AC 2010-274: MEASURING DIFFERENCES IN STUDENT OUTCOMES IN A BASIC MATERIALS ENGINEERING COURSE FROM COLLABORATIVE EXPERIENCES FOCUSED ON BIOMEDICAL APPLICATIONS

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Abstract

During the past seven years several known best practices in teaching to improve student learning outcomes have been integrated into our Introduction to Materials Engineering course, transforming it from a traditional lecture only course to a course focused on conceptual learning with many active, collaborative experiences. In addition to serving engineering technology students, the course is the basic materials engineering component of a new interdisciplinary Materials Science minor that includes chemistry, physics, and geology students. The course is also required for manufacturing and supply chain management majors. For the past two years, biomedical devices and case studies have been introduced as focus areas with the intention of improving student learning in fundamentals such as structure-property relationships, materials selection based on mechanical properties/design criteria, and phase transformations. These areas were targeted because previous assessment data revealed that several student outcomes in these areas could be improved. Collaborative exercises which build upon materials selection and performance in devices experiencing significant loads during service, such as orthopedic replacement devices and stents, seem to be promising tools in improving certain student learning outcomes and have built student interest and excitement in the course. Even in this diverse audience, students have a conceptual foundation from which scaffolding can be built to enhance their knowledge base in materials engineering. To illustrate, it is essential that the femoral stem in a hip replacement load the bone appropriately so that bone loss does not occur from stress shielding. And, the interplay of material properties with design geometry is obvious in these constrained systems. Another example used in developing understanding in structure-property relationships is the use ultra high molecular weight polyethylene in joint replacement wear surfaces. It is possible to conceptually link the required mechanical properties of components to the effect of the degree of polymerization, examine the difference between semi-crystalline and amorphous plastics, and the resulting differences in wear properties.

This paper compares the student learning outcomes that were measured for the course sections which used collaborative work based upon biomedical devices and collaborative written research work to the outcomes of previous course sections that did not use the biomedical device focus or collaborative written work. The paper also highlights differences in student performance with a previous, different focus area - music strings and stringed musical instrument design. Student learning style data is also detailed within the paper. Pre- and post-course concept questionnaires and traditional tests scores were used as evaluation tools. The pre- and post-course concept questionnaires were modified this academic year to further probe existing misconceptions and conceptual gains. The paper concludes with summary of the assessment information, lessons learned, and future directions for this course.

Introduction

During the past seven years several known best practices in teaching to improve student learning outcomes have been integrated into our Introduction to Materials Engineering course,
transforming it from a traditional lecture only course to a course focused on conceptual learning with many active and collaborative experiences. During this development period, several papers that outline the various aspects of these changes and describe the resulting changes in student learning outcomes (with remaining challenges) have been published elsewhere\(^1\text{-}^8\). Based upon the conclusions drawn from many research studies in engineering education, most of the elements of a student-centered approach are now present in the course: cooperative learning, case-based teaching, active/inquiry learning, concept learning, problem-based learning, and constructive alignment\(^9\text{-}^{24}\). Additionally, educational research indicates that learning takes place when students are able to build scaffolds from existing cognitive structures to new information\(^{25}\text{-}^{28}\). Similarly, in cognitive constructivism, experiences lead to knowledge, and knowledge acquisition is highly influenced by prior learning. Researchers such as Biggs\(^11\), Felder\(^9\), and Prince\(^9\) have confirmed fundamental principles such as “instruction should begin with content and experiences likely to be familiar to the students and that new material should be presented in the context of its intended real world applications”\(^9\). It is also known that motivation to learn affects student outcomes and that learners are motivated “when they can see the usefulness of what they are learning and when they can use it to do something that has an impact on others”\(^{25,9}\). Thus, it seems appropriate to find contexts for materials engineering course activities that draw upon the students’ pre-existing knowledge and their previous/personal experiences. In our courses, we have tried two such context areas. One of these focus areas used music strings and stringed instrument design and the other, newer focus area uses biomedical devices that experience significant loads in service. The student response to the two different context areas differed and those differences are highlighted below. However, this paper focuses mainly on the biomedical device context area results since these activities are able to address a broader range of important student learning outcomes in materials engineering and other papers have already described the stringed instrument design approach\(^2,5\). A previous conference paper describes these newly developed biomedical based activities in much more technical detail\(^1\).

Engineering education research also indicates that individual learning styles must be considered in course structure and content and that it is important that students understand their own learning style\(^29\text{-}^{37}\). In our research, the Felder/Soloman Index of Learning Styles (ILS) was used to examine student-learning styles. The ILS results presented here show that the students in the course do indeed have a wide range of learning styles and, overall, were similar in nature to larger studies done elsewhere\(^{28\text{-}39}\), with some minor exceptions. Additionally, pre- and post-course concept questionnaires were used to evaluate the success of course modifications and to further probe how students actually learn materials engineering. In these questionnaires we have identified cases where students try to create new mental structures based upon their prior knowledge and also upon their pre-existing misconceptions. For example, students have a difficult time reconstructing their pre-existing misconception that metals, such as copper, should be bonded with either ionic or covalent bonds. We think this difficulty may be because chemistry courses focus on these two bonding types and because the students can construct scenarios (although, incorrect ones) where electrons in metals can be shared or transferred to make their mental models work correctly. Students also have a difficult time connecting new knowledge where they do not have an existing knowledge base if it is not presented in context. And it is also known that the context or contexts must be repeated a number of times for it to be effective. To illustrate, students have a difficult time connecting isotropic material properties to polycrystalline materials likely because “iso” means one, and “poly” means many, and because
the students have little prior knowledge or experience with these terms and ideas. (Both context areas address these concepts but use completely different instructional techniques.)

