Active Learning in an Introductory Materials Science Course

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Abstract

A lecture-based introductory materials science course was converted to an active learning experience without altering the scheduling of the course, classroom location, or faculty contact hours. Group lab activities, using simple and inexpensive materials, were incorporated into the course to enhance student engagement and understanding. Throughout a 15 week semester, 10 labs were performed. Each lab was completed and submitted during a class period, with students working in groups of 4. Periodic video lectures were posted prior to class to prepare students for specific in-class activities. No core content was removed from the original lecture-based version of the course. Each lab activity was a modular unit enabling adoption of the course structure by multiple professors. The in-class labs are described here, along with preliminary data on student experience and outcomes. Metrics of analysis include exam performance, student feedback, and observations of student engagement. The redesigned course has been taught twice, by two different professors. Data from lab-based courses is compared to data from previous iterations of the standard lecture-based model, as taught by the same faculty members.

Introduction

Educational research has shown clear benefits to student-centered and active learning [1]. Providing students the opportunity to talk through challenging concepts, as opposed to passively listening to lecture, provides measurable benefits in terms of understanding and retention of information [2]. There is often resistance, however, at both the faculty and student level, to incorporate active leaning in undergraduate STEM courses [3]. Classroom space, availability of resources, and scheduling logistics can make active learning challenging. At the University of Southern California, *MASC 310: Materials Behavior and Processing* is a high-enrollment course that introduces engineering students from a range of backgrounds to the basics of materials science. The course is taught 4 times each academic year, by 3 different professors, and serves approximately 120 students total (~30 per class section). Continuity in content is important across all sections of the course to ensure that students have an equitable learning experience. The course meets for 3 hours per week, divided between two class periods. There is no recitation or lab section for the course, and allocated classroom space for lecture is determined by university classroom scheduling. As *MASC 310* serves a large student population and is the only exposure many undergraduate engineering students at USC have to the discipline of materials science, an internal request was funded by the engineering school to redesign the course.

The *MASC 310* course was an excellent fit for an active learning redesign, as several of the key concepts introduced in an undergraduate materials class can be explored using hands-on activities, and exposure to such actives enhances student engagement and understanding [4]. The benefits of a lab component in an introductory materials course have been observed directly at USC, as the aerospace engineering version of the class (*AME 231L: Mechanical Behavior of Materials*) incorporates a materials testing lab. *AME 231L* is a smaller course, capped at 30 students, and taught once per year. The small class size, and the availability of lab space and equipment, enable a hands-on learning experience for students. Anecdotal evidence from instructors suggest that students in *AME 231L* develop a deeper and more complete understanding of concepts (strengthening mechanisms, heat treatments, etc.) as they perform

experiments in lab and observe the phenomena described in class. The synergy between lab and lecture creates a dynamic and impactful learning experience. The goal with redesigning the *MASC 310* course was to achieve a lab-like experience within the existing confines of course topics, classroom space, and contact hours. Course activities were designed to utilize simple and portable supplies, with each activity created as a stand-alone module that could be facilitated by any of the course instructors or teaching assistants and fit into the syllabus at the instructors pace and discretion.

The underlying goals of the redesign were to increase student engagement along with understanding and retention of course content. An additional aim was to provide students with the opportunity to carry out meaningful group work in multidisciplinary teams, to better prepare them to enter the engineering workforce. Finally, as *MASC 310* is the only materials course taken by many undergraduate engineering students at USC, the redesigned course was intended to provide a positive learning experience and foster interest in the discipline.

Methods

In-class activities were developed to enable a more active learning atmosphere in *MASC 310*. These activities were referred to as "in-class labs" on the course syllabus. Students were informed at the beginning of the semester that labs would take place approximately once a week, with no labs on exam weeks, and that each student's two lowest lab scores would be dropped at the end of the semester. The policy of dropping two lab scores was intended to accommodate classes missed because of illness, travel, or other conflicts, and make lab grades a participation and achievement score as opposed to an attendance score. In total, 10 labs were completed in the 15 week semester. Each lab consisted of a series of activities, completed in groups of 4 (8 total student groups in each section of approximately 30 students). Students selected their own groups and were free to work in different groups for each lab. Labs culminated in an online quiz. Lab quizzes required students to answer a series of questions related to the lab activities, with quizzes completed and submitted online prior to the end of the class period. While lab activities were completed in groups, quizzes were completed and scored individually.

To create a seamless learning environment for students all class materials were accessible via Blackboard, the learning management system used at USC. The textbook for the class was Callister and Rethwisch's *Fundamentals of Materials Science and Engineering, an Integrated Approach* [5]. The text, published by Wiley, provides the option for an eBook and online homework integration through Blackboard via the WileyPLUS platform. All students enrolled in MASC 310 (both lab-based and traditional lecture sections) were required to purchase WileyPLUS access. The price point was comparable to the purchase of a traditional textbook. The Blackboard page for the lab-based sections of the course was organized in weekly modules, as described below.

In the folder for each week students could access three sub-folders. The first, labeled "Before Class," contained a link to the textbook reading for the week, along with any videos students were expected to watch prior to class. The "In Class" folder contained lecture slides for content covered during class, as well as lab instructions, worksheets, and quizzes, which were programed to appear only during the class period in which the lab was performed. Lab quizzes were automatically graded, providing students real time feedback. When each group finished the lab

activities they were given a password to access the online quiz via Blackboard. Two attempts were given for each quiz, allowing students to revisit incorrect answers. The final “After Class” folder was used for web-based WileyPLUS homework assignments. A small number of homework problems were assigned after each class meeting. Homework was intended to reinforce key concepts, but not be time consuming or overly difficult. As with lab quizzes, students were given multiple attempts on homework problems, and each problem contained links to the relevant section of the eBook for further reference. All problems assigned in a week were due, via Blackboard, by the start of the first class meeting the following week. Lab quizzes and WileyPLUS homework assignments were graded instantly and synced directly with the gradebook in Blackboard.

