



## Deepening Conceptual Understanding in an Introductory Material Science Course Through Active learning Strategies

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## Introduction

In this paper we report on a quasi-experimental study to explore the effect of instructional methodologies on student learning gains in a core materials science course at a large research university in the Northeast. The course in question, *Structure of Materials*, is an entry point into the undergraduate curriculum in materials science and engineering (MSE) taken by most prospective major students in the autumn of their second year of study. Being a gateway science course, it is important for students to develop a deep conceptual understanding of foundational topics before they embark on more advanced coursework. *Structure of Materials* is also taken by students from other departments, most notably from biomedical engineering, who can take it as an elective as part of a focused group of courses on biomaterials. These students are typically at a more advanced level of study (third or fourth year) than the MSE majors.

The primary instructor has taught *Structure of Materials* at the undergraduate level for four years and a related course covering similar topics at the graduate level for ten years. Both courses cover the structure of materials (metals, ceramics, and polymers) over a range of length scales from atomic to microscopic, as well as experimental techniques used to investigate these structures, especially diffraction and microscopy.

The instructor became increasingly interested in pedagogical techniques that have the potential to be more effective than the traditional lecture-based format. In particular, he has been influenced by Eric Mazur's peer instruction method (which is based on in-class concept tests) and more broadly by approaches that favor having students engaged in group activities rather than passive content reception.<sup>1,2</sup> A common theme of these "flipped classroom" approaches is that students complete activities before class focused on content delivery—assigned readings or watching pre-recorded lectures, for instance—freeing the instructor to spend class time working with students in various ways that emphasize active participation.<sup>3</sup>

From an instructor's point of view, the flipped classroom is appealing because it provides a stimulating classroom environment. Such perceptions, however, cannot show whether such a change in methodology is actually more effective than traditional lectures. In the fall of 2011 the research team embarked on the present study designed to provide both quantitative data on student learning gains and student perceptions of learning gains along with qualitative information about students' responses to instructional effectiveness under an active learning approach as compared to an approach focused on content delivery via lectures. Our work was driven by the following research question: *Does active learning help students develop a deeper conceptual understanding of topics taught in the Structure of Materials course?* Our hypothesis was that students taught with an emphasis on active learning would indeed acquire a deeper conceptual understanding than those who took the course in a traditional lecture format.

## Active learning techniques

The active-learning techniques used were inspired by the concept test technique for peer instruction developed by Eric Mazur of Harvard University for his *Introduction to Physics*

course.<sup>14</sup> This method uses a think-pair-share like approach in which the instructor asks students conceptual questions to which they respond individually (by raising hands or using in-class voting technology). Depending on the percentage of correct responses, the instructor either continues to the next topic or requests students debate their answer with a neighbor before submitting a response again. This inquiry-based teaching method replaces the traditional lecture in most cases, although the instructor may occasionally lecture to clarify conceptual ideas for students.

Besides the concept test approach, other active learning strategies were employed. At several stages in the course groups of students spent class time working out detailed problems that traditionally might have been presented as part of a lecture. For example, the students determined the appearance of a single-crystal electron diffraction pattern using an Ewald sphere construction. The instructor walks through the classroom as students work asking questions to encourage students' critical reflection while also answering student questions. Two computational modules were also integrated into the course, in which students either used supplied software or developed software tools (using MATLAB) to model equilibrium structures of materials.

To facilitate the active learning approach, the course in fall 2012 was located in a classroom specifically designed to foster collaboration and active learning. The classroom (shown in Fig. 1) has five round tables with six chairs each and walls covered with whiteboard surface. Although it was not used in this course, the classroom also has the ability for students to project computer displays from their tables onto the walls for all to see.



Figure 1: Classroom used for active learning instruction in fall 2012

## Research methods

We are using a quasi-experimental approach to evaluate the impact of the active learning teaching method. The results presented here are the preliminary findings of a four-year study in which the *Structure of Materials* course is taught using a traditional lecture approach and an

active learning approach in alternate years. The study began in fall 2011 with a lecture-based format and continued in fall 2012 with the active learning approach. Prior to this the instructor had taught *Structure of Materials* twice at the undergraduate level and nine times at the graduate level. He is an experienced instructor on the course topics prior to the onset of the study.

