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How You Teach It: A Flipped Classroom, Collaborative Learning Approach to Teaching Metal Crystal Structures

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Introduction

Crystal structures, in particular those of metals, are generally agreed to be one of the fundamental principles of an introductory materials science course (e.g., [1]). This is true regardless of whether the course is taught for students with majors in materials engineering or other engineering disciplines. This "How You Teach It" paper will describe a lesson designed to introduce students to crystal structures using evidence-based educational approaches of flipped classroom and collaborative learning. Resources will also be included in a link at the end.

Context

The following lesson is taught in an introductory Material Science course for students with Integrated Engineering majors. It is a required course for all students in the major, regardless of their disciplinary focus (e.g., mechanical, electrical, civil) within the major. I started teaching the Material Science course during the Fall 2019 semester, and the following Metal Crystal Structures lesson has been part of the course since the beginning. In terms of content, the purpose of the Metal Crystal Structures lesson is to introduce students to common metal crystal structures and important quantities associated with crystal structures (e.g., number of atoms per unit cell, atomic packing factor, coordination number). The activities have been slightly modified over the years, but the main deliverables have remained, with one exception: due to time constraints, I have developed a *long version* and a *short version* of the main in-class activity that is part of the lesson. Both are described below.

Pre-Work

One of the evidence-based educational approaches used for the lesson is the flipped classroom approach (e.g., [2]). In the flipped classroom approach, students acquire the main ideas of the lesson before class, for example by watching videos of "lectures" and/or reading textbooks. In this way, the class is "flipped" because the lecture occurs outside of class, and class time is used to work on activities and problems. For the Metal Crystal Structures lesson, I created two lecture videos, *Crystalline Solids* (10.5 minutes) and *Metal Crystal Structures* (21 minutes). (The videos, as well as their transcripts and fill-in-the-blank slides, are included in the resources link at the end of the paper.) The *Crystalline Solids* video introduces students to more general vocabulary about crystalline solids, including crystal structures, unit cell, and crystalline points, directions, and planes. The *Metal Crystal Structures* video describes four important crystal structures as well as the important quantities associated with crystal structures. The four crystal structures focused on in this lesson are Simple Cubic (SC), Body-Centered Cubic (BCC), Face-Centered

Cubic (FCC), and Hexagonal Close-Packed (HCP). The main quantities introduced are number of atoms per unit cell, atomic packing factor (APF), and coordination number. In the *Metal Crystal Structures* video, I also demonstrate how to find those important crystal structure quantities for the SC and HCP crystal structures, leaving the derivation of the BCC and FCC quantities as an in-class activity for the students.

In addition to watching the videos, the pre-work also includes two other assignments. The main pre-work assignment for this lesson is the *Crystal Structures Video Concept Check Quiz*, which is a 7-question, multiple choice quiz about the main ideas of the videos. The main goal of the concept check quiz is for students to receive immediate feedback about how well they understood the main points of the videos. Therefore, the questions are fairly easy; the students need to identify information in their notes, not apply the concepts to solve more advanced problems. For example, one question is: "A crystal structure that has a cubic unit cell with one atom on each of the 8 cube corners and one atom in the center is the ____________________ crystal structure. (Multiple choice options of SC, BCC, FCC, HCP)." The other pre-work assignment is for students to submit at least two questions and/or comments about the videos. As the instructor, I look at these submissions before class to see if there are any common questions I should address during class. For this "How You Teach It" paper, the *Crystal Structures Video Concept Check Quiz* is included as a google form in the resources folder, but the questions and/or comments assignment is not included due to how it is set up in the learning management system.

In summary, the pre-work is to watch two videos (totalling a little over 30 minutes), complete a quick and fairly easy concept check quiz, and submit two questions and/or comments about the videos. The latter two assignments count toward students' grades, but pre-work is a small portion of the overall grade (5%), so they are fairly low-stakes assignments.

In-Class Activities

Because students have already had the "lecture" part of the course before class, class time can be used for small group activities, other active learning activities, and supplemental mini-lectures (e.g., answering student questions about the pre-work videos). In the Metal Crystal Structures lesson, I typically spend 5-15 minutes at the beginning of class time answering common questions from the pre-work questions and/or comments assignment. Some examples of these questions are in the *MatSci_CrystalStructures* slide deck, which is in the resources link. Answering these questions at the beginning of the class allows me to control the transition from the pre-work "lecture" to the in-class activity; I can spend a little time reviewing the main ideas from the videos which will be most important for the main in-class activity.

Most of class time is spent on the main activity, in which students derive the important crystal structure quantities for the FCC or BCC crystal structure. This activity is done in small groups, encouraging collaborative learning (e.g., [3]). There are two versions of the activity, one for a longer class time and one for more limited in-class time. For the rest of the paper, they will be called the *long version* and the *short version*. Slides for both are included in the *MatSci_Crystal Structures* slide deck, with notes distinguishing which specific slides go with which version.