In a typical week, students were assigned a chapter of reading, 4-8 total homework problems, and occasionally a 20-minute video to watch prior to class. With a greater amount of problem-solving taking place during class time the quantity of homework assigned to students was reduced as compared to the traditional lecture model for the course. Overall, efforts were made to maintain the existing levels of student time commitment outside of class to create an equitable experience for students regardless of which section of MASC 310 they were enrolled in. This was important as traditional lecture-based and redesigned lab-based sections of the course were offered concurrently. No core content was cut from the course, but to enable in-class activities various examples and specific details were often omitted from lecture in favor of focusing time on underlying concepts. With two class meetings per week, all or some of one class was dedicated to an in-class lab, while the remaining class was largely a traditional lecture format. To keep the direct instruction portion of the class engaging various demonstrations and visuals were presented, discussion was encouraged, and think-pair-share opportunities were provided. Think-pair-share discussion was utilized on the first day of class and the first lab was completed in the second week of the semester. This was planned intentionally, to set the tone that *MASC 310* would be an active learning experience and provide students with a clear picture of what they could expect in the classroom.

Each in-class lab module was designed with a series of learning objectives in mind, targeted at key concepts covered in the course. Priority for lab topics was given to concepts that students typically find challenging or confusing in introductory materials courses [6]. Brief descriptions of each lab, along with the lab supplies required, and the teaching purpose of each activity [7], are presented in Appendix A of this paper.

The collaborative in-class lab activities described in Appendix A, when integrated into a broader learning experience involving lecture, discussion with professors and peers, and homework assignments, provided students with a positive introduction to the field of materials science and a strong foundation in the subject. While the model is relatively new, initial work has been carried out to assess student outcomes against a range of relevant metrics.

Results

Approval to report anonymous student exam scores and evaluation feedback (both current and archival), and administer and analyze student surveys, was obtained from the University of Southern California Institutional Review Board (USC IRB). The IRB designee determined that

the information reported here meets the requirements outlined in 45 CFR 46.101(b) categories (1) (2) and (4) and the study therefore qualified for exemption.

A tiered approach has been used for the implementation of the lab-based model of *MASC 310* at USC. Of the 3 faculty members who teach *MASC 310*, two (referred to here as Instructor A and Instructor B) have implemented the redesigned model utilizing in-class labs, while the third (Instructor C) is teaching using a lecture-based approach. Instructors A and B have also taught *MASC 310* using a traditional lecture model in the recent past.

The influence of in-class labs on exam performance was examined using two metrics. First, average exam scores from final exam questions given by Instructor A in past iterations of the course, in which a lecture-based model was used, were compared to average exam scores on the same questions in 2 sections of the MASC course taught by the same professor (Instructor A) using a lab-based approach. The specific questions selected for analysis (referred to as Q1 and Q2) both covered phase transformations, which is a subject area students traditionally find challenging. Results are presented in Figure 1, which shows both the class average (mean) on each question, as well as a full histogram of the grade breakdown for each question. Histogram data is presented as % enrollment, as the number of students in each section of the course varied. Mean scores on the 2 common exam questions administered for this study showed no statistically significant difference based on instructional method (t=-1.44, p=0.15 for Q1 and t=-0.82, p=0.41 for Q2). Error bars indicate standard deviation.

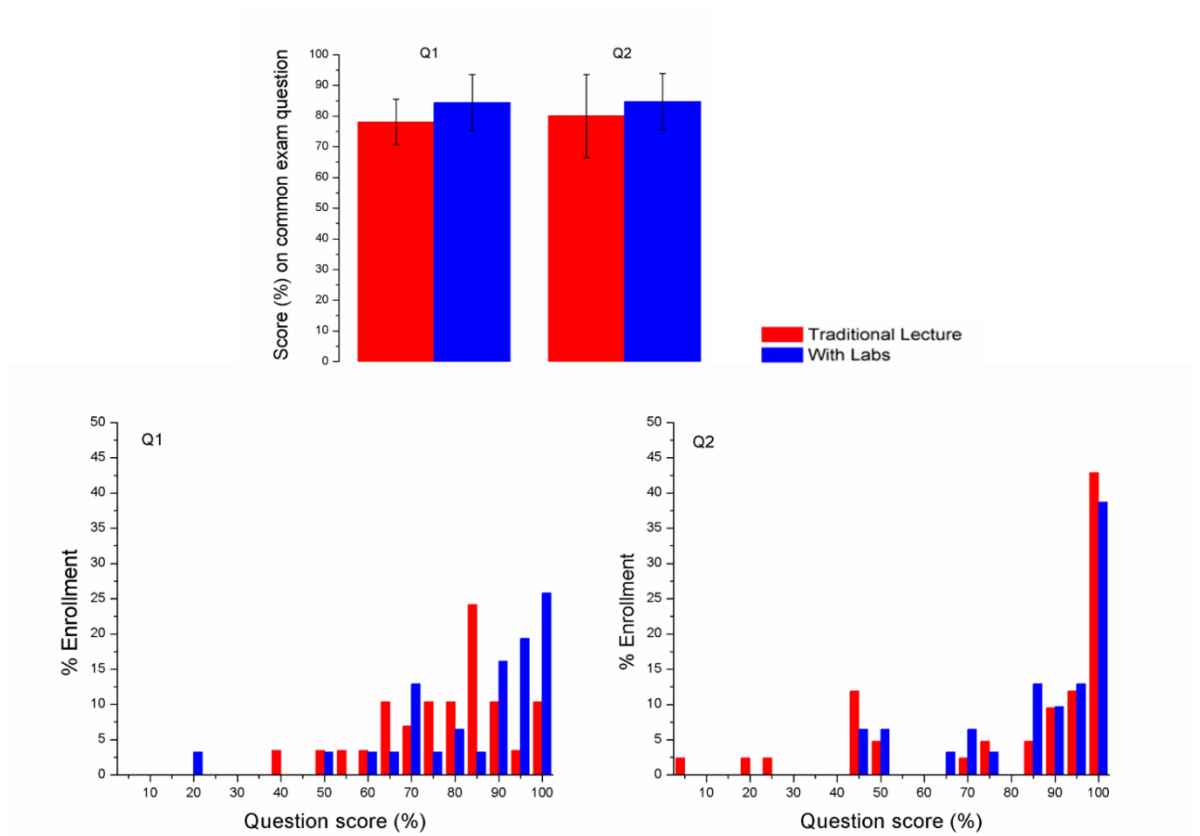

Figure 1. Class average and individual student performance on common final exam questions

As a second metric for the influence of in-class labs and active learning on exam performance, the average midterm and final exam scores from the most recent lecture-based offering of the course by Instructor A were compared to the average exam scores in a MASC 310 section taught by Instructor A implementing a lab-based model. The same information was obtained for two sections of the course taught by Instructor B. Scores, presented in Figure 2, are normalized with the first midterm (MT1) set as the zero point, and other exam averages represented in terms of percent change.

