The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
Paper ID #42656

Student-Tool Interactions from a Conceptually Challenging Adaptive Learning Module for Materials Science

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The use of computers as automated adaptive instructional tools to support students in STEM education continues to grow. However, these tools often focus on development of declarative knowledge and procedural skills; it is uncommon and challenging to develop adaptive learning tools that specifically focus on developing conceptual understanding. In part, this difficulty stems from limited understanding of how students' conceptual knowledge emerges through interaction with these adaptive tools. In a previous study, we have explained the components and how we quantitatively tested the adaptive logic of a newly developed Crystallography Adaptive Learning Module (CALM) in materials science. In the current study, we use a knowledge-in-pieces framework that views learning as the activation and coordination of resources. We seek to identify and explicate student-tool interactions that may lead to or hinder the activation of conceptual resources leading to canonical understanding. Utilizing a qualitative think-aloud design, four students completed the CALM while being recorded and prompted to explain their thinking. Sessions lasted two to three hours per participant. Audio recordings of students thinking aloud were supplemented by video recordings of their screens as they completed the module. We also collected and analyzed the notes they wrote as they completed the CALM. Comparing across the four cases, the activation and coordination of resources was more idiosyncratic than we previously envisioned. For example, part of the CALM contains three two-part multiple-choice questions used for formative assessment with the initial question asking a conceptually challenging question and the follow-up question having the students select a response that aligns with their reasoning. We constructed the possible choices for reasons in the second question based on our analysis of students' free responses in previous terms. While students found the follow-up choices provided on some questions align with their initial reasoning when they selected the answer from the first approach, on most questions they re-thought their choice based on the reasons provided. There were also instances where students responded based on how they interpreted the tool's response should be. For example, the summative assessment was designed to be adaptive with students who answered a question correctly receiving a more difficult question and those who did not answer correctly receiving a less difficult question. However, sometimes, when correct, a student interpreted a similar question as an indication they were incorrect the first time. We also describe differences in the ways students negotiated uncertainty and how they engaged in the more extensive instructional tools. This paper contributes both to how students conceptually engage with complex materials science content and how student-technology interactions can support or hinder learning.

Keywords: conceptual learning, knowledge in pieces, adaptive learning module, think aloud, materials science.

Introduction

Engineering educators are increasingly emphasizing the importance of students' conceptual learning [1]. At the same time, the growth in educational technology has led to the promise of Advanced Personalized Learning, one of the National Academy of Engineering's fourteen Grand Challenges for Engineering for the 21st century [2]. In response, we have crafted an adaptive automated system for development of conceptual understanding in introductory materials science courses – the Crystallography Adaptive Learning Module (CALM). The components and adaptive logic in the CALM as well as quantitative studies related to the tool have been reported previously [3], [4], [5] and are briefly discussed later in this paper.

However, due to the challenges in developing such adaptive computerized tools [6], [7] as well as conceptual learning activities [5], [8], research that combine these aspects is limited. Various research focuses on developing and testing these adaptive tools from either the design of the programming and frameworks aspect [7], [9], [10] or to quantify their effectiveness in promoting conceptual learning based on performance (such as scores) [4], [11], [12] and perceptions [12], [13], [14]. Rarely do they focus on exploring *how* students develop their conceptual knowledge while navigating through and interacting with such tools.

In this study, we sought to understand the ways that our newly developed CALM could be supporting (or hindering) students conceptual learning. We took a qualitative approach to further investigate how students interact with the CALM through the guided adaptive path each student received. Examples of scenarios we found interesting are presented here, focusing on students' thinking and reasoning. Ultimately, the purpose of this work is to understand how students make sense of each concept in the CALM and how student-tool interactions – through the challenging concept questions, activities and supplemental resources, and feedback – affect students learning. The findings can support educators in developing and deploying adaptive learning tools in engineering.

Background

Conceptual Learning and Concept-Based Coupled Multiple Response Assessments

There are two main stances in research on conceptual learning. The first common stance views incorrect concepts as misconceptions – robust beliefs that arise commonly among students [15], [16]. The focus is on identifying and "repairing" misconceptions by providing the correct concepts. The second common stance, *knowledge-in-pieces*, interprets learning as connecting and activating fragments of knowledge [17], [18]. Incorrect or partially correct explanations are considered as resources for developing conceptual understanding [19], [20]. The sense making process emerges and is flexible, changing dynamically [21], [22]. In this study, we incorporate the knowledge-in-pieces while interpreting our findings.

Concept-based questions are a well-established tool to promote conceptual learning. In the CALM we use a coupled multiple response (CMR) format for formative concept questions [4]. The CMR provides two questions: the initial concept-based question and a follow-up question asking the students to reason '*Why?*'. Here, students can choose more than one response as well as type their own if none of the options provided make sense for them. The logic for the formative assessment in the CALM is shown in Figure 1, as discussed previously [3].

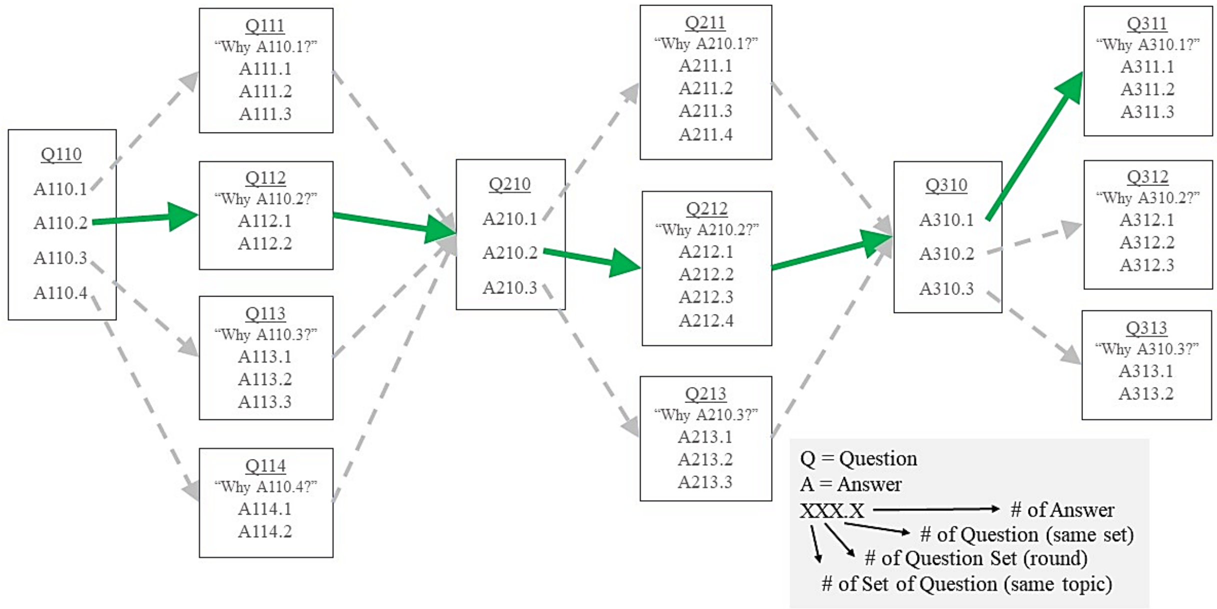


Figure 1. The formative assessment logic in the CALM. Solid green arrows show a sample student path. Dashed grey arrows show other possible paths.