We are assessing the effectiveness of the active learning approach using three instruments. To measure student gains in conceptual understanding (see research question above) we use a concept inventory developed by the instructor administered at the beginning and again at the end of each semester. We use the same set of 18 questions (reproduced in Appendix 1) each time, allowing us to directly compare increases in student scores between semesters and thus between instructional methodologies. The concept inventory developed was based on the course learning objectives.

To capture the students' perception of their own mastery of course material we ask them to complete a web-based survey at the beginning and end of each semester (Appendix 2). The first ten questions of the survey gauge students' self-perception of their knowledge of general course concepts. The next 10 questions of the survey are based on the Participant Perception Indicator (PPI) survey developed at the University of Michigan.<sup>5</sup> It asks students to report on their self-perceived mastery of specific learning objectives across three dimensions: knowledge (cognitive domain), experience (behavior domain), and confidence (affective domain). The format of the survey is explained to students with the following example:

#### **Application of Knowledge**

The following questions have been designed to measure your perception of your knowledge, experience, and confidence on various items. With each statement are three indicators of your involvement. For each of the questions indicate how you feel about your knowledge, experience, and confidence. Example: Select one number in each of the three boxes.

Change a flat tire.

-----Low-----High

Knowledge 1 2 3 4 5

Experience 1 2 3 4 5

Confidence 1 2 3 4 5

This would mean that I have a great deal of knowledge (response of 5) about changing a flat tire. I have an average amount of experience (response of 3) with changing a flat tire. I am not confident (response of 1) in my ability to change a flat tire in the future. Now complete all the items below. For each statement below, please rate your perceived knowledge, level of experience, and confidence in completing the activity.

It is important to understand that this survey does not assess student learning gains directly; rather, it assesses students' perceptions of their own abilities. This is an important difference with respect to the concept tests which, presumably, are a more direct measurement of student achievement.

Finally, we conduct a student focus group at the end of each semester to collect more detailed feedback on students' opinions about the teaching methods, using an interview protocol to guide the conversation. Students were recruited through an email sent to the entire class offering a \$10 gift card to a local coffee shop for the first 6 students who volunteered to participate. A third-party evaluator from the campus-wide teaching and learning center conducts the focus group, allowing student responses to be reported anonymously in summary form to the instructor.

Response rates for each of our three instruments for the first two years of our study are presented in Table 1.

	Sept 2011	Dec 2011	Sept 2012	Dec 2012
Concept Inventory	33 out of 33	19 out of 29	24 out of 26	19 out of 22
Self-perception Survey	29 out of 33	29 out of 29	25 out of 26	12 out of 22
Focus Groups	N/A	7 students	N/A	4 students