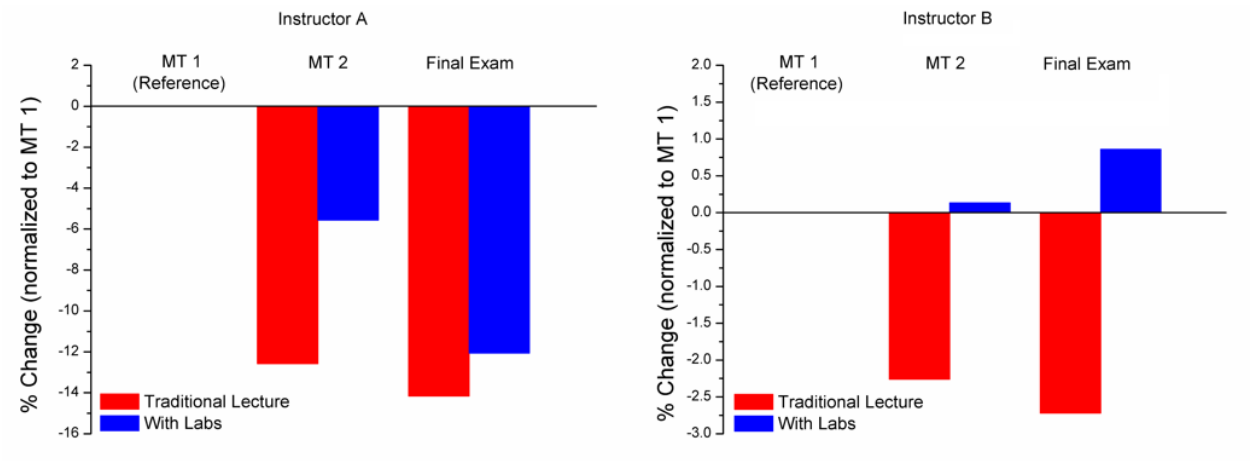

Figure 2. Normalized class average scores on midterm and final exams

Finally, student course evaluation data was examined to elucidate student attitudes toward an active learning classroom. Data was obtained from archival evaluations for traditional lecture-based sections of the course taught by both Instructor A and Instructor B, and compared to student rankings of the same professors under a lab-based model. USC course evaluations are rated on a scale of 1-5 (with 5 being the best). The two culminating questions asked on evaluations are "overall, how would you rate this course?" and "overall, how would you rate this instructor?" Student feedback on those broad questions is presented in Figure 3 (mean value with error bars showing standard deviation).

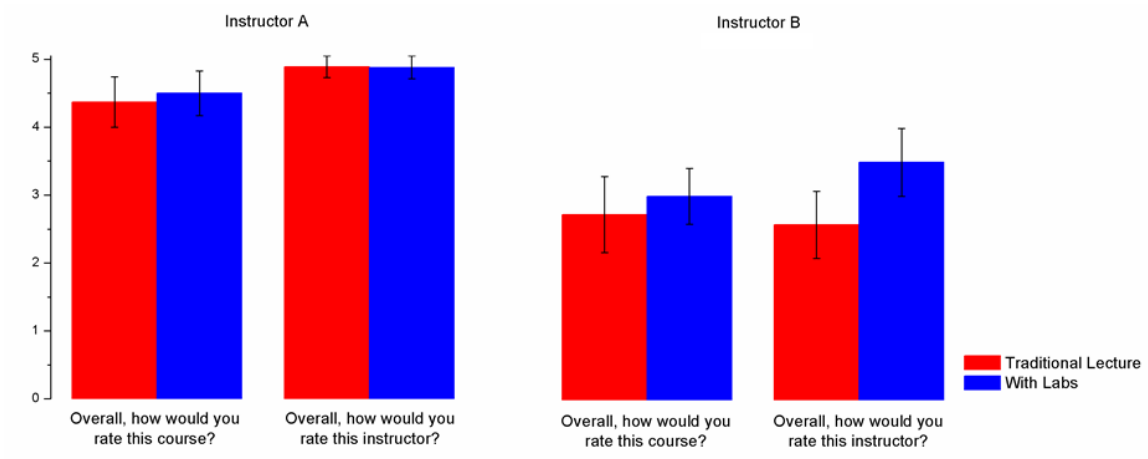

Figure 3. Student responses for culminating course evaluation questions

Discussion

While there are many variables at play when considering multiple class sections over multiple years, taught by multiple professors using different approaches, the data presented above was selected for analysis to achieve like-for-like comparison wherever possible.

The most direct comparison obtained for student performance in an active classroom is the common exam question scores presented in Figure 1. In two exam questions, given to two different active learning class sections, increases in mean score for lab-based sections when compared to lecture-based sections taught by the same instructor were observed, but the level of increase was not statistically significant. What is clear from the data is that the shift in instructional method did not hinder student learning or adversely influence performance.

More illuminating than mean scores for each class, however, the histograms of individual student performance presented in Figure 1 reveal that group work and active learning assisted in closing the gap between high and low performing students. With the exception of a single outlier in the active learning classroom tested using common question Q1, the active classroom data (blue bars) spans a narrower range of overall scores than the lecture-based class data (red bars), with a more pronounced right skew.

One goal of the active learning model developed for *MASC 310* was to use group work and hands-on activities to bring students from a range of grade levels and backgrounds to a common understanding. *MASC 310* serves students from all engineering majors, as well as students from USC's Iovine and Young Academy of Arts, Technology and the Business of Innovation. While the course is offered at the 300 level, the grades represented in each section range from sophomores to seniors. For these reasons the disparity in prior knowledge is large. Lecture-based teaching does not address this knowledge gap, but group work can enable students to draw from varied backgrounds and help to level the playing field.