Also, it became clear during our review of both the pre- and post course concept questionnaires and the scores from individual questions on traditional exams, that the students were still having difficulties making proper connections between engineering design constraints and material indices or properties that are appropriate to use when assigning materials for the design case. For example, the students often make the case that a product or part should be as lightweight as possible. However, linking the lightweight design requirement to the appropriate material index (such as yield/density for simple tension members) still seemed challenging for many students, even after many alterations had been made to the course. The students were also having a difficult time linking together all the different pieces learned in course modules to the “big picture” of materials engineering. Some students seemed to need more tangible reasons to help them link together structure and properties. Finally, the higher order thinking needed to differentiate between material properties and geometry effects needed further development.

Ultimately, we agreed with the research literature that tells us that "usable knowledge" is not the same as a mere list of disconnected facts. “Experts' knowledge is connected and organized around important concepts (e.g., Newton's second law of motion); it is "conditionalized" to specify the contexts in which it is applicable; it supports understanding and transfer (to other contexts) rather than only the ability to remember.”

Thus, there was reason to believe that materials used in biomedical devices, which experience significant loads during service, such as orthopedic replacement devices (knees and hips) and stents, would provide accessible contexts for our fundamental materials engineering course. Students who enter the course do already have some conceptual idea of what a hip replacement is or why an arterial stent might be needed and already know that these devices should last as long as possible. In fact, it has proven to be straightforward to stimulate students to think carefully about what information they need to know about these applications so that they can make decisions about which materials might be “best” to use in a biomedical device. The students readily grasp that it is important that joint replacement components be as light as possible at the beginning of the term. By the end of the term, the students are able to properly connect the mechanical properties needed to accomplish design constraints, and were able to sort out the complex interplay between material properties and product geometry. Our preliminary data from using the biomedical device approach is promising and shows some enhanced outcomes based on improvements in traditional exam scores and in pre- and post-course concept gains in the use of the elastic constant, tensile and compressive strength, specific stiffness, specific tensile strength, specific compressive strength, fatigue life, creep, and wear resistance. The increased number of collaborative experiences in the course certainly also helped improve these same outcomes. Currently, the students not only complete a collaborative term long research paper in teams, but they also complete all other in-class active exercises with these same team members. Most class sessions now include active, team based work.

We carefully reviewed all of our assessment data and of the 40 detailed Student Learning Outcomes (SLOs) for the course, the following 13 outcomes were targeted for improvement using the biomedical device focus approach.
Targeted Students Learning Objectives

1. Select the appropriate engineering materials for specific engineering applications using:
   yield strength, tensile strength, ductility or elongation, flexural strength, hardness, fatigue
   life, wear, and creep;
2. Describe why each of the fundamental mechanical engineering properties of materials
   covered in the course (stress, strain, elastic constant, creep, fatigue, wear, hardness,
   Poisson’s ratio, toughness, ductility, flexural strength, impact strength, elongation) are
   each important in engineering design and how they interact;
3. Explain the differences in mechanical properties for isotropic and anisotropic materials
   (including orthotropic materials);
4. Explain the differences in mechanical materials properties for single crystalline,
   polycrystalline, semi-crystalline and amorphous materials;
5. Describe the basic structure of and properties for engineering polymers;
6. Identify key differences in the properties of and applications for thermoplastics,
   elastomers, and thermostetting plastics;
7. Distinguish between geometric and material properties effects in engineering designs;
8. Be able to calculate engineering stress, strain and the elastic constant from data and for
   basic engineering applications;
9. Size basic parts for simple engineering designs using safety factors;
10. Classify the basic stress/strain behaviors of viscoelastic materials;
11. Explain strengthening mechanisms for mechanical properties;
12. Describe the fundamentals of how engineering materials fracture or fail (and the usual
    causes of failure) in practice; and
13. Evaluate the effect of the in-service operating environment on the estimated life-time of
    materials or on fit for use.