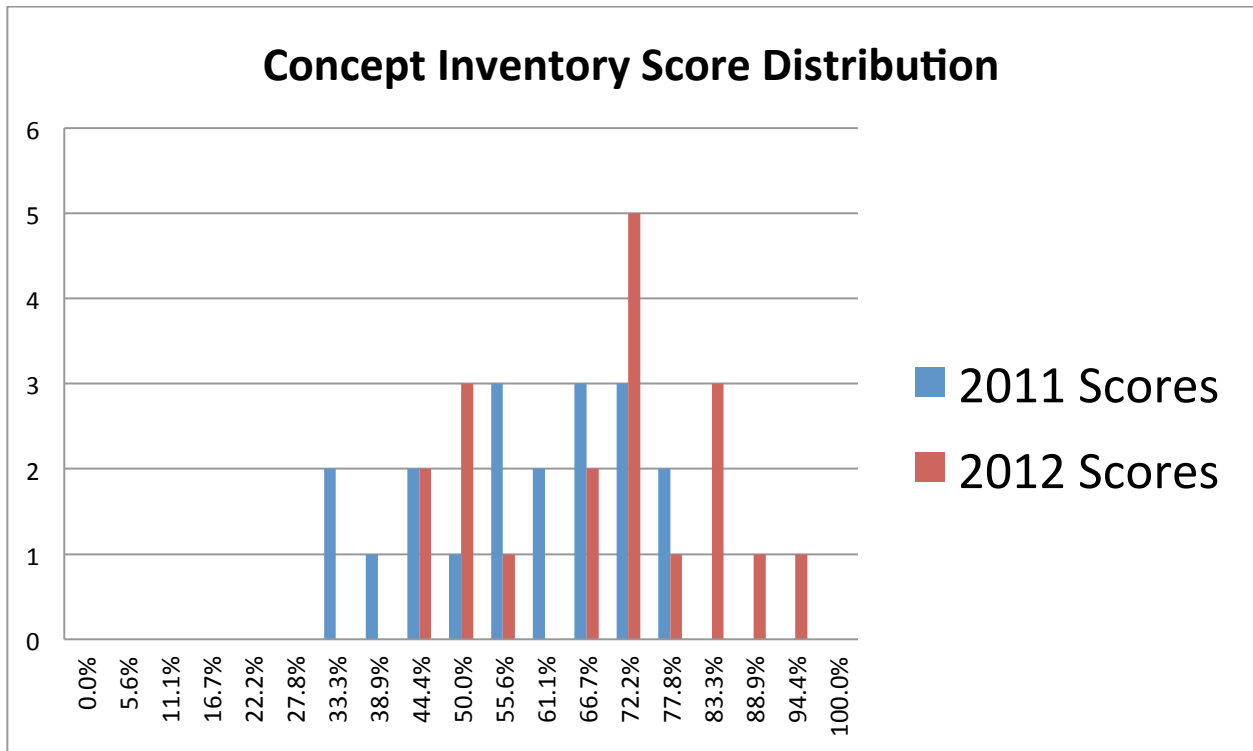
*Table 1: Response rates for the three evaluation instruments.*

## Results and discussion

Table 2 shows student scores on the concept inventory, administered at the beginning and end of each semester. There was essentially no difference in the beginning-of-semester scores (mean of 30-32%) but there was a much larger gain over the course of the semester during which the active-learning approach was employed. Under the lecture approach (fall 2011) the gain was 20.8 percentage points, but under the active learning approach (fall 2012) the gain was nearly twice as large, 38.3 percentage points. Gains in median and mode scores were also significantly larger in the fall 2012 semester. Figure 2 shows complete distributions of the scores at the end of each semester. We believe these data show that students demonstrated a significantly improved conceptual understanding of core course topics when the course was taught with the active learning approach.

	Average	SD	Median	Mode
Sept 2011(Early semester)	31.8	16.6	25	25
Dec 2011 (End Semester)	52.6	14.3	55.6	50
Sept 2012(Early semester)	30.1	9.0	30.6	33.3
Dec 2012 (End Semester)	68.4	15.4	72.2	72.2

*Table 2: Concept inventory results for the fall 2011 (lecture format) and fall 2012 (active learning) semesters.*



**Figure 2: Distribution of End-of-Semester Concept Inventory Scores**

Interestingly, the improved performance of the students enrolled in the active learning format semester was not reflected in students' perceptions of their achievements. At the end of the respective semesters, students in the active learning course rated their mastery of course concepts lower than students in the lecture course. Similarly, the gains in perceived mastery from the beginning to the end of each semester were lower for the students in the active learning format.

Typical results are presented in Fig. 3, which shows the end-of-semester rating and the gain from beginning to end of the semester for students' self-perception of their mastery of course concepts in the knowledge domain (questions 11-20). (Results for the experience and confidence domains were qualitatively similar; detailed results are presented in Table 3 below.) On most questions the end-of-semester ratings and the semester gains were higher for the students in the lecture format (2011) than in the active learning format (2012).