A common issue with the lecture-based version of *MASC 310* has been sustained engagement throughout the 15 week semester. Students begin the semester with enthusiasm, and average scores are typically high for the first exam in the course. It has been observed by all three *MASC 310* instructors, however, that following this initial exam, performance and attendance in the course drop. A combination of the increase in difficulty level in material throughout the semester, and a decrease in student attendance and engagement, leads to progressively lower scores on the subsequent midterm exam and final. As shown in Figure 2, the active learning classrooms showed a less significant decrease in exam performance in one case (Instructor A) and an increase in performance in the other (Instructor B). While in-class labs were not meant to force attendance, and it was made clear at the start of the semester that the two lowest labs scores would be dropped, most students attended all classes throughout the semester and completed all labs. On occasions where labs were missed for legitimate reasons, students made the effort to contact their instructor and make up the lab activities in office hours. This indicates that students found class time to be a valuable component of their learning experience in the course, and viewed labs as a tool to further their understanding.

Anecdotally, in classrooms where in-class labs were performed students asked more questions during lecture and were engaged in think-pair-share exercises and class-wide discussions. While

labs took place once a week, the use of group work in the course contributed to a shift in the culture of the classroom, which influenced the more traditional lecture-based segments of the class as well. Because they were talking and working together regularly, students were more comfortable with one another, and with the professor, and consequently more confident speaking out during lecture.

A common argument against active learning is student resistance [3]. To gauge how a shift from a traditional lecture course to an active environment influenced student perceptions of both the *MASC 310* course and its instructors, average rankings on end of semester course evaluations were examined. As seen in Figure 3, for Instructor A, a slight increase in mean student ratings of the course were observed, with no change in instructor rating. An increase in both ratings was observed with Instructor B. This is an encouraging result, indicating that students are willing to accept an unfamiliar course structure and providing evidence that different instructors can utilize the modular lab activities with success.

Open-ended responses from the course evaluations of the lab-based sections taught by Instructor A and Instructor B were also examined for positive and negative comments related to any of the changes in the redesigned model of the course. Students are asked in USC course evaluations to comment on the most and least valuable aspects of a course. While not all students provide comments, responses from these two categories, related specifically to components of the redesigned course (labs, online homework, videos, etc.) are presented below.

Table 1. Open-ended student comments on university course evaluations.

Please describe the MOST valuable aspect(s) of this course
• The real–life applications and labs were great for understanding why this was important and making it more interesting. • Really engaged lectures. • I enjoyed how our homework assignments were short, but still helpful. Also, I like how we have hands–on labs during class to help us better understand the material. • Organization and clear expectations really facilitated my learning in this course. Labs were fun and created diversity from lecture. • The labs and lectures together really encouraged me to always attend class and the concepts were well reinforced with the labs and homeworks. The demonstrations and models also helped bring what we were learning into context and make it easier to visualize • Clear information and clear expectations. Constructive environment. • Use of technology and diverse small activities to supplement the lectures and directly applied to what we just learned • I felt that I really understood … the basic concepts that underly material behavior. I have a great base understanding and context going forward and have already found the class helping me in my other coursework. • The information was taught really clearly and I feel I understood it well. Everything we learned was related back to practical examples, so I feel like I have a much better perspective on strength of materials and manufacturing processes that I can use in design.

Please describe the LEAST valuable aspect(s) of this course
• Online homework tolerances could be frustrating but were addressed in terms of grading points. • Lack of practice problems or examples similar to those on the exams – homework problems were usually simpler • I did not like using Wiley Plus. Although the questions were helpful for studying materials, the ebook was not easy to navigate. • The Wiley PLUS assignments were frustrating when involving graphs and diagrams especially phase diagrams, since the answers would be marked incorrect even if they were right. Just hearing that this would be the case beforehand would help so I didn't feel like I was getting a question wrong when I actually understood it.

The comments above indicate that students found in-class labs to be a valuable component of the course. No negative comments were made about the labs. While the theory has not been tested, it is possible that the terminology choice of "Labs" for class activities labs was beneficial, as engineering students are familiar with a lab setting and respect labs as a valuable component of the discipline. This can be contrasted with connotations that may exist for words like "activities" or "group projects," which may engender student resistance.

Most negative comments related to the online system used for textbook readings and homework, an issue encountered in previous studies in which the same system has been implemented [8]. While it has flaws, the WileyPLUS system enabled access to all course materials from one location (the Blackboard site), and provided a way to automate submission and grading of homework. The online homework problems also generated different numbers for each student on numerical questions, creating a built in safe-guard against copying, and encouraging students to work through the assigned problems independently. While there were issues with technology, consistent and organized delivery of course content and active learning opportunities is critical for success in a non-traditional classroom, as students are most likely to succeed when expectations are clear [3, 8]. The benefits and drawbacks of the use of WileyPLUS will be weighed in planning future course offerings.

In addition to course evaluations, direct examination of student perceptions of the lab-based model of the course were obtained through a survey. The two most recent sections of the course taught by Instructor A, using the lab-based model, were surveyed along with one section taught in the same semester by Instructor C, using a traditional lecture model. Unfortunately, IRB approval to survey current students came in after the semester ended, leading to delayed survey administration and low student response rates. In total 14/63 students from the two sections taught by instructor A and 4/31 from the section taught by Instructor C completed the survey. This sample size is too small to draw meaningful conclusions. To further complicate comparisons, the differences in the courses were not simply lecture vs active learning, but also different faulty members. Because of these imperfections, survey results will not be discussed in detail, but are presented and briefly addressed in Appendix B.

Conclusions

A lecture-based introductory materials science course was redesigned to engage students in active learning through in-class lab activities. The effectiveness of the lab-based model was quantified based on student performance along with evaluation and survey feedback. Initial data suggests that the redesigned course was well received by students, and achieved equal, if not better, learning outcomes. Results indicate that, with proper planning and execution, student resistance to active learning techniques can be overcome in an undergraduate materials classroom. While the lab-based model is new and still under development, the trends reported here are promising, and plans are in place to roll out the redesigned course across all future *MASC 310* offerings at USC.

A significant portion of *MASC 310*, even with the incorporation of in-class labs, relied on direct instruction. In the future, it is desirable to further increase the amount of non-authoritative instruction and add additional connections to real-world applications. In its current form, however, key aims of the redesign, such as increasing sustained student attendance and engagement, and promoting collaboration and productive group work, were accomplished in the lab-based course. A positive side effect of an active learning classroom was more dynamic lectures with increased student involvement and discussion.