In previous course sections, we had used music strings and stringed musical instrument design as
a somewhat similar platform in order to enhance several (but not all) of these same SLOs. While
the approach was particularly effective for students who were interested in music and
instruments, it did not engage all the students equally well. The students who had some
connection to musical instruments were especially inspired by this approach, but the students
with no interest in music were observed to be less engaged in the in-class exercises, although at
that time the exercises were not all completed collaboratively. In other words, the musical
instrument approach was not stimulating enhanced interest for all students, although the gains in
outcomes were, positive overall, but were not across the same breadth of SLOs as is the case for
the biomedical device approach. There is also another significant difference that we observed
between the two approaches. In the musical instrument approach, some students still had a
difficult time knowing whether their answers were reasonable or not. In the biomedical device
approach, the size limits are very obvious and the students can easily determine, with only a
small amount of practice, whether their answers are indeed reasonable. For example, a
replacement femoral stem must fit inside a human femur, and the stem cannot be something
impractical like ten times the diameter of the bone. Currently, the students measure the
approximate size of the appropriate bones from a full-size plastic model of a human skeleton
during an in-class collaborative exercise; and those design limits seem “sticky” in that the
students remember the approximate sizes for the remainder of the term. Even the students who
miss a collaborative exercise are able to judge the appropriateness of their answers for biomedical applications. In the musical instrument approach, some design answers were wildly wrong, but a small number of students had difficulty in knowing so. And, only the students with some experience with a stringed instrument knew how big a string ought to be, for example. The biomedical device approach seems to be more uniformly appealing, perhaps because it is easy to see the importance of knowing about the materials in the devices since those materials directly affect the life and performance of the device. And, it may be because all the students come to the class knowing something about the devices, readily grasp design constraints, and consider the devices important. However, the biomedical device approach did not inspire any students to go way beyond the materials selection and design work required for class in a way that the musical instrument approach did. In the musical instrument approach, a significant number of students created unique instruments from interesting materials and appropriately justified the use of those materials for particular components. The musical instrument approach also improved student outcomes in differentiating isotropic and anisotropic material properties more than the biomedical device approach does. Perhaps there is a unique combination of these two focus areas that may prove most effective in improving all the targeted SLOs. In-class opportunity time is the factor that will limit the use of combinations of focus areas during a term. The ability of a theme to cover many different kinds of SLOs so that theme can be repeated and built upon throughout the term makes the biomedical device approach especially appealing.

**Student Learning Styles**

The research literature in engineering education also emphasizes the importance of understanding and considering student learning styles in developing effective teaching strategies\(^{25-37}\). We used the Felder/Soloman ILS to understand student-learning styles in our materials engineering course. The ILS evaluates four dimensions: active-reflective, sensing-intuitive, visual-verbal, and sequential-global; and the reliability and validity of the instrument has been investigated\(^{30,39,40}\). While the ILS may or may not be a perfect instrument, it is certainly widely used to investigate student-learning styles and much research work has included student data obtained from the ILS\(^{28-38}\). Felder and Spurlin suggest two principal applications for the ILS\(^{39}\). “The first use is to provide guidance to instructors on the diversity of learning styles within their classes and the second use is to give individual students insights into their possible learning strengths and weaknesses”\(^{39}\). With these appropriate uses in mind, we asked the students to voluntarily take the ILS at the beginning of the term at the same time we asked them to voluntarily complete the pre-course concept questionnaire. We use birth date to identify the survey takers as to keep the data anonymous and to help the students understand that their grades are in no way linked to the outcome of the ILS or surveys. Usually, more than 90% of the students voluntarily complete the pre-course concept questionnaires and last term a similar percentage completed the ILS. Survey response was much lower (~50%) when class time was not devoted to the instruments. Additionally, we also devote class time to helping the students understand why the ILS information is important to them personally. Most of the students report that they have never inventoried their own learning styles before and found the exercise informative. Several of the students have made specific positive comments about the use of these instruments in their evaluation of the course. Many of the students seem genuinely interested in the ILS and also value the personal insights they gain from the ILS.
We were curious to see how different our students would be from the literature reports of student learning styles that were obtained from much larger ILS data sets. Additionally, we were also interested in how different separate sections of the class would be from each other with regard to the ILS as there certainly are differences in performance noted in different sections of the same course even with the same instructor. Figure 1 shows the ILS data from one section of a materials engineering course where 100% of the students completed the ILS survey. The blue bars show the students scoring 1-3 in one dimension and the red bars show the students scoring moderate (5-7) or high (9-11) in one dimension. On the ILS, a score of 1-3 indicates that a student is fairly well balanced on the two dimensions of the scale, while a 5-7 indicates a moderate preference, and a 9-11 indicates a strong preference. From our experience, Felder is certainly correct in stating that faculty members must be aware of the wide variety of student learning styles within their own courses. Examining the data from the ILS closely reveals that in any section of a course, there are many students who have a strong preference or moderate preference for one learning style over another and that all the students taken as a group have vastly different needs as individuals. It was somewhat surprising to us to find out how different each section could be with regard to the ILS data. While the N values in our data are small, there are reports in the literature with much larger N values. For example, the Rose-Hulman Institute of Technology published the ILS data from 1726 students and that data revealed a wide distribution of student learning styles for these students. It should be noted that our data shows somewhat higher numbers of students reporting moderate or strong preference for a visual learning style than in the literature, but our N values are all much smaller. And, it could be that the unique set of majors of students within this class, engineering technology, chemistry, physics, and business students, might produce different ILS data sets from the students enrolled in typical engineering courses. But, without a great deal more data, this is impossible to sort this out in any meaningful way. It seems more important to know what the ILS reveals for each particular section of the course.