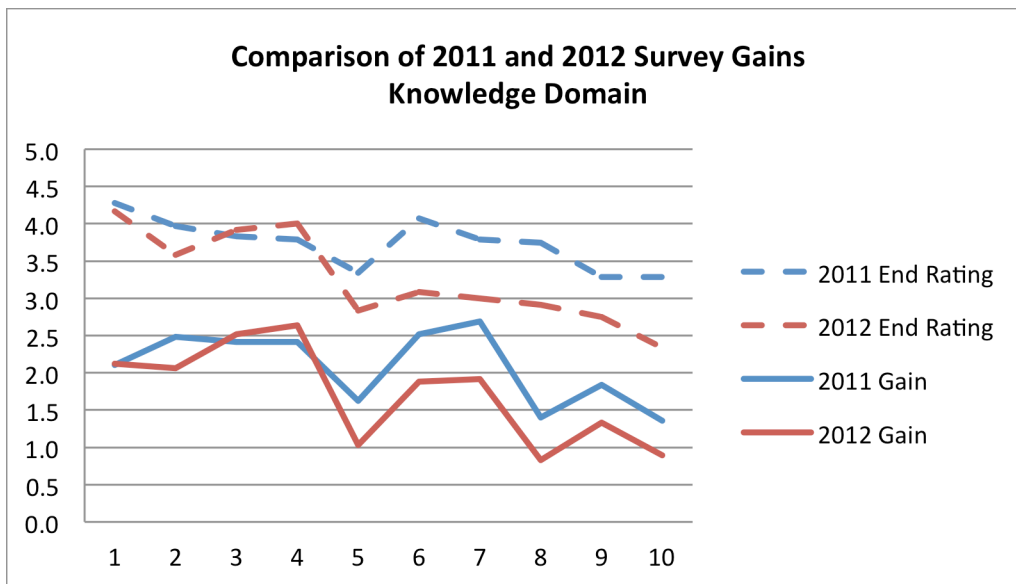


Figure 3: End-of-semester PPI ratings in the knowledge domain, along with the gains from beginning to end of the semester.

The apparent contradiction of improved performance but lower self-perceived mastery is interesting. It is a common experience that the more one learns about a subject the more one is aware of one’s own limitations; this may partly explain our observation. Also, the active learning format forces students to grapple with challenging problems in class, both on the concept tests (which are designed to probe for common misconceptions) and in the detailed examples worked. It is easy for a student to passively watch an expert demonstrate problems in a lecture and believe that they understand what is presented; being expected to work out the same problems for one’s self is a much more challenging proposition.

The student focus groups allowed us to explore this assumption. The same interview protocol (i.e., question list) was used for both semesters. Student comments in the active learning focus group (fall 2012) emphasized that the course workload and intellectual challenge was more difficult than the other courses they took that semester, specifically citing the difficulty of certain assignments like the computational modules. This was not the case during the fall 2011 focus group in which student comments focused less on the intellectual challenge of the course and more on the lecture logistics (e.g., students requested more blackboards so the instructor doesn’t have to erase the board before moving on to a new topic).