It should be noted that classroom space designed with collaboration in mind led to a more seamless transition between lecture and group work, consistent with studies that have examined the impact of physical space on active learning [9]. Labs were designed, as often as possible, to utilize shared equipment, which necessitated group work as opposed to a “divide and conquer” approach. One set of lab supplies was provided to each group of 4 students. Classroom layout was observed to influence the feasibility of this approach. Of the two lab-based sections of the course taught most recently, one was scheduled in a classroom with individual mobile desks on wheels, while the other took place in a classroom space equipped with long stationary tables. The mobile desks allowed students to reconfigure, with the preferred orientation during lecture being rows facing the front of the room and the most common format during labs being 4 students facing one another in a ring-like arrangement. This classroom was observed to be more dynamic during group activities as well as think-pair-share opportunities. In the classroom with less flexible seating student groups often arranged in a row of 4, with less opportunity for whole group discussions and sharing of lab supplies as well as ideas. In future course offerings effort will be made to secure optimal classroom assignments.

While undergraduate MASC class sizes at USC are relatively small (approx. 30 students) the activities implemented in this study could scale to larger lecture courses, provided enough sets of lab materials were obtained. Lab groups of 4 students were effective and allowed all students the ability to participate in activities, but larger groups could be formed if resources were limited.

As a final note, one goal at the heart of this work was to provide students with a positive experience and a strong foundation in the field of materials science. While the results of this effort remain to be seen, metrics for future analysis include student enrollment in materials-related emphasis programs within their existing majors, along with student applications to materials science progressive master’s degree programs at USC.

Acknowledgements

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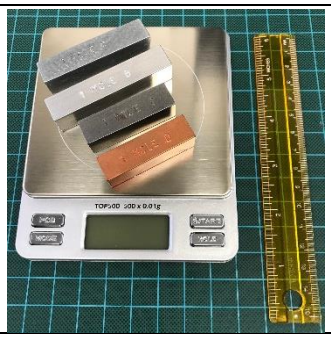
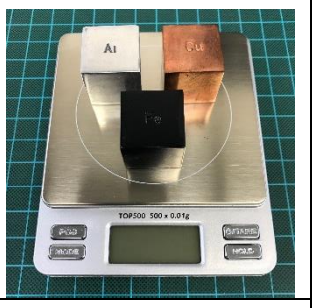
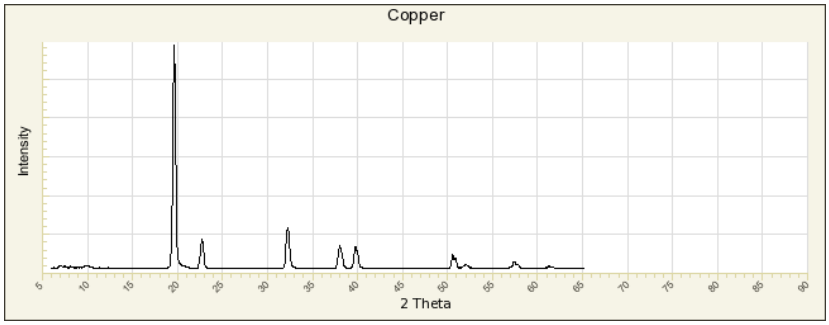
Appendix A: In-class labs

Lab 1: Atomic Structure	
Before lab basic concepts of electron structure and bonding were introduced in lecture. Students were also provided with an optional video refresher on quantum numbers and electron configuration (which was review for most of the class, but new to some).	
Supplies • Mole sets (one mole samples of various metals – Fe, Al, Zn, Cu) • Scales • Rulers • Periodic tables	
Activity	Teaching purpose
Use the provided supplies to identify each element in the mole set	*Check for understanding:* The mass of one mole, in g, is equal to the atomic number, in amu)
Write the electron configuration for each element	*Check for understanding:* Demonstrate mastery of electron structure and energy levels
Given information about one of the two stable isotopes of copper (mass and abundance) determine the number of protons, neutrons and electrons in the isotope and determine the mass number of the second stable isotope	*Transfer understanding*: Apply several concepts (the atomic weight of an element is the weighted average over the stable isotopes, an element has a fixed number of protons but the number of neutrons varies by isotope, the mass of a proton and a neutron in the amu system is close to 1, etc.)
Propose a method to determine the atomic radius of aluminum. Make note of any assumptions made in your approach. Use your method to calculate an atomic radius for aluminum and make note of your result	*Activate prior connections:* Retrieve knowledge of atoms and solids (atoms are often depicted as spheres, the atoms of a given element are the same size, there are 6.022×10^{23} atoms in a mole, in solids atoms are largely fixed in position, etc.) *Express your thoughts:* Share prior knowledge in a group and discuss how to approach an undefined task

Lab 2: Crystal structure of metals	
Before lab the crystal structures of metals were introduced in a 20 minute video, and expanded upon in lecture.	
Supplies • Density cubes (1 in^3 samples of various metals – Al, Cu, C-Steel) • Scales • Periodic tables 	
Activity	Teaching purpose
Given the fact that copper has a cubic crystal structure, and a given lattice parameter, determine the crystal structure of copper	*Transfer understanding*: Utilize the theoretical density equation, along with an actual density measurement, in a new way
Given the fact that aluminum has an FCC crystal structure, perform a new calculation for the radius of an aluminum atom. Compare this value to the one you calculated in Lab 1.	*Activate prior connections*: Revisit past assumptions about atomic packing in the new framework of crystal structures *Check for understanding*: Again, utilize the theoretical density equation, along with a density measurement, to solve for a different unknown
Given the atomic radius of iron and the fact that iron, at room temperature, has a BCC crystal structure, calculate the theoretical density of iron. Speculate as to how the addition of a small amount of carbon atoms to form low carbon steel will alter density. Measure the density of the steel sample and discuss your observations.	*Check for understanding*: More practice with theoretical density *Express your thoughts*: Discuss in a group how you expect the addition of carbon to alter the density of iron and justify your idea. Compare your prediction with a density measurement and rethink/challenge your assumptions. Try to explain what you observe.
Given the information that iron is a polymorphic element (transitions from BCC to FCC at 912˚ C), without performing any calculations, and neglecting thermal expansion, determine if the density of iron will increase or decrease above 912˚ C.	*Give information*: Introduce the concept and term polymorphic *Express your thoughts*: Justify your viewpoint in a group and discuss the concepts of atomic packing and density *Check for understanding*: Demonstrate understanding of the packing efficiency of various crystal structure