![Figure 1. ILS Data from One Section of Materials Engineering (N=46)](image-url)
There are various research studies in engineering education literature that try to tie different outcomes to the students’ various learning styles. One study reported that, “learning styles seemed to affect the performance of the students when working together and the tendency seemed to be that mixed pairs in the active-reflective and the sensing-intuitive dimensions work better and that heterogeneous groups … and got better results”\textsuperscript{32}. Other researchers disagree and state “rather than using learning styles to adapt instruction to individual learners, educators’ effort will be better spent ensuring the most effective instructional methods are used for a given learning objective”\textsuperscript{36}. One study asserted that “whilst the ILS may have some value, as its authors recommend, as an instrument to assist students, particularly those of engineering, to specify their preferences for learning, extension beyond that is not advisable and … the use of the ILS as a predictor in a selection context was not at all successful”\textsuperscript{41}. Research is also currently underway as to whether the ILS or a similar instrument will be useful in creating media rich, web-based or computer-assisted instruction (CAI) that will be useful for students with differing learning preferences\textsuperscript{36}. Cook and others\textsuperscript{36} found that there was no difference in overall student performance between problem-first versus information-first (sensing-intuitive) learning.

Because there are collaborative exercises, reports, and presentations in our materials engineering course, it will be interesting to investigate whether the effectiveness of the collaborative teams could be enhanced by the “cognitive diversity” approach described in “Teamology” by Wilde\textsuperscript{48} or the heterogeneous group approach\textsuperscript{32} described above. Informal observations of our collaborative teams seem to support the idea that teams composed of individuals with vastly different learning styles are initially more challenging for team cohesiveness in exercises, but produce good project outcomes. However, no measurements have been attempted yet to evaluate team composition on collaborative outcome.

Based upon all the available information and research regarding the ILS, it seems that at this point the best use of the ILS is to inform both the instructor and their students about differences in learning styles and that instructors should be certain that there are opportunities for students
with these different learning styles to be successful in their courses. Interestingly, this, of course, was Felder’s main point when he developed the ILS in that he stated many times that not all students will be successful in courses which emphasize only deductive practice and that, at the time, most of the engineering education practiced in the United States emphasized only deductive practice. In our own materials engineering courses, the ILS data proved that there are indeed vastly different learning styles for the groups of students who take the course and that the inclusion of inductive practice in the course should improve student outcomes for most of the students. Thus, it is seems necessary to include the foundations of inductive teaching and learning in basic materials engineering courses to improve student learning. Cooperative learning experiences using biomedical devices that experience significant loads in service seem to be a good foundation for this inductive practice since it so clearly fits the basic tenets of this inductive practice:

- “it is possible to begin with content and experiences likely to be familiar to the students, so they can make connections to their existing knowledge structures.”
- “material is not presented in a way that requires students to alter their cognitive models abruptly and drastically.”
- “requires students to fill in gaps and extrapolate material presented in class.”
- “it involves students working together in small groups.”
- “… (it) seems likely that knowledge and skills acquired in one class will transfer to real world settings (as it) is a function of the similarity of the two environments.”

Biomedical devices have the fundamental advantage of having easily accessible and tangible contexts. Students who enter the course have a conceptual base for them and, additionally, the theme for medical devices can be continued throughout the course, starting from the introductory lecture. Even on the first day of the course, the concept of the elastic constant can be explained in enough depth so that the students can appreciate that the elastic constant of the femoral stem should match the elastic constant of bone or bone loss will occur from stress shielding. And, that enough stress needs to be placed upon the bone to prevent bone loss (remodeling) in an active material. Even on the first day, a discussion can begin about stress being a function of both load and geometry (and not material type). Similarly, vascular and peripheral stents made from shape memory materials provide excellent venues for hands-on learning about phase transitions and makes martensite/austenite transitions seem immediately important and interesting. Device recall case studies provide opportunities to link both structure and properties to in-service failures, as well as intriguing platforms from which to introduce ethical principles into materials engineering courses.

**Pre-Course Concept Questionnaires**

To help us assess the course outcomes, the students were asked to voluntarily complete a 25-question pre- and post-course concept questionnaire. We use them to identify the students’ prior knowledge, understand their existing misconceptions, formulate new teaching strategies, and evaluate the effectiveness of various teaching strategies. Approximately 50% of the questions evaluate knowledge of facts or properties and 50% of the questions evaluate conceptual applications of properties and facts. Similar to findings in other disciplines, an analysis of the results from the pre-course questionnaires show that sophomore level students enter the
course with only a limited understanding of materials, materials science or material properties and hold several, sometimes robust misperceptions. On the pre-course concept questionnaire, fewer than 50% of the students can cite a correct example of a ceramic or a polymer (see Figure 3), although almost all of them can identify a metal. Fewer than 20% of the students declare metallic as a primary bond type between two copper atoms, and almost all students (~80%) try to construct a reason for the bond being either covalent or ionic. Upon further investigation, this is not as surprising as we first thought since freshman chemistry courses do not cover metallic bonding in depth until near the end of the text and a specialist in chemistry education stated that “I would not expect the students to learn about metallic bonding in high school chemistry”. This particular misconception is robust and even though much of the understanding metals depend on understanding metallic bonds, not all students are able to deconstruct their misconceptions about primary bonds and some leave the course still convinced that somehow the “loose electrons in metals form covalent or ionic bonds”. Interestingly, more than 95% of the students know metals have the highest electrical conductivity, but they seem not to be able to link that knowledge with primary bond type. It is somewhat curious that not all the students are able to cite metallic as the primary bond type of metals after completing a materials engineering course. A deeper examination of this data shows that many of the students who answer this question incorrectly perplexingly do understand dislocation movement in metals (almost ~50%). We also speculate that some of the students who answer this question incorrectly must have had low course attendance as we have informal evidence linking poor course attendance to low course grades. Thus, there could be a relationship between the number of times the student actually completed the exercises that were designed to reconstruct knowledge and their ability to do so. When asked about this very question, chemistry professors keep emphasizing the fact that there is very little material in either high school or college chemistry about metallic bonding and state they are not surprised at all that students know almost nothing about metallic bonding after taking basic chemistry pre-requisites. So, it is probably not that surprising that some students answer this question too quickly and simply revert back to their more robust knowledge base about ionic and covalent bonding. Since materials engineering students usually complete both high school and university chemistry courses before taking materials engineering, it may not be completely surprising that not all students are able to reconstruct their knowledge in only one course, especially if they are answering quickly and not forced to think conceptually. When the students are forced to think conceptually before answering, their success rate is indeed higher.