<b>Table 3: Class-level Results for Students' Perceived Master of Course Content</b>					
<b>STATEMENT</b>	<b>FALL 2011 AVG</b>	<b>FALL 2012 AVG</b>	<b>FALL 2011 GAIN</b>	<b>FALL 2012 GAIN</b>	<b>DIFF</b>
<i>PPI Questions (1-low → 5-high) K= Knowledge; E= Experience; C = Confidence</i>					
Describe the structure of crystalline elements and common compounds in terms of a lattice and a basis.	K: 4.3 E: 3.8 C: 3.6	K: 4.2 E: 3.8 C: 3.3	K: 2.1 E: 2.1 C: 2.1	K: 2.1 E: 2.3 C: 1.8	K: 0.0 E: -0.1 C: 0.3
Determine the sizes of interstitial sites in various structures, and use this to predict the crystal structure of metallic and ionic compounds.	K: 4.0 E: 3.6 C: 3.3	K: 3.6 E: 3.4 C: 2.9	K: 2.5 E: 2.4 C: 2.0	K: 2.1 E: 2.3 C: 1.7	K: 0.4 E: 0.2 C: 0.2
Determine the proper point group and space group for various 2D and 3D structures.	K: 3.8 E: 3.7 C: 3.2	K: 3.9 E: 3.8 C: 3.2	K: 2.4 E: 2.5 C: 1.9	K: 2.5 E: 2.6 C: 1.9	K: -0.1 E: -0.1 C: 0.0
Use space group information (from the International Tables) to determine atomic positions in crystalline solids.	K: 3.8 E: 3.6 C: 3.3	K: 4.0 E: 4.2 C: 3.5	K: 2.4 E: 2.5 C: 2.0	K: 2.6 E: 2.8 C: 2.2	K: -0.2 E: -0.3 C: -0.2
Draw the atomic arrangements around an edge dislocation in a simple crystal.	K: 3.3 E: 2.9 C: 3.0	K: 2.8 E: 2.2 C: 2.5	K: 1.6 E: 1.5 C: 1.4	K: 1.0 E: 0.6 C: 1.0	K: 0.6 E: 0.9 C: 0.4
Use Bragg's Law and the structure factor to determine the position and intensity of diffraction peaks.	K: 4.1 E: 3.6 C: 3.5	K: 3.1 E: 2.8 C: 2.2	K: 2.5 E: 2.2 C: 2.2	K: 1.9 E: 1.6 C: 1.0	K: 0.6 E: 0.6 C: 1.1
Use Ewald's sphere to illustrate diffraction techniques.	K: 3.8 E: 3.4 C: 3.1	K: 3.0 E: 2.8 C: 2.3	K: 2.7 E: 2.3 C: 1.9	K: 1.9 E: 1.7 C: 1.2	K: 0.8 E: 0.6 C: 0.7
Describe chain structures of polymers.	K: 3.8 E: 3.4 C: 3.5	K: 2.9 E: 2.5 C: 2.5	K: 1.4 E: 1.6 C: 1.8	K: 0.8 E: 0.6 C: 0.7	K: 0.6 E: 0.9 C: 1.0
Describe polymer conformations in melts and in solutions.	K: 3.3 E: 2.9 C: 3.0	K: 2.8 E: 2.2 C: 2.2	K: 1.8 E: 1.6 C: 1.7	K: 1.3 E: 1.0 C: 0.9	K: 0.5 E: 0.6 C: 0.8
Describe techniques for structural characterization of polymers.	K: 3.3 E: 2.9 C: 3.0	K: 2.3 E: 1.8 C: 1.9	K: 1.4 E: 1.4 C: 1.3	K: 0.9 E: 0.5 C: 0.6	K: 0.5 E: 0.9 C: 0.7

Despite the perception of increased workload and more challenging assignments, students preferred the active learning teaching approach. One student audited the course in fall 2011 to help her decide if she would switch majors into Materials Science and Engineering. She commented that the fall 2012 course was a big improvement. "It was more interactive. There is more of a closeness (between faculty and students) this semester." Another student said he has trouble staying awake in most classes, but that "I was never tired in this class." Another student laughed saying "you slept everyday in (another) course."

Students liked the active learning approach for several reasons. First, they appreciated the instructor walking around the classroom asking questions to prompt student thinking before they raised their hand. Students also felt they learned from their peers. One student said he struggled throughout the semester, but that his tablemates really helped him. “My table really helped me when I was struggling. The professor can only talk to so many students at one time, and the group dynamics at my table were great.” Not all students felt their group was supportive. One student commented that other students at her table were competitive and sometimes not nice, but that she still preferred learning with the “new” approach.

Students did request more lecture because they appreciated the explanations provided. It appears some students didn’t get much from the readings and needed more explanation from the professor. This was most apparent in comparing the units on symmetry and diffraction. Students commented that there was a great balance with the symmetry unit. The readings were complemented with good explanations and examples that they applied through in-class activities and homework. In the diffraction unit, all of the students commented how they struggled and one of the biggest reasons was that no examples were fully completed during class. (Superstorm Sandy in October 2012 caused class to be cancelled as the diffraction unit began thus compressing the time that content had to be covered.)

### **Limitations**

At this point our study is limited by the low number of students in the class and that data have only been collected once for the control group (traditional lecture) and experimental group (active learning approach). The course will be taught in fall 2013 with the traditional lecture and in fall 2014 with the experimental approach to collect additional data.