CMR assessment, or sometimes called "two-tier" multiple-choice instrument [23], was first introduced by Tamir in 1970's [24]. Wilcox and Pollock [25], studied a comparison between students' written justification and the CMR responses in physics. They reported that students performed equally between the two versions, advocating for the use of CMR as it increases usability and scalability. We found one work-in-progress [26] that focused on making and assessing this type of CMR assessment, also for physics concepts. On the other hand, research specifically focusing on analyzing the quality of students' explanations of the free-response testing format is more common [27], [28]. There is limited research focusing on how CMR promotes students' further conceptual thinking. Part of this research captures and reports findings related to this gap.

Adaptive Learning Tools with Conceptual Learning

Adaptive individualize learning strategies, with the use of computers, has been integrated into education for over the past half-century [29], [30], [31], [32], [33]). One approach is to provide personalized content based on a student's prior performance. To this end, the CALM developed a responsive system that assigns students either more difficult or easier concept questions based on the correctness in their previous ones [3], [4], [5]. The purpose of this adaptive summative assessment is to assess the competency on each concept for each student. We have reported student performance quantitatively in our previous studies [3], [4], [5]. In this paper, we report qualitative analysis of how students interacted with the assessments.

While researchers have reported how conceptual learning emerges in students by observing classroom/lab activities [34], [35], [36], interviews of students working through problems/questions [37], [38], [39] and oral exams [40], there is limited research of students navigating and interacting with computer-based adaptive learning systems. Students can experience productive or unproductive epistemic emotions (such as confusions) that can either promote or hinder further conceptual learning while interacting with such personalized digital learning tools [41], [42]. Factors that can led to these emotions include individually based variables (prior knowledge and self-regulation), design of the tools (sequence and structure between activities and tasks), and feedback process (timing and type) [42]. However, research with adaptive tools commonly focuses on quantifiable results, such as scores or correct percentages on tasks [4], [11], [12], concept inventories and exams [43], [44], timing [14], or number of attempts [11]. Another research thread reports on student perceptions from the end of the lesson surveys or interviews [12], [13], [14]. We have not found research focused on students' interaction with such adaptive learning technologies as they work through the activity. This study helps address this gap.

Research Questions

We are interested in understanding how students interact and learn while progressing through the CALM. Following the knowledge-in-pieces framework [17], [18], we also seek to inquire how the CALM promotes or hinders students' sense making of the concepts. Specifically, we ask the following questions:

1. What indications do students show that they are developing conceptual understanding in crystallography topics?
2. In what ways does the CALM promote or hinder students' activation and coordination of resources and/or conceptual change on these topics?

Methods

Setting and Participants

Four junior and senior engineering students enrolled in a materials science introductory course for their first time participated in this study (IRB-2020-0775). The course was offered in Fall 2021 and recruitment occurred on the first day of the course. Consenting participants met with the researcher by video conference and completed the CALM before they attended their course lecture when the same concepts were introduced. Sessions ranged from two to three hours. To protect their identities, pseudonyms were used during the data collection, analysis, discussion, and report processes. Participants' voices and screens were recorded. Their scratch paper notes were collected after the session. All participants were compensated for their time with a $25 electronic gift card.

To understand students' cognitive processes and capture their sense making, a think aloud protocol [45] was used in this study. Here, participants' interactions and thoughts are recorded using screen casting with audio narration while they individually navigate through the adaptive learning module. They say aloud what they see or read, what they think or their reasoning through any questions, what they feel, and what they do or type at that moment. The main role of the researcher during the think aloud sessions was to regularly remind participants to continue verbalizing their thoughts without providing any guidance or answering any content related questions during the activities.

The Crystallography Adaptive Learning Module (CALM)

The CALM focuses on three main knowledge constructs: crystal structure, atomic packing factor (APF), and theoretical density. Four crystal structures are introduced in the module: simple cubic (SC), body-centered cubic (BCC), face-centered cubic (FCC), and hexagonal close packed

(HCP). The module consists of a short introductory video and three lengths of interactive lectures with embedded pop-up low-stake questions for students to choose. Then students are guided to CMR questions as described earlier. Based on their performance, students may be directed to a set of short supplemental interactive videos. All students then continue with a more hands-on simulation instructional tool (3D Crystal Builder, https://conceptwarehouse.tufts.edu/cw/crystalVL/) and reflection activities before being presented with a resources review page. Lastly, students work on adaptive summative assessment with various difficulty levels of concept questions and a survey. More details of the structure and components of the CALM was previously described in the earlier work [3], [4].

Data Analysis

The first round of verbatim transcription was done through a paid service (Rev's Standard Captions). The researcher (first author) then revised the transcripts to ensure accuracy and added more detailed actions (e.g., the participants use their cursors to point or click on certain items) from the recorded voice and screen-sharing videos. The unique paths each student followed, their conceptual struggles and sense-making, and what supports the CALM provided for each participant were chosen as aspects to interpret the student-tool interactions through a *knowledge-in-pieces* theoretical stance [17], [18].

When reporting *excerpts* and *quotes* in this paper, we include actions that students did within brackets *[ ]*, such as laughs or clicks their cursor on a button on their screen. We use parentheses *( )* to include further specific explanations for certain words that students referred to. We use *underlined* and ***bold*** font for parts we are emphasizing related to conceptual reasoning (whether correct or not) and related to other interesting (or struggling) moments, respectively.

Findings

From the think aloud sessions and through the knowledge-in-pieces lens, we observed evidence of cognitive processes in developing conceptual understanding as well as some additional conceptual changes when the four participants moved along unique paths and receiving feedback support from the CALM. Here, we select three scenarios to compare and discuss. First, we focus on the CMR formative assessment where students worked on justifying their reasoning for their answers to the concept questions and the follow-up options provided. We provide a comparison between Sam and Alex on one of the questions as an example. Second, we compare how students worked their way through the same concept questions addressing the same knowledge constructs with different approaches in the summative assessment. Third, we explore how assigned supplemental resources promoted further conceptual learning and change.

CMR Formative Assessment

The CMR question pairs first ask students to select a multiple-choice answer and then select the follow-up explanations that support that answer (from the "Why?" question) as shown in Figure 1. We saw students interact with the follow-up explanations in three ways. First, we saw students show indications that the given list of explanations matched their initial thinking as follows:

> *"[chooses and answer] [laughs] That is why. [laughs]"*
> *"There we go. [chooses an answer] That follows my reasoning."*
> *"Yeah. I guess that was my original reasoning to go with that answer."*

> *"That's kinda what I used to explain myself anyways"*
> *"Um, this- is [chooses an answer and unchecks the option right away] maybe what I was thinkin. [reread the choice out loud] So, that is, that is [chooses the same answer] actually exactly what I'm thinking I'm pretty sure."*

Second, there was a case where one of the students could not match the provided CMR explanations with how they were thinking (*"So none of these follow, uh, my reasoning"*) and typed their own response in the "Other" option. Third, there were instances where the follow-up question with multiple options promoted students' thinking. The following section compares the interactions of Sam and Alex to the same formative question where they both answered the initial question correctly but for different reasons. From these examples, the follow-up part of the CMR concept question clearly provides an opportunity for students' further thinking as it activates resources they had not previously considered.