Lab 3: Directionality in crystals	
Before lab Miller indices for points, plans and directions were covered in a 20 minute video and examples were worked in class. The experimental setup and equations related to diffraction were briefly discussed.	
Supplies • Diffraction pattern for copper (data from Rruff.info)  	
Activity	Teaching purpose
The first peak in the diffraction pattern for copper, an FCC metal, corresponds to the first order reflection of the (220) planes. Using this information, determine the lattice parameter and atomic radius of copper.	*Transfer understanding*: Utilize equations for interplanar spacing and diffraction condition to determine lattice parameter, and observe how equations relate to actual experimental data *Activate prior connections*: Reactivate knowledge of crystal structures and geometry to relate lattice parameter to atomic radius
Draw the (220) plane within an FCC unit cell. Draw the 2D projection of atoms on the (220) plane in FCC and calculate the planar density for (220) in copper	*Transfer understanding*: Apply knowledge of crystal structures and geometry, practice indexing and drawing crystallographic planes, perform planar density calculation
Determine the expected diffraction angle for the first order reflection of the (111) set of planes in copper, and locate the corresponding peak in the diffraction pattern	*Check for understanding*: Demonstrate understanding of diffraction calculations and ability to perform relevant calculations

Lab 4: Molecular weight of polymers

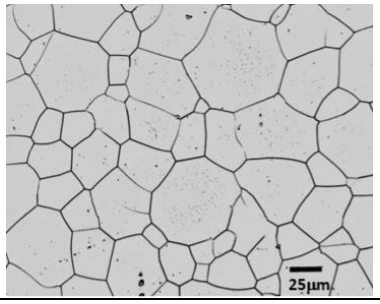
Students completed this lab as their first introduction to the ideas of number and weight average molecular weight, there was no preparatory lecture or video. Following the lab, the concepts were applied to real polymeric materials and expanded upon in lecture.

Supplies

- Bags of 100 paper clips
- Scales
- Worksheet describing number and weight average molecular weight
- Collaborative google spreadsheet

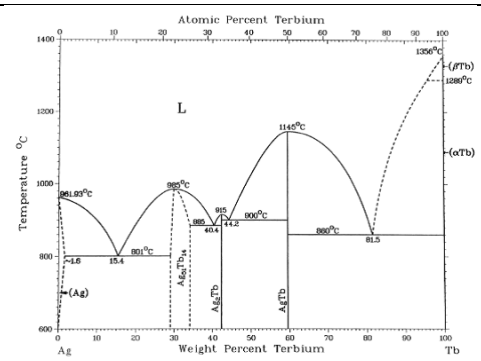
18	n5	n10	n15			m5	m10	m15	
1	6	4	2			28.49	37.95	28.48	
2	5	3	3			23.69	28.36	42.6	
3	6	4	2			28.44	37.91	28.45	
4	6	4	2			28.4	37.87	28.44	
5	4	5	2			18.96	47.33	28.42	
6	4	5	2			18.95	47.37	28.42	
7	8	3	2			37.84	28.37	28.41	
8	5	3	3			24.96	28.44	42.67	
	44	31	18	93		209.73	293.6	255.89	759.22
x	0.4731182796	0.3333333333	0.1935483871		w	0.2762440399	0.3867126788	0.3370432813	
						4.75	9.5	14.25	
M_n=	8.172043011				M_w=	9.788796396			
DP=	9								
PDI=	1.197839559								

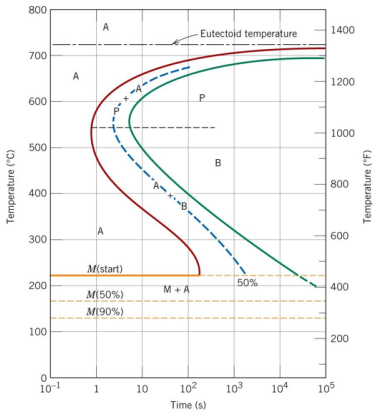
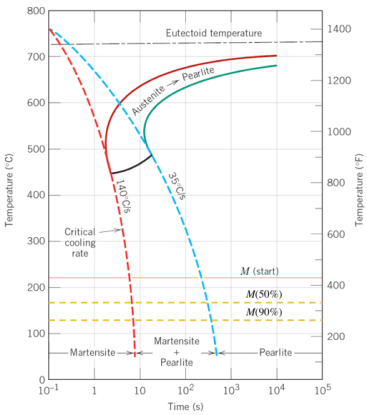
Activity	Teaching purpose
Build paperclip chains of lengths 5, 10, and 15, using all 100 clips provided. Follow instructions on a worksheet to calculate the weight average and number average "molecular weight" of the resulting sample of paperclip chains.	*Give information*: Introduce repeat units, polymer molecular structure, and the averaging techniques used to characterize polymers via a worksheet and hands-on activity
Input data on paperclip chains into a collaborative google sheet	*Give information*: Introduce degree of polymerization and polydispersity index
Discuss the values on the screen for the whole class paperclip "polymer" sample and compare/contrast with the numbers calculated by each individual group. Discuss how the paperclip model is a good and/or bad representation of a real polymer sample	*Express your thoughts*: Discuss how sample size influences averaging, how restricting chain lengths to increments of 5, 10, and 15 effects results, speculate about the molecular structure of real polymers

Lab 5: Defects	
Before lab crystallographic defects (solute atoms, grain boundaries, etc.) were discussed. The terminology for solid solutions was presented, along with the Hume Rothery rules for solid solubility.	
Supplies • Micrograph of stainless steel • Worksheet describing grain size measurement methods • Characteristics of selected elements sheet (atomic radii, crystal structure, valence, melting point) • Electronegativity table	
Activity	Teaching purpose
Classify each element in stainless steel (Fe, C, Cr) as a solvent or solute. Classify all solute atom(s) as interstitial or substitutional	*Check for understanding*: Demonstrate knowledge of key terminology and principles related to solid solutions
Apply to Hume Rothery rules to Fe and Cr. Determine if there a solubility limit for Cr and Fe, and if so which rules are violated.	*Transfer understanding*: Recall and apply the Hume Rothery rules and use them to predict solid solubility
Use the worksheet to calculate the grain size of the polycrystalline stainless steel in the micrograph provided, using both mean intercept length and ASTM grain size methods.	*Give information*: Introduce grain size measurement techniques and practice using the methods on an actual micrograph
Consider the definitions of mean intercept length and the ASTM grain size classifications – as mean intercept length increases does ASTM grain size number increase or decrease?	*Express your thoughts*: Examine new information and uncover the relationship between two common grain size designations. Discuss ideas with a group and come to a consensus.