Another limitation is that the concept inventory has not been tested with a large number of students to ensure that it provides a valid measure of student learning gains. As mentioned above, however, the instructor is an experienced instructor in this course, and he developed the concept inventory based on specific learning objectives for the course. Thus, we believe that the concept inventory does provide a valid indication of student learning in the context of this study.

### **Conclusion**

Student learning gains in a core course on structure of materials were significantly greater (by nearly a factor of two) under an active-learning format emphasizing frequent concept testing than under a traditional lecture format. This suggests that active learning leads to a deeper conceptual understanding of key course concepts. The improved learning gains were not, however, reflected in students’ self-perception of their mastery of key course concepts, which was lower under the active learning format. Students did prefer the active learning approach specifically citing the sense of a supportive classroom community. Data will be collected over two more offerings of this course, once each in traditional lecture and active learning formats, to provide more robust support for these conclusions.

## Acknowledgements

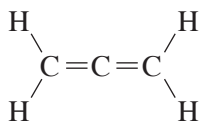
We gratefully acknowledge the students enrolled in *Structure of Materials* over the past two years; without their enthusiastic participation in the concept inventories, surveys, and focus groups this work would not have been possible. This research is supported by the National Science Foundation under grant DMR-1107838.

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## Appendix 1 – Concept Inventory

1. The chemical structure of allene is shown here:



What can we say about the relative orientations of the two pairs of H atoms?

- The pair of H atoms at one end is perpendicular to the pair at the other end
  - The two pairs of H atoms lie in the same plane
  - No definitive statement can be made, because the two ends can rotate independently about the axis of the molecule
2. Which of the following combinations of atomic orbitals cannot form a  $\sigma$  molecular orbital?
- s+s
  - s+p
  - p+p
  - None of these---they can all form  $\sigma$  molecular orbitals.
3. Under ordinary conditions the bonding in Si (which has the diamond cubic structure) is predominantly covalent. Upon melting, Si experiences a volume change of approximately -10%. Which of the following statements is most likely to be true?
- Melting does not change the character of bonding in silicon
  - Melting causes the bonding in Si to become partly ionic in character
  - Melting causes the bonding in Si to become partly metallic in character
4. Which of these is *not* a valid unit cell for a close-packed plane?

*Figure removed for copyright restrictions*

- A
  - B
  - C
  - D
  - None of them---they're all fine.
5. A crystal of an elemental metal undergoes a transformation from the body-centered cubic (bcc) structure to the face-centered cubic (fcc) structure. Assuming that the size of the atoms themselves is unchanged, the volume of the crystal will

- a) Increase
- b) Decrease
- c) Remain the same

6. Which phase is thermodynamically stable at temperatures above  $T_{eq}$ ?

*Figure removed for copyright restrictions*

- a) A
- b) B
- c) They are in equilibrium with each other above  $T_{eq}$ .
- d) Can't tell from the information given.

7. In order for a solid solution to be thermodynamically more stable than the unmixed, pure elements, the enthalpy of mixing ...

- a) Must be positive
- b) Must be negative
- c) Must be zero
- d) Can be any of these (positive, negative, or zero) depending on the situation.

8. An atom absorbs an x-ray photon, and subsequently emits a fluorescent x-ray photon. Which one of these statements is true?

- a) The energy of the fluorescent photon is greater than the energy of the incident photon
- b) The energy of the fluorescent photon is less than the energy of the incident photon
- c) The energy of the fluorescent photon is the same as that of the incident photon
- d) Any of the above may be true, depending on the type of absorbing atom and the energy of the incident photon.

9. Which point symmetry operation is illustrated here?

*Figure removed for copyright restrictions*

- a) Centre of symmetry
- b) Mirror plane
- c) Diad (two-fold axis of rotation)
- d) None of these

10. What is the point symmetry of a water molecule?

*Figure removed for copyright restrictions*

- a) 2
- b) m
- c) 2mm
- d) mmm

11. Which of the following symmetry elements is *not* present?

*Figure removed for copyright restrictions*

- a) Diad (2)
- b) Screw diad ( $2_1$ )
- c) Mirror (m)
- d) Tetrad (4)

12. The CsCl structure has a cubic unit cell, with Cl at the corners and Cs in the body-center position. Which of these is the correct Bravais lattice for this structure?