When Sam was working on the question, they answered the initial part correctly by using their notes – the summary table from the lecture that they copied down – as a resource to compare the ratios of radii and lattice parameters across the three cubic crystal structures. The follow-up CMR promoted further thinking as shown from Sam's verbal response:

> *Sam: "[after finished reading out loud the question] So, we got my table's already coming in handy. We got simple cubic, BCC, and FCC, and, I have written down that lattice parameters are.. two R for single cubic, four R over root two for FCC, and four R over root three BCC, um, I believe four R over root two is the greatest of those?.. Let me ...* ***I'm gonna- I'm gonna guess that.*** *So, FCC [choses the third option -- FCC] is the answer. [clicks the Submit button] Is my answer.*
> *[the options for the initial part turns grey and the follow-up CMR shows]*
> ***'Why?'.. Um.., that's a good question. Um, [scrolls the screen up and down]*** *so, um, lattice parameter is this distance. [scrolls the screen back up to see the figure]* ***Actually, it should probably be the same for all of them now that I'm thinking about it. Um, but.. um,*** *[skips reading out loud for the first four choices] '(Because) FCC has the highest atomic packing factor.' That [choses the fifth option] is actually true. I know that that is a true thing. So, that is what I'm gonna say. [clicks the Submit button]*
> *[the screen shows the next question]* ***I wish that they told me if that was wrong. I'm hoping they will later. [laughs] I think it might have been wrong.****"*

When Sam justified their reason, they picked an incorrect option (shown with a check mark in Figure 2) while providing an affirmative comment. Although the statement is true (as well as some other options), Sam did not provide any justification on how this fact might connect with this question – the APF actually would not directly affect the lattice parameter. Sam started on the right path (*"lattice parameter is this distance. [scrolls the screen back up to see the figure]"*) but when utilizing the provided resource (the figure in the question) Sam had the thought that another answer might be more correct, possibly because all structures in the figure were showing the same unit cell size. Additionally, after submitting their response and there was no immediate feedback, Sam made a comment showing uncertainty; their answer might have been wrong. What Sam did not know at that point is that the CALM does not provide the correct answer to these formative assessment questions; rather adaptive feedback is provided as supplemental instructions after they completed all three pairs of questions.

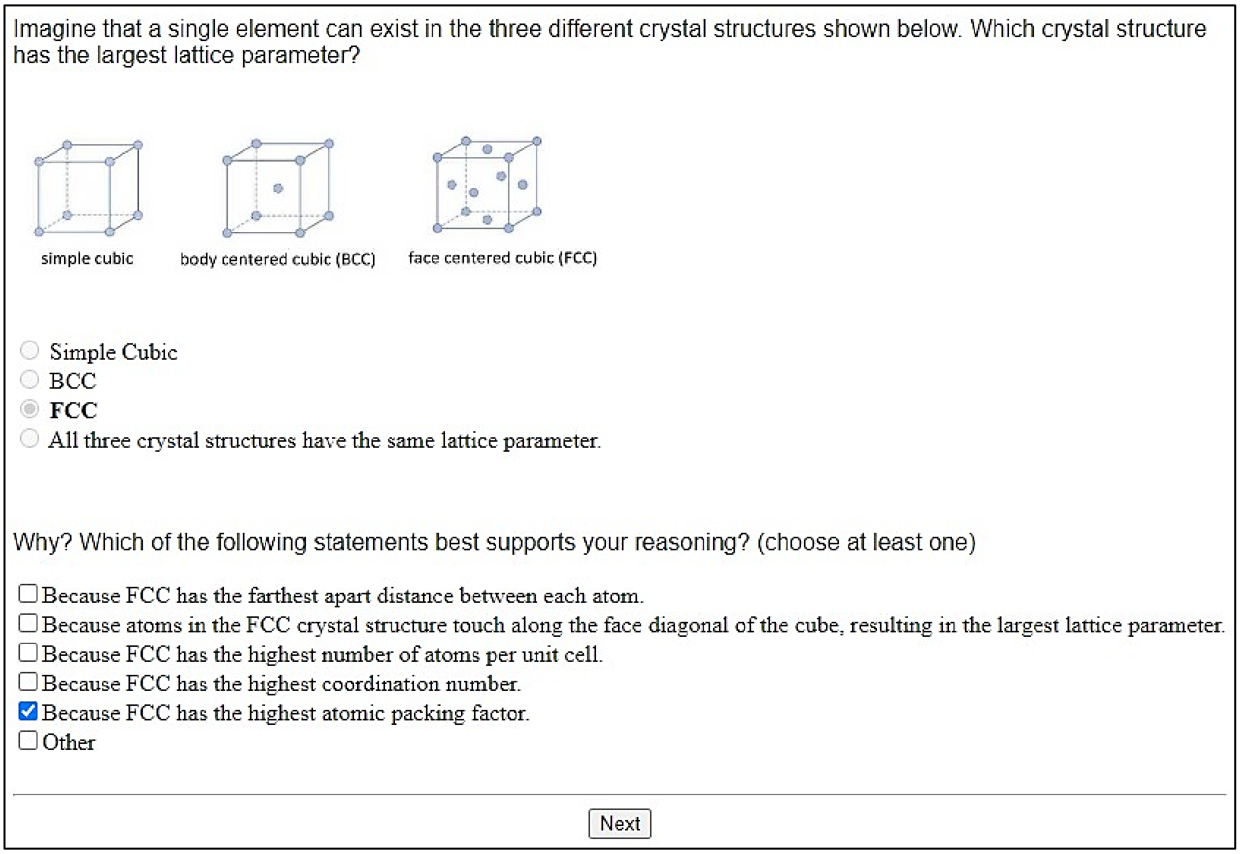


Figure 2. An example of a formative assessment question for the crystal structure knowledge construct in the CALM with the follow-up question and a list of reasons after submitted the answer to the initial concept question.

For this same question, Alex approached the initial question in a similar way as Sam did, using their notes and comparing the ratios. In addition, when justifying their comparison between BCC and FCC, Alex considered another factor that can also affect the size of the unit cell, which is the number of atoms. For the following CMR part of this question, Alex navigated back to the provided figure on the question after reading through the second option. At this point, Alex showed signs of further thinking based off the second option provided.

> *Alex: "[after read the question, page flipping noise – possibly looking down to their notes as the continue speaking voice has slightly lower volume] So let's see. Lattice.. parameter, ... uh, just thinking so it's 2R for simple, 4R (over square root of three) for.. body-centered and (4R over square root of two for) face-centered, uh, <u>but the cube (a unit cell for cubic structures) of.. two (atoms) is going to be smaller than the cube of four (atoms)</u>. So face-centered cubic, [chooses the third option] will have the largest lattice parameter. [clicks the Submit button]*
>
> *[the options for the initial part turns grey and the follow-up CMR shows] 'Why? Which of the following statements best supports your reasoning?' Uh, [reads the first and*

> *second options out loud,* <u>*scrolls the screen back up to see the figure] ... That does.. make sense, so, then we have*</u>*,* ***... [makes thinking noises by blowing into teeth quickly a few times then forms a round shape with their mouth to produce a sh--ch-chooo sound]*** *so it's along the edge.* <u>*Well, the body-centered is what, it's touch, it touches (atoms are touching) along the diagonal (of the cube's body).*</u>
>
> *So, [reads the last three options out loud,* ***page flipping noise, possibly looking down to the notes as the continue speaking voice has slightly lower volume] ... Well, mine was just based off of the, table from earlier but if I look, at the ... uh, calculation ... for, how to find the lattice parameter ... it is ... so let's see****, face-centered cubic.. had the A squared plus A squared. ... ... Okay. So based off the earlier reasoning,* ***if I'm remembering this correctly, and if my notes are good enough, um, ...*** <u>*it is, because, the structure.. touches along the face, of, the cube.*</u> *... [chooses the second option] That is.. the- answer I'm going to submit. [clicks the Submit button]"*

Although Alex had an unclear explanation for the FCC (direction where atoms are touching), they also imagined where atoms would touch for the BCC. This comparison is similar to that where Alex previously used for the number of atoms between these two structures.

