL questions needs to be considered. Here, one possibility is to use QBU questions that relate to assigned CRL questions.

This QBU-CRL approach provides many opportunities for the instructor to tailor the course to student needs and his/her preferences. For example, considerable flexibility is afforded in several areas. Two of these are topical organization and content; the instructor has complete control over what is taught how, without any constraints such as the content and organization of an adopted textbook. To provide some sense of continuity of topical content, students probably will need to jump from one chapter to others in finding answers to CRL questions. When an instructor wants to skip over a topic, he/she might want to assign a couple of QBU questions. On the other hand, several CRL questions might be assigned when in-depth student understanding is desired.

Another possible option is to make group assignments, wherein each of three or four students is assigned to answer a different a CRL question outside of class, and then they meet in-class to share and discuss their answers.

At this time it is appropriate to provide three caveats as suggestions for implementation of this approach:

- Regarding homework assignments, in addition to answering CRL and QBU questions, students should also be assigned to solve problems (using equations).

- Exams and quizzes should include some of the questions students were assigned to answer in homework assignments.
- This approach can be used in concert and to complement other modes of teaching.

Perhaps the most significant deterrent to the adoption of this mode of teaching is assessing and grading student responses to assignments. There is the need for someone (i.e., the course instructor, a graduate assistant or assistants) to assume these responsibilities, which are laborious and time-consuming (and expensive). One possible resolution to this issue is the implementation of artificial intelligence, which would require the development of appropriate software. Another possible solution is to have students discuss and other students' assignments in class.

Summary

This paper presents a new and novel method of instruction that incorporates two approaches to teaching/learning not often found in traditional materials science and engineering courses. For one approach, the goal is to develop student understanding of materials concepts. Students are assigned to provide, in their own words, written explanations/definitions/descriptions to concept-related questions. Answers to these questions are presented in the textbook, and concept understanding is fostered from student searching, finding, writing activities. This approach is termed Question-Based Understanding.

The framework for the other approach is the Paradigm of Materials Science and Engineering, which consists of four components: properties, structure, and processing. Students are assigned to provide, for some material, phenomenon, or situation, a written explanation of the relationship between one component and another component. Concept-Related Learning is used to identify this approach.

Questions for both QBU and CRL approaches will be generated by the authors. They would like to encourage (and would also appreciate) question contributions from MSE instructors and content experts. Also welcome are comments and suggestions that could improve and fine tune this instructional technique.

Finally, as the title of this paper suggests, this instruction mode may be thought of as a new paradigm of learning the fundamentals of materials science and engineering.

Please note: this new approach for teaching an introductory materials course has been in a state of flux and evolving over the past several months (between about October 2022 and April 2023). Consequently, during this period a few changes (in terminology, procedures, and explanations) were made. Thus, Conference attendees will notice some inconsistencies between digital and oral presentations.

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