- a) Primitive cubic (cubic-P)
- b) Body-centered cubic (cubic-I)
- c) Face-centered cubic (cubic-F)
- d) None of these

13. Is it possible to make a crystal which has no vacant lattice sites (at room temperature)?

- a) Yes.
- b) Yes in theory, but in practice it cannot be done.
- c) No, because the presence of vacancies increases the enthalpy of the crystal.
- d) No, because the presence of vacancies increases the entropy of crystal.

14. A schematic dislocation in simple cubic structure is shown below. If a shear stress  $\gamma_{zy}$  is applied to this crystal, in which direction will the dislocation move? (You may assume that the applied shear stress is greater than the critical resolved shear stress for dislocation motion.)

*Figure removed for copyright restrictions*

- a) The dislocation will move parallel to the  $x$  axis.
- b) The dislocation will move parallel to the  $y$  axis.
- c) The dislocation will move parallel to the  $z$  axis.
- d) The dislocation will not move in response to this shear stress.

15. Consider a material with a simple cubic unit cell (with an atom at the each corner), and from which we record a powder x-ray diffraction pattern. Now imagine that an atom (of the same type) is added exactly at the center of each unit cell, and again we record the diffraction pattern. Comparing the two diffraction patterns, which of the following statements is true?

- a) The diffraction patterns are the same in both cases.
- b) The same diffraction peaks will appear in both cases, but their positions will change.
- c) New diffraction peaks will appear when the atom is added to the center of the unit cell.
- d) Some diffraction peaks will disappear when the atom is added to the center of the unit cell.

16. Consider an x-ray diffraction experiment performed on a polycrystalline specimen. How does the diffraction peak width depend on the crystal size?

- a) Bigger crystals give broader peaks
- b) Bigger crystals give narrower peaks
- c) The size of the crystals does not affect the diffraction peak width

17. For a given linear polymer, which of the following configurations is *least* likely to be able to crystallize?

- a) Isotactic
- b) Syndiotactic
- c) Atactic

18. The end-to-end distance for a particular kind of linear polymer is observed to be longer when the polymer is dissolved in a particular solvent, as compared to that when the polymer is in the molten state. Based on this, one can conclude...

- a) The attractive interaction between a monomer and the solvent is stronger than the attraction between two monomers
- b) The attractive interaction between a monomer and the solvent is weaker than the attraction between two monomers
- c) The attractive interaction between a monomer and the solvent is the same as the attraction between two monomers

19. A certain rod-like molecule exists as a crystalline solid at low temperatures, but upon heating transforms to a smectic liquid crystal at  $T=31\text{ }^{\circ}\text{C}$ . Based on this knowledge, comparing the two structural forms, it is most likely that

- a) The bonding between molecules is stronger in the smectic liquid crystal
- b) The bonding between molecules is stronger in the crystalline solid
- c) The entropy per molecule is greater in the smectic liquid crystal
- d) The entropy per molecule is greater in the crystalline solid

20. It is desired to build a transmission electron microscope capable of atomic resolution. All other things being equal, which of the following statements is most likely to be true?

- a) The resolution will be independent of the electron energy
- b) Resolution increases with increasing electron energy
- c) Resolution decreases with increasing electron energy



## Appendix 2 – Student Self-Perception Survey

This survey allows you to self-report your mastery of the key learning objectives in the class. There are no right or wrong answers, and all answers will remain anonymous. The survey will be given both at the beginning and at end of the semester to measure the change in overall response of the class.

There are two sets of questions with different formats. Please read the instructions carefully for each section.

---

### **Foundational Knowledge**

*Choose your level of understanding for each statement below.*

As of today, I understand the following concepts explored in this class...