Through a more conceptual thought, Alex was able to justify the correct reason compared to Sam, where they both picked the same initial answer. Alex utilized two relationships at the beginning and, further from that second comparison (BCC versus FCC), they use it again while justifying their reasoning. Sam, on the other hand, went through the provided list of reasons quickly (without reading aloud) and picked one of the options that, although a true statement, does not connect to the parameter in discussion for this question. From a knowledge-in-pieces stance, Alex was able to connect the given resources (the second option and the given figure) with their previous knowledge they had (the closer lattice parameter in comparison is BCC and FCC while SC is already ruled out). Moreover, the CALM provided a material tool to facilitate this connection.

<u>Adaptive Summative Assessment</u>

Within the adaptive summative assessment, the four participants were guided along different paths based on their performances as summarized in Figure 3. In this section, we focus on Max and Ray working through their three assigned questions for knowledge construct 2 (APF). Both Max and Ray addressed the same three concept-based questions, answering the first two correctly and submitting the same incorrect answer for the last one. The correct percentage of these three questions, based on collected data in our previous study, are 67%, 38%, and 21%, respectively [5]. In this study, the two students' approaches to these answers differed and Ray's reaction from receiving these three subsequent questions surprised us.

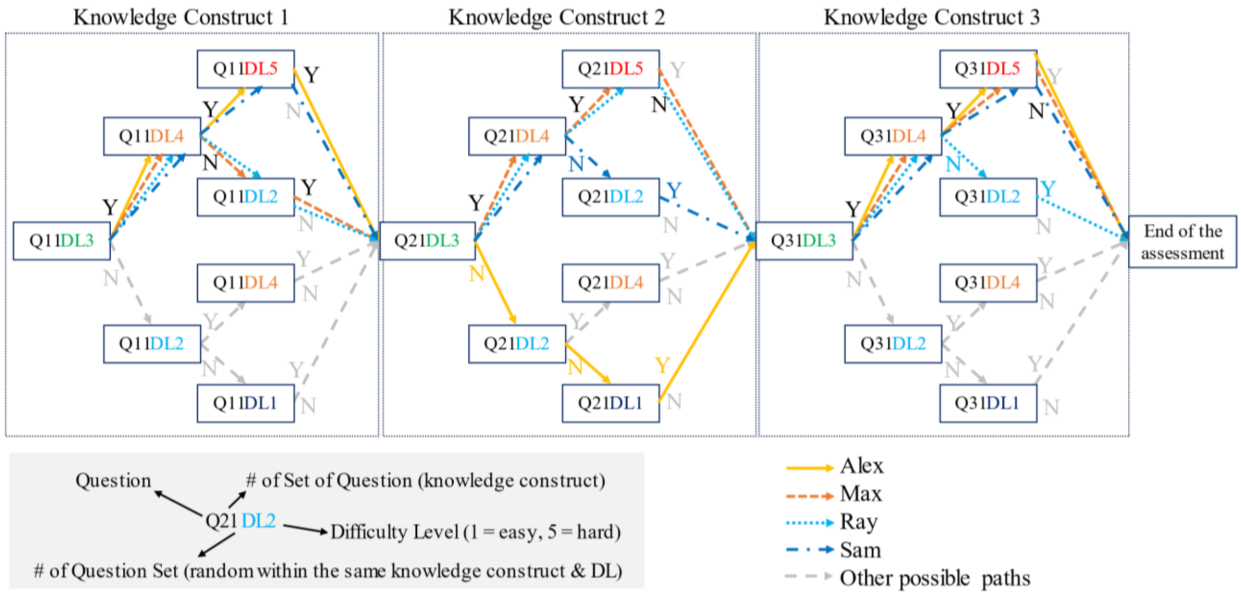
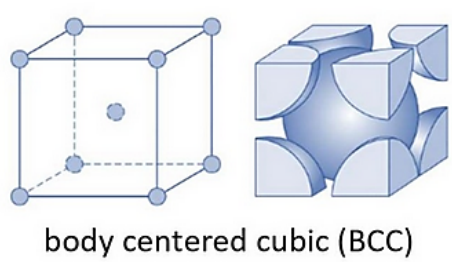


Figure 3. The summative assessment adaptive logic. Different arrows represent different paths for the four participants in the think aloud and the other possible paths students can take.

The first concept question for this construct (Q21DL3 in Figure 3) that all students encountered is shown in Figure 4.

Both Iron and chromium have a body centered cubic (BCC) structure at room temperature. Iron's atomic weight is higher than chromium, but its atomic radius is smaller than chromium. Which element has higher atomic packing factor (APF) for its BCC structure?



- ○ Iron has higher APF.
- ○ Chromium has higher APF.
- ○ Neither. The APF for iron and chromium are the same.
- ○ There is not enough information to make a comparison.

Figure 4. The first summative assessment question for the APF knowledge construct (DL 3).

On this question, Max read the question and immediately chose an incorrect answer that would be a correct answer if the question asked for density. While explaining their reasoning, Max paused themselves and was able to identify that this problem is about APF and not density.

> Max: *"[after finished reading out loud the question] It'd be iron [chooses the first option] 'cause higher weight, multi-* ***wait. ... Atomic packing factor. Volume of atoms... I feel like density, density is, okay that's wrong.***
>
> *So... packing factor would be the same (for both elements) [changes answer to third option] <u>because we're looking at, the ratio of R (radius) and a (lattice parameter) more or less. It's, it's how tight you can get in there and BCC has the same tightness</u> of the, uh ... Was it .74? So yeah. [clicks the Submit button]"*

Next, Max approached this question by utilizing a conceptualized relationship among related parameters. Max brought not just the given parameter in the question (atomic radius) but also connected with another related parameter (lattice parameter). Max also used the term *"tight"* that shows an understanding of the APF concept while further elaborating their thought, regardless of a small error of the APF number mentioned at the end.

Ray's thinking process on the same question differed.

> Ray: *"[after finished reading out loud the question] And [chooses the third option] they're gonna have the same. Um,* ***because atomic weight is on the top (of the density equation). Oh wait.***
>
> ***Atom packing factor [highlights "atomic packing factor (APF)" text on the question]*** *<u>for that isn't affected by density, which atomic weight</u> [highlights "atomic weight" text on the question] <u>and radius</u> [highlights "atomic radius" text on the question] <u>affect density. So yeah. I think they're (APF for both elements) gonna be the same.</u> [clicks the Submit button]"*

At the beginning, Ray briefly mentioned the density equation when referring to atomic weight, similarly to Max, and paused to rethink. Ray then approached this question using relationship transfer between knowledge: A (APF) isn't affected by B (density), but C (atomic weight) and D (atomic radius) affects B, thus A isn't affected by C and D. Although the final answer is correct, the thinking process here did not evidence a direct conceptual understanding of the APF and how it relates to other parameters as Max did. However, Ray was able to make sense of this question using different connections of knowledge by grounding themselves to another concept, which is density, and using logical inferences from there.