Students also enter the course with very little understanding of basic engineering design. Initially, most of the students (~90%) think that the material plays a role in determining the stress within a particular engineered part in the pre-course concept questionnaire. Virtually, all of the students predict that a polyethylene diving board would deflect more than a steel diving board. Several of these same students made the case that a steel diving board would be under more stress than a polyethylene diving board because it is “stronger” (43%). By the end of the term, no student that attended the class regularly made this conceptual error since the introduction of the biomedical devices (an overall improvement of ~5%). Understanding the selection of materials for total joint replacements and working in collaborative groups seems to help the students separate design constraints from geometry effects and material properties. There collaborative research papers demonstrated significant improvement and will be discussed in a future paper in detail.
The questionnaire also examined what the students know about the connections between material properties and structure. Almost all the students (90%) knew that a material should get less stiff as the temperature of the material increased, and about 80% of the students gave a correct answer as to why this is so. Unfortunately, 90% of the students then conclude that the modulus of elasticity then should go up with increasing temperature. Additionally, the students seem to have only a limited understanding of any of basic properties of materials such as density, melting temperature, thermal expansion coefficient, and fracture toughness (impact resistance on the questionnaire) as they enter the course (see Figures 4 through 7).

Surprisingly, about 40 percent of the students think that either a ceramic or a polymer should have a higher density, in general, than a metal. Fewer than 10% of the students respond with meaningful answers why and, occasionally (< 5%), they report that if must be the structure of metals that make them so dense. About 30% of the students know lead is a dense metal and state that as a reason why they think metals are dense. About two-thirds of the students think that ceramics are the stiffest materials, but a third of those students think that is because the material
is hard. Most of the students who can correctly cite an example of a ceramic also report ceramics as being hard or brittle.

![Highest Stiffness Chart]

**Figure 5. Material Classification with the Highest Stiffness - Percent of Students Responding**

![Highest Melting Temperature Chart]

**Figure 6. Material Classification with the Highest Melting Temperature - Percent Responding**

Perhaps because of their personal experiences with commodity plastics, three quarters of the students think that polymers will have the highest fracture toughness or impact resistance. Most often the students cite that plastics don’t break when they are dropped, but almost none of them compare this behavior to metals. Approximately 15% of the students think that metals are tough because they dent, but these students do not compare metals to plastics either. None of the students who thought ceramics would be tough responded with a reason for believing so, but almost half of them also responded that ceramics are stiff and hard in response to other questions. The responses to the thermal expansion coefficient were the most varied and the reasons for their answers were not at all well constructed.
Overall, the findings from these surveys show how important it is to understand what the students know, in general, and what their misperceptions are about materials, as they enter our classrooms. Often, we have found pre-course findings surprising based upon our understanding of the content of pre-requisite courses and our assumptions about what the students retained from those classes. Most of the students’ responses seem to be based upon their personal experiences with materials rather than from them connecting knowledge from chemistry or physics to those properties. And, many of the students had not really given materials and their behaviors a great deal of thought before the course. All of these surveys have guided our course development and teaching strategies. Based upon our findings, it is certainly important to cover metallic bonding in depth in the course and repeatedly to help the students reconstruct their robust and sticky notion that metals are bonded with ionic or covalent bonds so that they conceptually understand the fundamental behavior of metals. Similarly, it is important to reconstruct the notion that metal bonds get weaker each time they are bent (the most reported response to what happens when a
bent paper clip eventually breaks). Although there is certainly variation from section to section in pre-course questionnaires, the “big picture” findings are not so conceptually different from each other. Understanding what the students know or think they know is certainly vitally important when choices are made as to how to best help the students learn materials engineering.

Class Findings – Post Biomedical Device Introduction

Students often rate our course in materials engineering as challenging and demanding likely because it draws upon basic conceptual knowledge from both chemistry and physics, requires a considerable command of mathematics to complete successfully, and covers a great deal of new material and terminology. In the past, students also reported that the design problems in the course were too difficult and required too many challenging calculations. Part of the issue surely resides with the wide range of sizes that the students encounter in any materials engineering course. Atoms are very small, Avogadro’s number very big, and mechanical properties such as tensile strength and elastic constant are somewhere in between. However, another part of the difficulty may lie in what kind of problems students are asked to solve. A student may not really know what a reasonable answer is for a design problem for which they have no personal context. Although the students may not know what the best material is for a joint replacement component prior to the course, they do know that it cannot be wildly bigger than the bone it is to replace and they do know why a change in length or diameter under load might be important for a metal stem inserted within a bone. Simply stated, the students can correctly guess the approximate size limits for biomedical devices. Even when we used a more contextual stringed instrument design focus for problems, students without a background in music had a difficult time understanding when their answers were impractical. Many textbooks do ask the students to solve materials problems without a fully developed context or in isolation. Thus, it seems appropriate to reconsider the types of problems students are asked to solve in materials engineering courses. Without contextual links, the students will not be able to form for themselves, the “big picture” of materials engineering or develop higher order thinking skills they need to make good choices for materials in practice.