Lab 6: Elastic deformation	
Before lab mechanical test methods were described, and the definitions of engineering stress and strain were presented. Elastic constants were introduced. At the start of lab a steel sample was loaded into a tensile load frame and the load-displacement data was projected onto the screen at the front of the room, along with a camera view of the gauge length of the sample. The sample was loaded and unloaded elastically 5 times. The sample was then pulled to failure. The data was exported to and Excel file and uploaded to the course Blackboard website.	
Supplies • Tabletop load frame (PASCO Materials Testing System) • Steel tensile sample (initial dimensions provided) • Excel data from 5 elastic runs 	
Activity	Teaching purpose
Download the Excel raw data file from the steel tensile test. Convert load displacement data to stress strain data.	*Check for understanding*: Demonstrate knowledge of engineering stress and strain and data manipulation.
Plot the stress strain data for all 5 elastic runs, with stress in MPa. Determine the elastic modulus of the steel sample, in GPa.	*Check for understanding*: Demonstrate knowledge of data plotting and unit conversion *Transfer understanding*: Determine modulus from graphical data – compare data from each run, calculate an average, and observe variability.
Given the Poisson's ratio of the steel sample, estimate the shear modulus and bulk modulus of the sample. Compare your values to those in the appendix of the textbook.	*Transfer understanding*: Apply modulus relationships using real experimental data. Compare calculations with tabulated values. Consider sources of experimental error.
When the steel sample has elongated by 0.02 mm, determine corresponding reduction in diameter.	*Transfer understanding*: Working in a group, use the concept of Poisson's ratio and the definition of strain to approach an unfamiliar problem

Lab 7: Plastic deformation	
Before lab the mechanisms of plastic deformation were presented, and several mechanical properties were introduced along with descriptions of how various properties can be determined from tensile test data. At the start of lab the full stress strain curve from steel (generated in the previous lab) was put on the projector, and additional tests were performed on aluminum and brass samples. Load displacement curves for all three tests were displayed on one set of axes and the data was exported to Excel and uploaded to the course Blackboard website.	
Supplies • Tabletop load frame (PASCO Materials Testing System) • Aluminum and brass tensile samples (same dimensions) • Excel data from full tensile tests • Plotting stress strain curves worksheet  	
Activity	Teaching purpose
Download the Excel raw data file from the tensile test deomnstration. Convert load displacement data to stress strain data. Plot the stress strain data for all three samples on a single set of axes.	*Check for understanding*: More practice with load to stress and displacement to strain calculations and unit conversions
Consult the full stress strain curve for brass. On a new graph, plot the first portion of the elastic region. Determine the elastic modulus of the brass sample in GPa.	*Transfer understanding*: Recall that modulus is determined from the linear-elastic portion of the curve. Plot an appropriate amount of data and apply a linear fit.
Follow the instructions on the worksheet to determine the yield strength of the brass sample.	*Give information*: Introduce the concept of a 0.2% offset yield strength with experimental data
Follow the instructions on the worksheet to determine the ultimate tensile strength, ductility (% elongation) and toughness of the brass sample	*Transfer understanding*: Connect the property definitions discussed in lecture to real data and practice with mechanical property determination
Examine the first plot, showing the stress strain curves of all three metals, to answer the following questions by visual comparison: Which metal has the (a) highest ductility, (b) lowest toughness, (c) lowest yield strength, (d) highest tensile strength, (e) lowest resilience?	*Transfer understanding*: Revisit mechanical property definitions to compare properties based on the features of stress strain curves.
Using the same data for all three metals, come to a consensus with your group as to which metal has the highest melting point. Justify your answer based on observations of the stress strain data.	*Express your thoughts/Transfer understanding*: Recall concepts related to the atomic structure of metals and connections between bond strength, modulus, and melting point. Justify your ideas in a group and come to a common understanding. Tie new material to concepts covered early in the course and make connections related to structure-property relationships.

Lab 8: Phase diagrams	
Before lab the basics of phase diagrams, isomorphous, binary eutectic and more complex phase diagrams were discussed	
Supplies • Characteristics of selected elements sheet (atomic radii, crystal structure, valence, melting point) • Silver-terbium phase diagram	
Activity	Teaching purpose
Construct a schematic phase diagram for silicon and germanium. What is the name given to this type of phase diagram?	*Transfer understanding*: Return to the Hume Rothery rules to realize that Si and Ge are fully soluble in solid solution and thus display isomorphous behavior. Utilize knowledge of phase diagrams to construct a schematic isomorphous phase diagram for Si and Ge.
Analyze the Si-Tb phase diagram to determine the following: Which has greater solubility: Ag in Tb or Tb in Ag? What is the melting point of the intermediate compound AgTb? How many eutectic points exist in the Ag -Tb system? For an alloy of specific composition, at a given temperature determine the following • What phases are present? • What are the compositions of the phases in wt% Tb? • What is the fraction of each phase present?	*Check for understanding*: Apply concepts of phase to the phase diagram for a real binary system. Demonstrate understanding of key features of a phase diagram, terminology, and the mechanics of lever rule calculations.
Schematically sketch the microstructure that would result if an alloy of given composition were cooled slowly from liquid to room temperature	*Transfer understanding*: Apply concepts of phase to development of equilibrium microstructure