Interestingly, Ray developed the connection that APF is not affected by density although the more traditional learning resources (interactive lecture and supplemental videos) in the CALM did not directly address this. However, Ray developed a strong connection that atomic radius and atomic weight affect density, especially that the atomic weight doesn't change the crystal structure size, while they played with the interactive instructional tool (3D Crystal Builder).

> Ray: *"And it's fun that <u>the mass</u> [drags atomic weight slider to higher and lower values, back and forth] <u>doesn't change it (the main simulation structure size) except for the density (value as shown in the simulation).</u>"*

Comparing Max and Ray's resources for this question, both students first activated the density concept from the given parameters, likely because both of these parameters are part of the density equation. Ray then used density and connected how these given parameters relate to it as resources to make sense of the APF. On the other hand, Max labelled their initial explanation as *"wrong"* when realizing that the question is not asking for the density and shifted their focus to which parameters are related to APF. This situation represents how some concepts, for certain situations, are solvable through different pieces of knowledge based on what resources students were able to activate.

When Max and Ray worked on the formative assessment for the APF concept in the CALM they both performed well on the CMR *Why?* question (Max chose both two correct explanations while Ray chose one of the main correct reasons). Therefore, they were not assigned to any supplemental video on this topic. Both Max and Ray also successfully made all three cubic structures (SC, BCC, and FCC) in the simulation (3D Crystal Builder) and were able to explore most options available in the tool. Later at the resources review page (right before the summative assessment), Max reviewed most of the provided optional resources including ones they have not yet interacted with (were not assigned to by the CALM). However, Ray skipped reviewing all resources on the review page, which Ray then reflected about this on the next question presented here.

The second question (DL4) is shown in Figure 5. Instead of giving the crystal structure type to compare like the previous question, this question asks students to imagine a physical scenario and link it to the APF concept.

Imagine there are two large boxes that have the same dimension standing on top of a shaking platform. A student fills up the first box with wooden balls of equal size. The same student fills up the second box with hollow bronze balls of equal size. The bronze balls have a bigger radius but weigh less than the wooden balls. Which set of balls has higher atomic packing factor (APF)? The size of the boxes are much larger than the size of the balls.

- ○ Box filled with wooden balls has higher APF.
- ○ Box filled with bronze balls has higher APF.
- ○ Neither. The APF of both boxes are the same.
- ○ There is not enough information to make a comparison.

Figure 5. The second summative assessment question for the APF knowledge construct (DL 4).

While reading this question, Max spent more time than Ray with pauses and said both rejective and affirmative responses to their own questions.

> *Max: "[after finished reading out loud the question] The smaller balls will fit more balls into- the box, so that'll have a tighter packing factor.* ***So- wait, no! Wait. ... Shoot ... [inaudible whispering, possibly rereads part of the question] So as our frame of reference the box itself? ... No. It w-, it would be on the ball level. ... Yeah****, so it would be the same (between the two setups), because, on a ball-by-ball level, they're gonna look identical. ...* ***[exhales] Right? ... Yeah, so my confusion I guess is just trying to understand... if it is in re- uh, relation to the box or the balls.***
>
> ***I think it's the balls****, so it (APF) would be the same [chooses the third option] ... because... the atomic packing factor... in this case would be like, 'ball' packing factor, and on a ball-by-ball level they'd both be the same formation. ... Yeah. ... [affirmative with slight uncertainty – lower volume]"*

Max appears to be negotiating this question's different frame of reference. To do this, Max used a simple term that was given in the scenario (*"ball"*) while explaining their reasoning and eventually was able to connect this frame to the APF concept (*"in this case would be like, 'ball' packing factor"*). Although Max got confused with the frame of reference for this question and showed signs of confusion, they justified their final decision (when they were submitting the answer) from a feeling (*"That sounds more right."*). Max also used a similar affective justification earlier while working through a formative assessment question and some of the pop-up questions during the videos, which might be a way to cope with their concerns and continue with the lesson.

When Ray encountered this question, Ray read through the question out loud with one continuous speed and, unlike Max, immediately connected it to the previous question. Ray, however, elaborated more on how the APF is not affected by the changes in atomic radius.

> *Ray: "[after finished reading out loud the question]* ***Okay. So, I feel like*** *[chooses the third option]* ***that's kind of like the same problem as last time.***
> *So, they both have... different radii and atomic weight, but they...* ***Oh. Atomic packing factor.*** *And then they're filling up the same space. ... Hmm. Okay.* ***I'm trying to think back to that- that, um, ... like, crystal structure module thing (referring to the instructional 3D Crystal Builder tool) of how they did that. Um-, and I suppose- ... When we're...*** *Okay. So when we change the radii, it didn't change how it was packed in there. It just change the... Like, it didn't change the structure is what I mean. It changed the, size of the atoms. ...*
> ***So- yeah. I guess that's what I'm gonna go with that.*** *[inaudible possibly says "Neither of that."] They're (APF values of the two setups) gonna be the same (between the two setups) 'cause they didn't change the structure. Change the density. But... Okay. [clicks the Submit button]"*

In comparison to the first question, although Ray was still using density to help ground their thinking, Ray now explained with a more concrete concept for APF – identifying the relationship between atomic radius and how the crystal structure is packed, which is similar to how Max explained their thinking when they encountered the first question.

The last question for this knowledge construct is shown in Figure 6.

Element A and element B have equal radii. Element A has higher atomic weight than element B. Which element has higher atomic packing factor (APF)?

- ○ Element A has higher APF.
- ○ Element B has higher APF.
- ○ Neither. The APF of both elements are the same.
- ○ There is not enough information to make a comparison.

Figure 6. The third summative assessment question for the APF knowledge construct (DL 5).

Max read through this question with a smoother pace (no pauses nor repeats, compared to how they read their previous two questions for this construct) and seemed to be more confident on their answer. Max paused a little after finishing reading the question, answered the question by saying out loud, then elaborated correctly that the atomic weight does not affect the APF.

> *Max: "[after finished reading out loud the question] Same ... because, weight does not play into the atomic packing factor equation. [chooses the third option then clicks the Submit button]"*

However, Max was unable to activate a different resource – the connection between APF and crystal structure.

Instead of showing signs of confidence like Max on this problem, Ray seemed concerned and unsure of their previous decisions as soon as they first glanced at this problem. Ray reflected again that all these three questions (of the same knowledge construct that they are encountering in series) are the same type of question.

> *Ray: "**Oh, boy. I feel like I keep getting it wrong 'cause they (the module) keep asking the same one. [laughs – nervous, said with a laughs-like voice while begin reading out loud the question text]***
>
> *[finish reading out loud the question text] **Well, now I'm wishing I watched that video (one of the videos on the resources review page) because I didn't think it had anything to do with atomic packing factor but, um, I ...***
>
> *Let's see. If they have equal radii... and element A has a higher- weight, ... the atomic packing factor **[laughs]***
>
> ***I don't know. I- I- I don't know why but my...** [chooses the third option] **I just keep thinking it's the same. I don't have like a reason why one of them would be higher. [points cursor on the first option]** So, they're the same radii [highlights "radii ..." text on the question], different weight. And now there'll be a different density. [clicks the Submit button] **But I'm not sure about the APF.**"*

Rather than addressing the content, Ray appears to be activating a resource about how schooling is completed – I receive repeat questions when I am incorrect.