To further explore the possibility of scaffolding from a preexisting knowledge base, the students were asked, in their pre-course concept questionnaire, why it is that total joint replacements only last for 15-20 years in service and what factors should be considered when designing the replacements. Their answers were surprisingly insightful and accurate. They cited items such as “wear from friction, internal flaws, constant use under cyclical strains, inability of the body to heal or regenerate artificial materials, biocompatibility, cost, weight, sterility, no fluid between artificial joints, too stiff for the body, plastic rubbing metal parts, too much stress on the remaining body parts, leaching of harmful metals into the body, fatigue, attack from body chemicals, too much stress on the artificial part, and too much flex on the area around the artificial part”. Unfortunately, a few students also cited “bonds weakening over time” as they did in the other pre-course concept questions reported earlier. More than 95% of the students answer the biomedical pre-course concept questions and, for the most part, the responses are interesting and insightful. In other words, the students do come to the course with some understanding of total joint replacements and, thus, enter the course with good contextual awareness of biomedical devices.
Most of the students are not familiar with smart materials pre-course. Almost 50% of them answered no idea in response on the pre-course questionnaire and another 30% had the wrong idea of what a smart material is (often confusing it with a composite material or a smart use of a material) before the course. Only 25% of the students correctly knew what a smart material was and could identify a correct example of one pre-course. No student confused a smart material with a composite material or the smart use of a material at the end of the quarter, and they certainly could all give an example of a smart material at the end of the term. The learning activities centered on Nitinol stents were also effective in phase transitions and wear. A question asking what classification of material the students would choose for a wear resistant application revealed that they really do not have a reasonably good understanding of the three basic classifications of materials as they enter the course. All but five to eight percent of the student could correctly draw “Ashby type” charts on wear resistance and other mechanical properties covered in biomedical device exercises at the end of the term. Of those five to eight percent, most students had minor detail errors and likely a few of them had poor class attendance.

During the terms which employed the biomedical device approach, the students had to compare elastic constant (E) values among material types, select appropriate E values, yield strengths, fatigue properties, material indices, etc. multiple times during the quarter and they worked on these problems cooperatively in several active in-class exercises. The structure-property-performance relationship theme was continued throughout the quarter and, perhaps, it was this repeated attention to these relationships that also improved several student outcomes and made the learning “sticky”. Gladwell in “Tipping Point” tells of marketing principles that assert that information must be interacted with six times in order for it to be remembered and made “sticky”. So, this repetition may prove to be a key component of improving student outcomes. Repetition and context are both possible with the biomedical device theme because the focus can be continued throughout the term and across a wide range of SLOs. Our experiences with using music strings and stringed musical instrument design approach did show that student engagement was affected by the context used for a particular exercise. And, it did show that students without a background in music had a more difficult time judging the appropriateness of their design solutions. It was also impossible to use that theme over the same breath of SLOs. Thus, it is difficult, even when considering this other data set, to be able to fully separate repetition versus context. The two different approaches did have different contexts, but the student experiences differed enough in detail, that it is not possible to directly compare the two experiences. Next term, we will be able to gather data where the biomedical device approach uses different levels of repetition from the current data sets to try to separate repetition from context effects.

It was found that biomedical device components which are made from Ultra High Molecular Weight Polyethylene (UHMWPE) provide appealing platforms from which conceptual understanding of the degree of polymerization (DP) and mechanical properties of polymers in-service can be improved. The differences in the mechanical properties of crystalline, semicrystalline and amorphous materials can also be addressed within this context. UHMWPE in itself provides ample opportunity to explore structure-property relationships in-depth, but its use in the demanding world of joint replacements and all that entails makes connecting many important basic concepts in materials engineering possible. The design and lifetime trade-offs involved in using materials other than UHMWPE can be used to sum several, important conceptual areas within the course. Unfortunately, the SLOs centered on the mechanical
properties/structures/degree of polymerization were not addressed to the same depth in the musical instrument focus so any direct comparison to that data set is impractical in these areas. Additionally, while music strings and musical instruments do use materials from all three basic classifications of materials, they are most often used in different components adding to the complexity of comparing these two focus area approaches directly. What makes joint replacement materials selection fit a fundamental course so well is the number of materials used in those components covers all three basic materials classifications, but the actual number of materials is small. The design trade-offs are significant and relatively easy to understand. Better yet, there is still no industry consensus on which material is best for several components and new combinations are still being developed and combinations debated, even in the current popular press\(^5\). An analogous item in the stringed musical instrument design focus is the popular debate about the “secrets” of Stradivarius violins, although the answer to that debate is much less clear from a materials science point of view. Another significant difference between the two focus areas is that ethics and recalls are easily connected to biomedical devices in accessible and personally meaningful ways. When the musical instrument approach was used, other unrelated case studies, such as the loss of Alaska Air Flight 261 (a deeply meaningful one in our region), were used, for these course dimensions. So, no comparisons are possible in the ethics SLOs.