Lab 9: Phase transformations	
Before lab TTT and CCT diagrams were introduced and the various phases and microstructures in carbon steel were presented.	
Supplies • TTT diagram for eutectoid steel • CCT diagram for eutectoid steel • For demo: Butane burner, paperclips, cup of cold water   	
Activity	Teaching purpose
Demonstrate the effect of heat treatment on mechanical properties • Heat one paperclip red hot and cool slowly in the flame • Heat a second paperclip red hot and quench in water • Heat and quench a third clip then warm in flame Show the resulting strength of each clip by unbending	*Give information/Transfer understanding*: Paperclips are low carbon steel. Heating a paperclip red hot and cooling via a range of pathways can be used to show the influence of heat treatment in a powerful visual to help solidify to students that the microstructure and property changes discussed in class truly are happening as metals are heated and cooled.
Beginning with austenite, consider a range of cooling pathways, cooling rates, and heat treatments, and determine which microstructure will form in each scenario. Identify the phases present in each resulting hypothetical sample.	*Check for understanding*: Demonstrate ability to read TTT and CCT diagrams, when to use each type of diagram, understanding of the various microstructures in carbon steel, and the ability to differential between a microstructure and a phase. Practice with terminology.
Rank all hypothetical samples on the basis of strength and ductility	*Check for understanding*: Demonstrate understanding of structure-property relationships and the relative properties of various steel microstructures.
Predict what will happen when low carbon steel paperclips are put through the following heat treatments: Heat to red hot then slow cool Heat to red hot then quench cool Heat to red hot, quench cool, and warm in flame	*Express your thoughts:* Make and justify a prediction on the basis of the heat treatment profiles and property relationships just reviewed *Transfer understanding*: Cement the ideas of process-induced property changes with observation of real material samples

Lab 10: Manufacturing	
This lab was completed as a take-home activity, assigned during Thanksgiving week	
Supplies • Videos of manufacturing methods (injection molding, blow molding, sand casting, investment casting, forging, powder processing)	
Activity	Teaching purpose
Watch videos of a range of common manufacturing methods and answer a series of questions	*Give information*: Show actual manufacturing processes to provide basic descriptions and a sense of scale, equipment requirements, etc.
Locate a disposable plastic water bottle. Speculate as to the manufacturing method used to produce the bottle. Examine the bottle for a seam – if you see one describe how the seam may have formed during manufacturing	*Transfer understanding*: Consider the manufacturing methods just shown in videos and determine which method would be used to create a hollow thermoplastic bottle *Express your thoughts:* Write a brief description of how the selected process would lead to the presence of a seam along the edge of the bottle

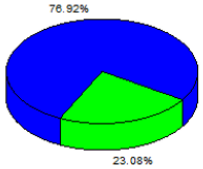
Appendix B: Student Survey Data

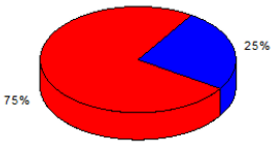
Instructor A
Lab-based (n=14)

Instructor C
Lecture-based (n=4)

Compared to my other engineering classes, I was

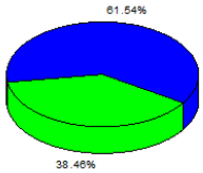
- Less likely to attend MASC 310
- Equally likely to attend MASC 310
- More likely to attend MASC 310

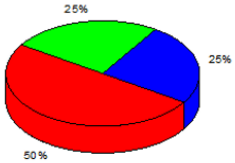




Compared to my other engineering classes, in MASC 310 I

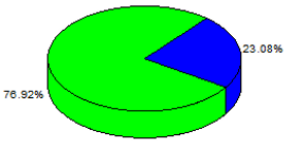
- Interacted less with other students
- Interacted the same amount with other students
- Interacted more with other students

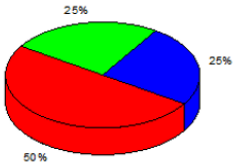




Compared to my other engineering classes, in MASC 310 I

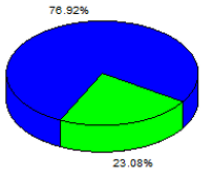
- Interacted less with the professor
- Interacted the same amount with the professor
- Interacted more with the professor

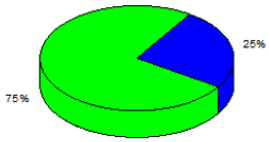




Compared to my other engineering classes, in MASC 310 I felt

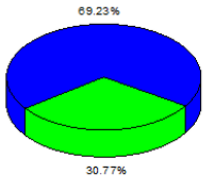
- Less comfortable asking questions during class
- Equally comfortable asking questions during class
- More comfortable asking questions during class

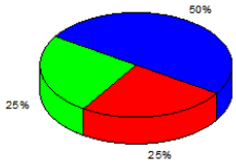




Compared to my other engineering classes, in MASC 310 I felt

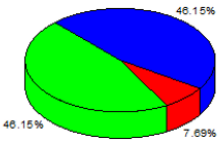
- Less prepared for exams
- Equally prepared for exams
- More prepared for exams

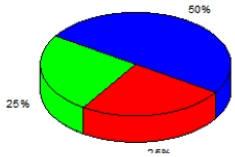




Compared to my other engineering classes, I found the content in MASC 310 to be

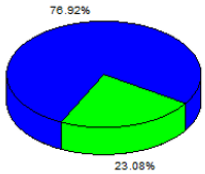
- Less applicable to real world applications
- Equally applicable to real world applications
- More applicable to real world applications

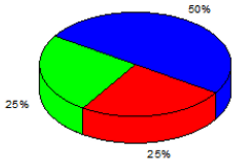




Compared to my other engineering classes, In MASC 310 I felt I had a

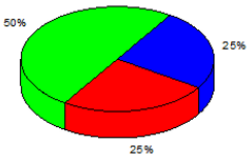
- Worse understanding of the course concepts
- Equal understanding of the course concepts
- Better understanding of the course concepts





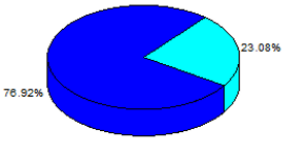
Compared to my other engineering classes, I believe I will retain knowledge of the content taught in MASC 310

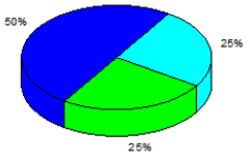
- To a lesser extent
- Equally
- To a greater extent



The resource that was most beneficial to my learning in MASC 310 was

- The textbook
- Class
- Homework





Based on responses from students who completed the survey, anecdotal instructor observations that students were more likely to attend class and more comfortable asking questions during class with the lab-based model were confirmed. Survey responses also verify the evaluation data presented in Figure 3, indicating that the active learning components of the course did not make the student experience worse, and may in fact have done the opposite. With a lab-based course design, students reported that they were more likely to interact with other students. This is a positive outcome, as one goal of the redesign was to provide opportunities for productive group work. Finally, students in the redesigned sections list class itself as a key resource for their learning, over homework or the textbook, indicating that the active learning opportunities provide a value-added component to physically attending class.