- 1) The nature and basic features of metallic, ionic, and covalent bonds  
not at all - just a little - somewhat - a lot - a great deal
- 2) The influence of bonding on the structure of materials  
not at all - just a little - somewhat - a lot - a great deal
- 3) The atomic-scale structure of metals, alloys, and ceramics  
not at all - just a little - somewhat - a lot - a great deal
- 4) The microstructure of metals, alloys, and ceramics  
not at all - just a little - somewhat - a lot - a great deal
- 5) Symmetry in crystals, including point groups and space groups  
not at all - just a little - somewhat - a lot - a great deal
- 6) Defects in crystalline solids (vacancies, dislocations, etc.)

not at all - just a little - somewhat - a lot - a great deal

7) How x-rays, electrons, and neutrons can be used to study the structure of materials

not at all - just a little - somewhat - a lot - a great deal

8) The use of optical, scanning-electron, and transmission-electron microscopy for studying structure of materials, and spectroscopy for measuring chemical composition

not at all - just a little - somewhat - a lot - a great deal

9) The structure of polymers

not at all - just a little - somewhat - a lot - a great deal

10) The structure of liquid crystals and amphiphilic materials.

not at all - just a little - somewhat - a lot - a great deal

### Application of Knowledge

The following questions measure your self-perceived knowledge, experience, and confidence on several activities.

#### Example to illustrate the style and intent of the survey questions:

Select one number in each of the three rows.

Change a flat tire.

	-----	Low	-----	High	
Knowledge	1	2	3	4	<b>5</b>
Experience	1	2	<b>3</b>	4	5
Confidence	<b>1</b>	2	3	4	5

This set of answers is interpreted as follows.

1. I have a great deal of knowledge (response of 5) about changing a flat tire.
2. I have an average amount of experience (response of 3) with changing a flat tire.
3. I am not confident (response of 1) in my ability to change a flat tire in the future.

For each statement below please rate your perceived knowledge, level of experience, and confidence in completing the activity.

- 1) Describe the structure of crystalline elements and common compounds in terms of a lattice and a basis.

----- Low ----- High

Knowledge	1	2	3	4	<b>5</b>
Experience	1	2	<b>3</b>	4	5
Confidence	<b>1</b>	2	3	4	5

- 2) Determine the sizes of interstitial sites in various structures, and use this to predict the crystal structure of metallic and ionic compounds.

----- Low ----- High

Knowledge	1	2	3	4	<b>5</b>
Experience	1	2	<b>3</b>	4	5
Confidence	<b>1</b>	2	3	4	5

- 3) Determine the proper point group and space group for various 2D and 3D structures

----- Low ----- High

Knowledge	1	2	3	4	<b>5</b>
Experience	1	2	<b>3</b>	4	5
Confidence	<b>1</b>	2	3	4	5

- 4) Use space group information (from the *International Tables*) to determine atomic positions in crystalline solids.

----- Low ----- High

Knowledge	1	2	3	4	<b>5</b>
Experience	1	2	<b>3</b>	4	5
Confidence	<b>1</b>	2	3	4	5

5) Draw the atomic arrangements around an edge dislocation in a simple crystal

----- Low ----- High

Knowledge	1	2	3	4	<b>5</b>
Experience	1	2	<b>3</b>	4	5
Confidence	<b>1</b>	2	3	4	5

6) Use Bragg's Law and the structure factor to determine the position and intensity of diffraction peaks.

----- Low ----- High

Knowledge	1	2	3	4	<b>5</b>
Experience	1	2	<b>3</b>	4	5
Confidence	<b>1</b>	2	3	4	5

7) Use Ewald's sphere to illustrate diffraction techniques.

----- Low ----- High

Knowledge	1	2	3	4	<b>5</b>
Experience	1	2	<b>3</b>	4	5
Confidence	<b>1</b>	2	3	4	5

8) Describe chain structures of polymers.

----- Low ----- High

Knowledge	1	2	3	4	<b>5</b>
Experience	1	2	<b>3</b>	4	5
Confidence	<b>1</b>	2	3	4	5

9) Describe polymer conformations in melts and in solutions.

----- Low ----- High

Knowledge	1	2	3	4	<b>5</b>
Experience	1	2	<b>3</b>	4	5
Confidence	<b>1</b>	2	3	4	5

10) Describe techniques for structural characterization of polymers.

----- Low ----- High

Knowledge	1	2	3	4	<b>5</b>
Experience	1	2	<b>3</b>	4	5
Confidence	<b>1</b>	2	3	4	5