For both versions, the main idea is for students to use unit cell geometry to derive - for a crystal structure - the number of atoms per unit cell, atomic packing factor, and coordination number. To help with the derivation of atomic packing factor, the worksheet and slide deck also prompt students to figure out several other calculations along the way. For example, students need to figure out the unit cell edge length (traditionally noted as a) in terms of the atomic radius R for a crystal structure. By the end of the class (or as homework), each student has one summary table of the important crystal structure quantities for SC, FCC, BCC, and HCP. These tables are in the *MatSci_HW1_CrystalStructures - Long Version* worksheet and the *MatSci_HW1_CrystalStructures - Short Version* sheet, both of which are in the resources link. Because this summary table is the main outcome of this lesson, the answer key - *MatSci_CrystalStructures_Summary Table Answers* - is included in the resources link and also in Appendix A of this document.

Long Version

With more time for the activity (e.g., 30+ minutes), student teams have time to get stuck, check their notes, and ask the instructor as needed. Because of this, the *long version* of the derivation activity is less guided. Students get into teams of 2-4. As the instructor, I make sure about half of the teams are working on BCC and half on FCC. The main resources students have are their notes from the pre-work, the *MatSci_HW1_CrystalStructures - Long Version* worksheet, and each other. During the activity, the instructor can answer questions and check to make sure student teams are on track.

There are two main variations with the *long version*. The version with the most student independence is to allow small groups to do the whole activity by themselves. If student groups seem to be struggling, an alternative option is to start the activity as a whole group. In this sub-version, I lead a whole-group discussion to determine the “atoms touch along which direction?” and “# atomic radii along touching direction within unit cell?” for BCC and FCC. Although students have been introduced to basic crystallographic directions, the main activity for that topic occurs after this Metal Crystal Structures activity, so it has been useful to guide the part of the activity that relies on this knowledge.

The other aspect that varies is how the activity ends. If the class is especially small and there are not many small groups (e.g., less than 5-6 groups), the students give short presentations to share their results with the rest of class. If the class is larger, then I pair each BCC group with an FCC group as the small groups finish their calculations. In this sub-version, the small groups explain their results to each other, completing the activity.

Short Version

When class time is limited, the *short version* of the activity is done. It is a more guided version of the derivation activity, which allows it to be finished more quickly. The main resource students use for this version is the *MatSci Face-Centered Cubic (FCC) Walk-Through* (google form). This quiz is set up so that students do one step at a time, and they receive an explanation within the quiz after each question submitted. An additional benefit of the guided quiz is that a student team can continue making progress, even if they are unsure; if they get one step incorrect, they see immediately that it is wrong and are able to course-correct before the next step. As the instructor, I still monitor the teams to answer questions and see their progress.

Because the *short version* involves all student teams doing the derivation for the FCC crystal structure, they still need to derive the important crystal structure quantities for the BCC structure. (As stated earlier, the SC and HCP values were derived via instructor demonstration in a pre-work video.) That BCC derivation is done as individual homework, using the *MatSci_HW1_CrystalStructures - Short Version* worksheet.

Regardless of version, I do not grade their in-class process (e.g., participation in small groups, final score on the *MatSci Face-Centered Cubic (FCC) Walk-Through* quiz). Instead, I grade their *MatSci_HW1_CrystalStructures* worksheet once it is submitted.

Student Feedback and Instructor Reflection

Because I have used the *long version* of the activity since I started teaching the Material Science course in Fall 2019, I have no data to compare the *long version* to another method of teaching about metal crystal structures. When I first implemented the *short version* of the activity during the Fall 2025 semester, students could opt in to a one-question survey about the activity. The question was: **One of the new things I tried this semester was the step-by-step 1.1 Face-Centered Cubic (FCC) Walk-Through. What feedback do you have for me about this change? (Did you like it or not? Do you think it helped your learning of Crystal Structures (and HW1a) more or less? etc.)**

Of the 32 students in the Fall 2025 Material Science course, 15 responded. All 15 responses about the *short version* of the activity were positive, stating that they liked and/or found it helpful. When students wrote additional explanations, there were a few common reasons for liking the activity. Some students said it helped them truly learn the crystal structure terms, and a couple of students specifically mentioned Atomic Packing Factor (APF), for example, "It gave me an opportunity to practice crystal structures…this was when the process of finding APF finally clicked and I understood how go about finding it.” A few students appreciated visuals and how the pictures connected to the equations and concepts. For example, one student wrote, “Yes, it was very helpful, enough text to get the point across, and enough images to create a mental picture.” Some students noted that they liked the step-by-step nature of the activity, and three specifically mentioned that the immediate answers and explanations for each question were helpful. A student wrote, “I liked that assignment. I like assignments that tie together in steps. It always helps to have the information after the question to reinforce learning.” Two students also mentioned that they went back to the quiz when studying for the final exam, so they appreciated the clear explanations that were built into the activity. The only somewhat negative feedback was that two students wished the activity was made for all of the crystal structures instead of focusing on just FCC. However, as the instructor, I designed the lesson to gradually increase responsibility: students watch the instructor deriving SC and HCP in the videos; then, students work in small groups on a guided derivation activity for FCC; finally, students work on their own to figure out the derivation for BCC.