Although Ray and Max encountered the same questions in the same order, their approaches to these questions were different. Max didn't seem to be bothered or notice that these questions were similar and, specifically for the last question, worked through the problem very quickly. On the other hand, Ray was more concerned about getting the same type of question and showed signs of unsettling while spending more time working on reasoning through later questions. Ray also reflected on their decision when they skipped watching videos while working through the third problem. Although Ray was not informed directly by the researcher that these questions were adaptively assigned to them based on their prior performance (correct and move on to a harder question), it appears that Ray believed that they have received similar questions due to their incorrect answers (stays on the same type of question until you got it right).

Additionally, both Ray and Max went through the problem using only parameters that were provided in the question (atomic weights for Max and both atomic weights and radii for Ray). From the previous two questions, the crystal structures were provided, and only Ray mentioned *"structure"* while working on the second question. When the structure type was not given in the last problem, Ray and Max did not connect this into their considerations nor able to activate resources related to this relationship (crystal structure type affects APF). It would be interesting to further explore if these three questions were not given in the back-to-back fashion (e.g. swap the order of questions across knowledge constructs) or if this relationship was emphasized more in certain activities during the module, would they be able to activate this relationship for this problem and able to justify the correct answer or not. Exploring more on these similar cases would be beneficial to pinpoint why these two students (as well as some or all in 79% out of 318 students in previous study [5]) answered this question incorrectly and how else can they better activate this relationship to solve this challenging concept question.

While we described the comparison of Max and Ray in detail, we noted differences in approaches among other students in how they approached questions as well. For example, in the set addressing crystal structure, Alex solved the first question (Q11DL3 in Figure 3) using the same way they did with the formative question previously explained (identify the structure types and then the number of atoms per cell in each type). On the other hand, Sam activated different resources compared to how they have solved the formative question (using resources that were similar to Alex instead). Sam also mentioned that they were not familiar with the given figure in the question (the question provided multiple connected unit cells to compare that was not previously shown during the module). However, on the second question (Q11DL4), which provided a figure of single unit cells similarly to the formative assessment questions, Sam switched back to use resources they used earlier while solving the formative question (compared the ratios of radii and lattice parameters from their notes). This shows how different representations on questions can support students' activation and connection of different resources.

<u>Supplemental Instruction Assigned from the Adaptive Logic</u>

The CALM was pre-designed with an adaptive logic that assign students to supplemental resources as feedback based on their performance from the formative assessment. Both the interactive lecture and these supplemental videos contain low-stake pop-up questions. These questions were designed to promote engagement and further learning, which we have seen evidence of from the four think aloud sessions. We occasionally found cases where additional resources promoted conceptual change, sometimes in ways we did not anticipate. We give an example case from Max when they change their definition of lattice point after they worked through an assigned supplemental video and reviewed the same video on the resources review page.

At the beginning of the CALM during the lecture interactive video, Max learned several new technical terms related to crystal structures, e.g., unit cell, lattice parameter, SC, BCC, FCC, etc. Max was using their notes to write these definitions down and referred to them while working through other parts of the CALM. Max answered the first (crystal structure) CMR formative question incorrectly (both their initial answer and a reason they chose). The adaptive logic of the CALM then assigned Max one supplemental video for this knowledge construct. During the assigned supplemental instructions where the video reviewed the definition of the lattice parameter (the slide is shown in Figure 7), Max manually paused the video and rephrased their understanding in their own words. At this point, Max showed signs of correct understanding of the terminology.

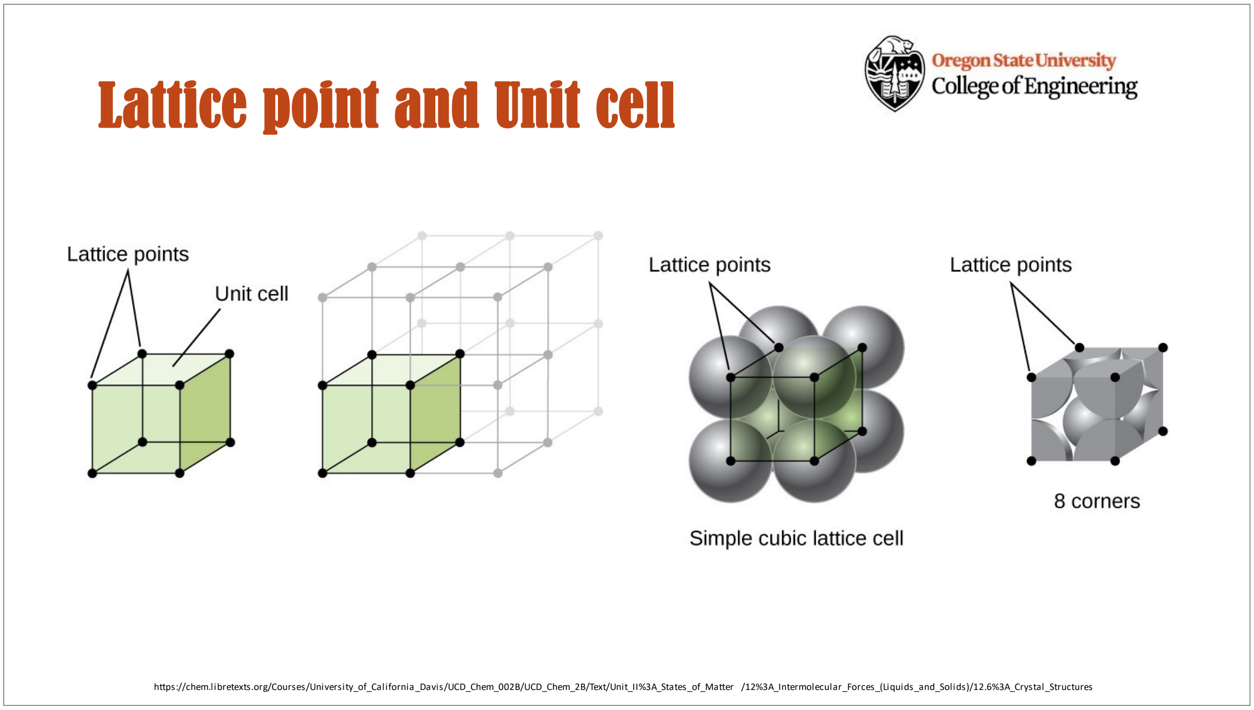


Figure 7. A supplemental video slide defining lattice points within a unit cell. The original pictures used in this slide are from [46].