Figure 9 compares student outcomes in several conceptual areas before and after the use of biomedical devices were used as a foundation for collaborative learning activities. Simultaneously, there was a change to a collaborative term long research project in the course from individual term long projects. Additionally, all active, in-class exercises were completed in these same collaborative teams this academic year. No attempt was made to separate the effects of these two, simultaneous changes. A separate paper\(^3\) covers the initial observations from changing to the collaborative approach for completion of the research project and a more detailed paper that includes the outcomes for this academic year is being prepared. No doubt part of the change in the outcomes described in this paper is due to the increase in the amount and frequency of collaborative work as outlined in the research literature\(^16-21\).

Overall there was a an increase in the percentage of students successfully completing the course with good conceptual understanding of the mechanical properties important to biomedical devices such as Elastic Constant (E), Yield Strength (YS), Tensile Strength (TS), Compressive Strength (CS), Safety Factor (SF), Fatigue Life (Fatigue), Creep Strength (Creep), Wear Rate (Wear), and Hardness (Hardness). In general, depending on the term and question, ten to fifteen percent of the students left the course with some conceptual misunderstanding on E, YS, UTS, fatigue strength, or creep by the end of the term (more detail is provided in Figures 9 and 10). After the introduction of biomedical devices as collaborative focus areas, these conceptual difficulties dropped. Fewer than three percent of the students left the course with conceptual difficulties with safety factors (more likely as a result of poor attendance rather than a course structure issues, however). Obviously, the students who do not complete particular activities cannot benefit from them. The data that is shown in Figure 9 is based upon the changes in the pre-course and post-course concept questionnaires and data taken from specific exam questions, where a 1 or no suffix indicates questions from concept questionnaires and a 2 indicates traditional test question data. Figure 10 shows the differences in the thirteen Student Learning Outcomes (SLOs) listed above before and after the use of biomedical device focus areas and collaborative research papers and active exercises. Additional data not presented here also
supports similar outcomes in these particular areas of SLOs. However, all these differences, although positive, are small and the overall number of students participating is relatively small.

An additional data set covers a design exercise where the students must articulate the reasons for making material selections for a femoral stem where they must minimize the weight of the stem, minimize change in length of the metallic stem, minimize the change in diameter of the stem, estimate the fatigue life, apply appropriate safety factors, use elastic constants, understand Poisson’s ratio, and consider cost. Even the students who are not able to calculate the change in diameter or length correctly, do use the correct methodology to solve the problem, use the correct material properties, and use appropriate safety factors. Most importantly they are able to clearly state why they made the design decisions they did and why they selected certain materials over others. If they did make a calculation error, all but one student (of 46 in one observation subset), understood that their answer was incorrect or impossible. The most frequent remaining problem area in the delta l and delta d calculations was improperly conversion of units, rather than a conceptual problem. In the musical instrument focus area, the students also did well on their design problems and several completed projects that were far beyond the assignment requirements. However, the number of students who completed the music focus area who could not recognize their answers were wrong on an exam was much higher (up to 10%), depending on the term, and were likely the students without a background or, more importantly, an interest in the focus area. The number of students with difficulties on their musical design project was artificially low because the students met with the instructor after their initial designs and had the opportunity to correct their basic design mistakes.

![Graph](image)

Figure 9. Percent of Students Completing Course with Conceptual Understanding by Study Area (before and after the use of Biomedical Devices (BMD)) [N=178]

Disappointingly, the use of biomedical devices made no difference in the number of students who exited the course still insisting that metals are bonded with ionic or covalent bonds (approximately 11%). As stated earlier in this paper, part of the reason the students may exit the course is that some students answer this question too quickly on the post-course concept questionnaire or on the final exam when the question is asked in isolation. About half of the students who answer the bonding incorrectly have the correct conceptual understanding of
dislocation motion. In order to sort out the conceptual problem here, we will refine our post-course and final exam questions in this area so that we can further investigate this important, but complex issue. More of the students seem to understand the basics of dislocation motion in metals, so more work is needed to determine concept problem from instant recall difficulty.

![Figure 10. Percent of Students Completing Course with Conceptual Understanding by SLO (before and after the use of Biomedical Devices (BMD)) [N=178]](image)