As noted above, I taught variations of the *long version* of this activity for six years and the *short version* in one semester. I have found that both versions can support student learning, especially when they have bought into the flipped classroom approach and come to class prepared. For both versions, the collaborative nature of the activity tends to prompt engaging discussions. One benefit of the *short version* that was obvious to me as the instructor was that key visuals were embedded in the quiz. Instead of spending time making sure that the whole student group was referring to the same image(s), which can happen with the *long version* of the activity, the student groups were able to immediately discuss the relevant features of the key visuals. Ultimately, both activities seem to work well in terms of student learning. Students generally do well on the Crystal Structures section of the end-of-course summative assessment, regardless of whether they did the *long version* or *short version* of the Metal Crystal Structures activity.

Additional Implementation Notes

The pre-work for this Metal Crystal Structures activity could be delivered via a variety of modes: videos, readings, a previous lecture, or some other means. I generally prefer videos for my core (required for the major) courses and readings for elective courses, but different instructors have different preferences. One aspect of the pre-work I highly recommend, especially for a flipped classroom approach, is a low-stakes concept check quiz. Students have consistently given me feedback that they appreciate the concept check quizzes so they can see if they understand the main ideas of the new concepts. As the instructor, I appreciate seeing if there are any conceptual misunderstandings about an idea among the whole class, and I can quickly identify individual students who are struggling with several ideas.

I have chosen between the *long version* and the *short version* of the in-class activity primarily based on time available. Although I have had certain groups of students finish the *long version* of the activity within 10-15 minutes, it typically takes student groups closer to 30 minutes to figure out the process. I find that the *short version* works better for 20 minutes or less because the process is more explicitly guided by the questions on the quiz. Another consideration for deciding between the *long* and *short versions* is the ratio of instructors/TAs to student groups. When there are a few student groups per instructor, it is more likely that the instructor will be able to help when a group gets stuck on a step. Thus, the *long version* is easier to implement with a smaller number of groups per instructor. In contrast, the *short version* allows students to move on to the next step even if they are stuck, since the explanations for each step are built into the quiz. Thus, this version can be more useful with a large number of student groups.

A final note is that the pre-work above includes an introduction to basic crystallographic points, directions, and planes (i.e., just those with 0s and 1s), which is what is needed to discuss differences between the SC, BCC, and FCC crystal structures. Additional information and practice about crystallography points, directions, and planes is included in the next lesson in my Material Science course, which is why it is not included in this How You Teach It paper.

Conclusion

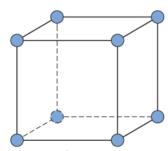
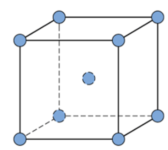
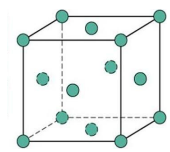
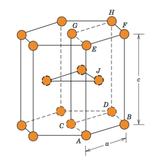
Throughout this "How You Teach It" paper, I described a flipped classroom, collaborative learning lesson for Metal Crystal Structures. Student feedback about the *short version* indicates that they found it useful for their learning. Additional information about the whole lesson, as well as both versions of the main in-class activity, can be found in the resources in the resources link below.

Resources Link:
https://tinyurl.com/MetalCrystalStructures

References
[1] Callister, W. D., & Rethwisch, D. G. (2018). *Materials science and engineering: An introduction* (10th ed.). Wiley.
[2] Kerr, B. (2015, September). The flipped classroom in engineering education: A survey of the research. In *2015 International Conference on Interactive Collaborative Learning (ICL)* (pp. 815-818). IEEE. https://doi.org/10.1109/ICL.2015.7318133
[3] Mercier, E., Goldstein, M. H., Baligar, P., & Rajarthinam, R. J. (2023). Collaborative learning in engineering education. In A. Johri (Ed.), *International Handbook of Engineering Education Research* (1st ed., pp. 402-432). Routledge. https://doi.org/10.4324/9781003287483

Appendix A

MatSci_CrystalStructures_Summary Table Answers

Quantity	Simple Cubic (SC)	Body-Centered Cubic (BCC)	Face-Centered Cubic (FCC	Hexagonal Close-Packed (HCP)
Sketch of unit cell (hard- and/or reduced-sphere model)				
Number of atoms per unit cell	1	2	4	6
Atoms touch along which direction?	[001]	[111]	[110]	
# atomic radii along touching direction within unit cell?	#R = 2 (2R)	#R = 4 (4R)	#R = 4 (4R)	
Unit cell edge length (i.e., lattice constant) in terms of R	a = 2R	$a = \frac{4R}{\sqrt{3}}$	$a = 2\sqrt{2}R$	
Unit cell volume in terms of R	$V=a^3= 8R^3$	$V=a^3=\frac{64R^3}{3\sqrt{3}}$	$V=a^3= 16\sqrt{2}R^3$	
Atomic Packing Factor (APF) = $V_{atoms}/V_{unitcell}$	$\frac{\pi}{6} \sim 0.52$	$\frac{\pi\sqrt{3}}{8} \sim 0.68$	$\frac{\pi}{3\sqrt{2}} \sim 0.74$	0.74 (same as FCC)
Coordination Number = # atoms touching 1 atom	6	8	12	12