> *CALM video: "Next, let's discuss what we mean by the terminology lattice point and unit cell. A lattice is the regular geometrical arrangement of points in crystal space. Atoms in crystal and solids are positioned in orderly and repeated patterns that are in contrast to the random and disordered atomic distribution found in non-crystalline or amorphous materials. The unit cell is defined as the basic structural unit of a crystal structure, it is generally defined in terms of atoms or ion positions within a parallelepiped volume. [Max: faint voice, possibly laughing] The unit cell is basically the smallest repeatable unit of a larger lattice."*

> *Max: "[pauses the video] Okay. As I understand it, lattice points... [points cursor on one of the lattice points on the full body structure picture, then moves the cursor to other lattice points in the same picture, pauses on each point a little] is, like... centers... of the atoms, while the unit cell [points cursor on the unit cell picture (the one without full-body atoms)] is... where you'd want the pattern to repeat. [points cursor in a circular continuous motion for the whole unit cell on the full-body structure picture]*
>
> *So... lattice point won't re-, necessarily be related to the center of the atoms, but... in this instance, it is, 'cause that's where the pattern repeats. ... So... I suppose technically you could have... the box moved anywhere you really want to, but this makes no sense for, like... actually making it easier to understand. [plays the video]"*

> *CALM video: "And so, the unit cell defines that lattice uniquely, and tells us all the information we need to know about it, because everything else is just a periodic image."*
>
> *Max: "Yeah. [affirmative]"*

Up until this point, Max was able to piece all the resources provided and interpret the lattice parameter correctly. Additionally, after Max summarized the definition of lattice parameter and unit cell in their own words, they also infer further how to apply the definition of the unit cell (*"moved anywhere you really want to,"*) using their own term (*"the box"*). Right after this part of the video, Max received a pop-up question (Figure 8). When Max got the question incorrect, they paused the video to review and try to make sense of the correct answers that the CALM provided.

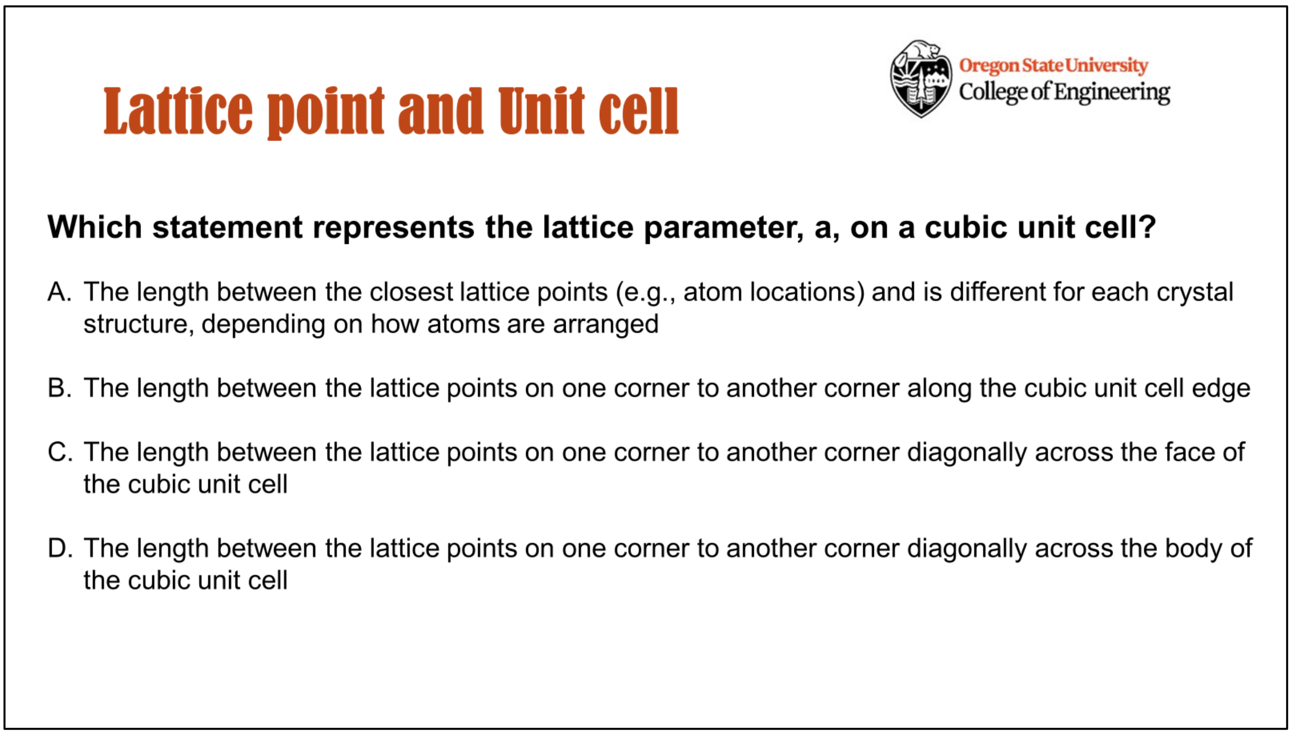


Figure 8. A pop-up low stakes question shown in one of the supplemental videos related to the crystal structure concept.

> *Max: "[pauses the video when the correct answer is shown]* ***Cool! [laughs] okay. All right, [reads and rereads the correct option]*** *The length between the lattice points on one corner [inaudible (to another corner)] along ... The length between the lattice points on one corner to another corner along the cubic unit cell edge. ...* ***[points cursor along the option A that they picked, possibly rereads without saying out loud]***
>
> ***Okay. So, I'm realizing... wait... so, I'm now confused, because... I understand that I am wrong... but, as I under-... but as I understand a)... that feels like it should be right? So, I'm just trying to... I'm trying to now understand why I'm wrong."***

From this example scenario, the supplemental video helped Max understand the "lattice point" terminology before the pop-up question. In addition, the supplementary lesson with low-stakes pop-up questions was able to promote further thinking on the concept as well as conceptual change. Max also showed signs of metacognition. However, after receiving further explanation from the CALM (Figure 9), Max's understanding of the definition appears to have changed and they wrote down one partially incorrect concept in their note (*"lattice points = corners"*). Max then used their note that contained this partially incorrect concept for later activities of the CALM. Although this does make sense when looking at the provided figures and brief explanation from the CALM, the intended correct connection would be "a lattice point represents an atom, usually located at the center of an atom, which are at corners of the unit cell for the SC structure." This connection was not established for Max.