The students did improve the use of materials specific terminology in their research papers. Since the papers were done cooperatively, the presence of the other members in the groups dramatically improved the overall quality of their papers. The overall effect was not only a general improvement in scores, but a flattening of the distribution of the scores on the project itself. Before the cooperative learning approach, the range of scores on the project varied by as much as 45% from top score to bottom score. In the cooperative learning approach, the range of scores varied by only 12% - 15% with similar class sizes. The overall scores on the cooperatively written papers increased by 10% - 12% through two observation sequences. Substantial improvements in higher order thinking and language skills (analyzing and relating design requirements to complex materials properties such as viscoelasticity, anisotropy, specific strength/stiffness, material indices and phase changes) were also observed both within the oral presentations of the groups and within the content of their posters and/or PowerPoint presentations. The term long research paper was also redesigned in order to place more emphasis on design constraints and the material properties/indices. In addition to using the biomedical devices, we developed specific concept questions to help the students distinguish material properties from each other and to help the students differentiate material properties from design constraints and geometry effects. The students were also asked to complete “Ashby” type charts from material property data from the text and from the Internet. The combination of these approaches worked to improve the specific higher order thinking skills we had targeted. Disappointingly, students still used the generic word strong too often in their oral presentations even though we had focused on removing the generic word strong to describe a wide variety of materials properties in their written work.
Overall, the students rate the instructor higher when the ILS, concept learning, cooperative learning and pre- and post-course surveys occur within the course structure. Several students have made specific comments on how taking the ILS and reading through the documentation on learning styles for the ILS has helped them personally within the materials engineering course and they also report knowing more about how to work within courses where the instruction is modeled for only one learning style. The change in the attitudes of the students about taking more responsibility for their own learning seems to be worth the trade-off in taking valuable class time away from content for the ILS and the concept questionnaires. The students also seem somehow reassured, but in a way that would be difficult to measure, that the instructor has deeply considered how students learn and is working toward more effective ways to teach them and help them learn. In other words, the approach seems to build confidence in the instructor. However, not all the students like working cooperatively, but ~85% of the students think that the cooperative approach should be continued in the class. Managing the cooperative teams and all the team peer ratings is certainly more time-consuming for the instructor. Even the students who dislike working in teams understand the necessity of learning how to do so effectively for their future careers. Some students, as predicted from their learning styles, also dislike active, cooperative work even if it does improve outcomes. Any instructor will certainly understand the challenge of finding the appropriate mix of activities for all the students who take their courses if they consider the data from the ILS carefully. It is certainly challenging to find the best combination of activities for a large number of individual learners, each having their own unique needs. The research literature tells us to use an approach that is most effective for each SLO in our courses and that cooperative learning and inductive practice is ideal. However, finding the exact approach is actually the most effective for each SLO is challenging and will require much effort and careful measurements on large numbers of students. Simply stated, we have much to learn about how students actually learn materials engineering and how we might be facilitate that learning.

Conclusions

Over the past seven years several known best practices in teaching to improve student learning outcomes have been integrated into our Introduction to Materials Engineering course, transforming it from a traditional lecture only course to a course more focused on conceptual learning with several active, collaborative experiences. During that time much has been learned about the value of pre-course concept questionnaires as the data from those surveys revealed that many of our basic assumptions about pre-requisite knowledge of our students were simply wrong and that the students enter the course with, sometimes stubborn and/or surprising, misconceptions. We also found that cooperative learning greatly enhanced the quality of student work, especially in their research papers and oral presentations. During the past two years, our initial assessment data shows that teaching materials engineering within the assessable context of biomedical devices likely improved thirteen important SLOs in the course. The biomedical device approach allowed us to cover a wide range of SLOs so that this basic theme could be repeated throughout the term and, thus, we had more time to repeat and reinforce several central key concepts. Another part of this study involved understanding the value of and appropriate uses for the ILS survey instrument. Data from the ILS has shown the complexity of finding appropriate activities so that all the students in the class have opportunities to succeed. ILS data has yet to be shown as an indicator of success in particular activities. Our experiences using a
different focus area, music strings and musical instrument design, showed us that students react differently to different focus areas and that not all experiences are equally effective or universally appealing. Each course SLO is affected by the particular focus area and its ability to allow concentrated and repeated activities throughout the term. Activities that target robust misperceptions are especially effective in helping the students reconstruct their knowledge if it is done within the context of biomedical devices or other appropriate contexts. Student assignments and problems should have a contextual base, although this is not universally true in textbooks. Overall, the initial data shows that biomedical devices, which experience significant loads in service, may be effective in improving certain outcomes, especially those in developing the conceptual understanding and use of mechanical properties. Some of these same SLOs were also improved with the music based focus area, but were not identical experiences, so it was difficult to directly compare outcomes from the two themes. One outcome that was more effective in the stringed musical instrument approach was in the understanding of anisotropic/orthotropic materials.

The next steps in the development of this course are to build upon the initial successes presented here, develop a deeper understanding of why some approaches are more successful than others, and probe deeply about what the best ways are to measure those successes. Understanding what factors are important in forming the most effective cooperative teams is another area that we wish to develop for this course. There are reports in the literature that the ILS or other similar surveys (modified Myers-Briggs) may be helpful in forming the most productive cooperative teams or assist in avoiding non-productive teams. We will also continue to examine ILS data to see if it is a useful predictor for success in particular activities, although the literature base regarding this idea shows inconsistent results. We are also particularly interested in adding computer/technology-aided support for the course and measuring the effectiveness of that assistance when added to the biomedical device base collaborative work described here. We hope these technology-supported activities may assist the students in their own self-awareness of their conceptual difficulties and help us understand more about how students learn materials engineering. Finally, we hope to make materials selection software available to the students next academic year. However, this software is different than the computer aided support we hope to develop ourselves for the course SLOs. There are several other SLOs for the course that certainly need to be improved and new strategies will have to be developed for them as well. Obviously, there are still improvements we need to make in the SLOs covered in this paper. Overall, good progress has been made in improving the course, yet much remains to be done. Developing the most effective approach for each SLO for audiences with diverse learning styles is indeed challenging and will require significantly more effort and research.

Bibliography