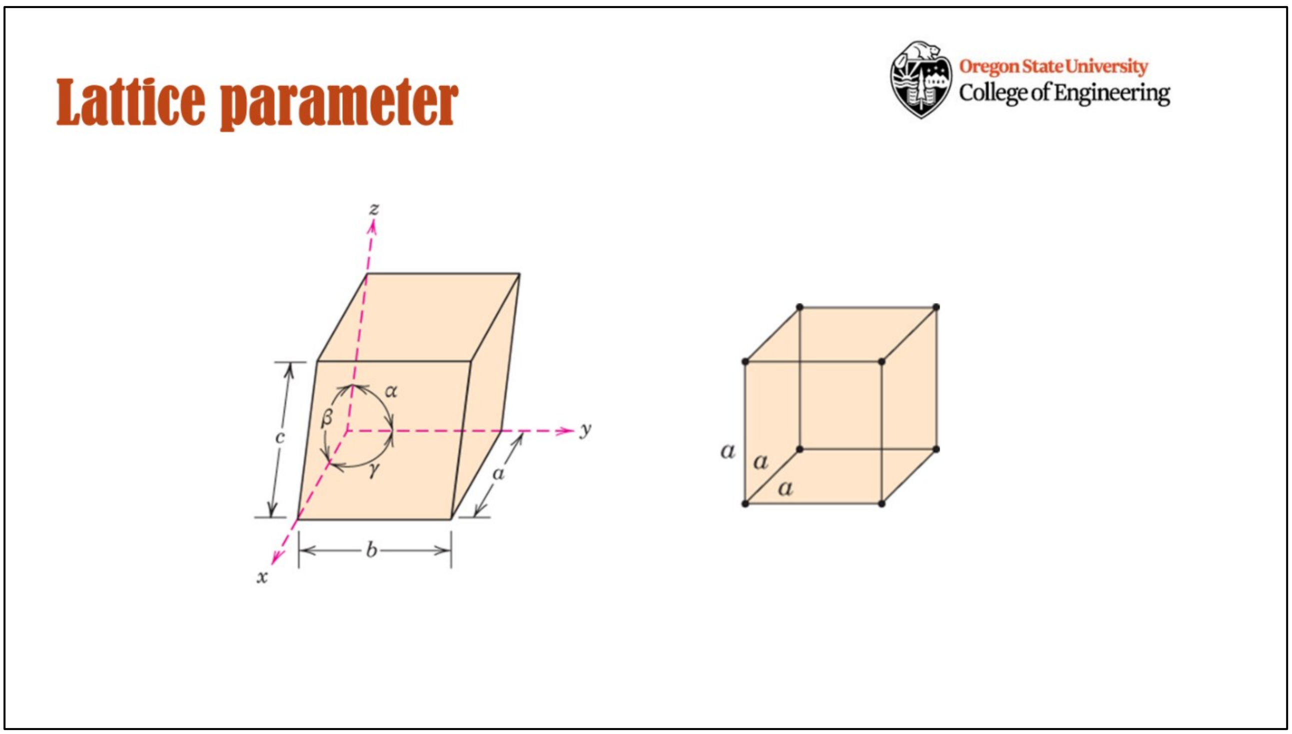


Figure 9. A supplemental video slide showing a concept of lattice parameter. The original pictures used in this slide are from [47], which is the required textbook in the course.

Discussion

This paper is part of our broader project addressing the development of conceptual understanding in adaptive personalized learning systems. In the study reported here, we observed in detail how four students interacted with the tool to develop their understanding while working through different guided paths and interacting with various conceptual promoted activities within the CALM. In addition to their voices, we recorded their actions on their screen and collected their written notes to support our analysis.

From these think-aloud sessions, there was evidence found among all four students of developing conceptual understanding while navigating and interacting with the CALM components, one of which is the CMR format of the formative assessment questions. Although CMR and multiple-choice assessment is easier to program for automatic grading and assigned pre-designed logic in adaptive learning systems, this format has its drawbacks. Some of the thinking processes to justify their answers were not as rigorous or conceptualized as deeply as we had hoped. We have seen some students show signs of trying to match their initial reasoning with the provided options or less conceptual explanations (reported as an example in this paper was Sam's case). However, we also noticed where students showed signs of further thinking on multiple provided options. In these cases, they were able to use those options as additional resources to piece together and able to justify the correct reasons (Alex's case). The material tool – the CMR format of this assessment – assisted further thinking by activating resources [20] that students might have not thought of or connected with yet.

Our concept-based summative assessment uses a multiple-choice format. Here, students approached the same questions and submitted the same answers but built their explanations from different directions. Students activated and utilized different resources they had available (e.g., using their notes, using understanding already established, and using some or all the provided parameters and figures from the questions) to respond to the questions. Max's and Ray's operationalization of the density resource was completely different even though both led to the same answer. Finally, in Ray's case, we noticed a student activating a resource tied to expectations about doing schooling rather than conceptual resources to build understanding. We should not lose sight that the CALM resides within the culture of the university and that students can interpret the tool's adaptive responses from that perspective.

We noticed and reported here more complex instance of conceptual change while Max worked through one of the pop-up questions during an assigned supplemental video. Although the conceptual change shifted from correct to incorrect, this finding supports previous research proposed by Brown [21] and Gouvea [22] that the conceptual development is a dynamic process. The idea of the assigned supplemental instructions based on pre-design logic was able to provide more resources for Max to construct understanding. The next step for us is to refine the resources to avoid confusion or misconnections of knowledge. For instance, the supplemental video slide (Figure 7 and/or Figure 9) can include another example of lattice points for other crystal structure types (BCC and/or FCC), not just SC. The choices on the pop-up question that have long text can also be shortened or replaced as figures. We also noticed other similar instances where students showed shifts in understanding (including from incorrect to correct) based on the resources we have provided in the module.

Through think aloud of four students we see multiple instances where students mentioned "*I know that ...*" This represents how students gain cognitive knowledge of what they already have, thus the resource-based framework and activation of those pieces would support their further connection of concepts [20]. Evidence of conceptual understanding developed from a non-lecture format was also found such as when Ray played with the 3D Crystal Maker interactive simulation. Additionally, some students showed strong signs of interest and engagement with these hands-on activities. However, we also observed students' frustrations and one incident of disengagement with the simulation tool. As summarized by Lodge et al. (see their Figure 1, [42]), confusions in digital learning environments that are resolved can enhance further conceptual learning and change in students (as shown in this paper with ***bold*** font) while those that remain unresolved for too long can result in deleterious effects on their conceptual learning (e.g., cause unproductive epistemic emotions and obstruct the activation of resources).

Future Research and Development

Findings from this work help our team understand how each component in the CALM supports student conceptual learning and what areas we can improve. Ultimately, the CALM will be available for educators to implement in their classes through the Concept Warehouse platform [48], [49]. Examples of future upgrade for the adaptive summative assessment may include enlarging concept-question pools for each DL, exploring different logics to avoid uncertainty (reported as an example in this paper was Ray case), and experimenting with different number of questions per knowledge construct assigned to each student. Another suggestion is to streamline supplemental instructions to avoid possible confusion (Max case) and to provide more specific resources for students to activate and connect based on their CMR formative assessment responses. Exploration and utilization of artificial intelligence to support the CALM adaptive logic is also a possible direction for the project.

Think aloud protocol [45] suggests researchers should encourage participants to include their motives or reasons for their actions when saying what they are thinking. However, this study did not incorporate this approach to minimize influence on their reasoning. As a methodological issue, we recommend future research to compare if having students describe what the question is asking and what they are seeing or thinking about the images prior to the solution process would improve their performance (on top of gaining more insight of student thinking process).

Conclusion

As technological computerized interventions are increasingly utilized and integrated into education, adaptive personalized tools are becoming more prevalent. However, many focus on promoting and assessing declarative and procedural proficiency instead of conceptual knowledge. This paper is part of a larger project to build a specific adaptive learning tool – the CALM. Our earlier papers report the development and quantitative assessment of the CALM and its component. This paper adds to that work by investigating how student-tool interactions can enhance or impede conceptual development in students. We collected and analyzed qualitative data from four students who were asked to think aloud while working through the CALM. We analyzed those data using a knowledge-in-pieces framework. We found strong evidence of students' developing conceptual understanding as well as conceptual change while working through different activities and receiving feedback from the module. We also observed an unexpected emotional response that contradicted with their performance that we attributed to the expectations of schooling.

Acknowledgements

The authors thank all students who volunteered to participate in this study. The authors would like to acknowledge Thomas W. Ekstedt and his team that supported the development of the CALM. The authors acknowledge the support from the Division of Undergraduate Education, National Science Foundation (Grant #1821439 and #2135190), the California Education Learning Lab at the State of California, and the 2021 – 22 Ecampus Research Fellows Program at Oregon State University.

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