Supplemental Material

CBE—Life Sciences Education

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Using Students' Concept-building Tendencies to Better Characterize Average-performing Student Learning and Problem-solving Approaches in General Chemistry

Supplemental Materials

These *Supplemental Materials* contain

I) The interview questions for the think-aloud interviews,
II) The IRB-approved script for the think-aloud interviews,
III) The Coding guide for the 4 problem-solving approaches with example quotes,
IV) The detailed analysis of the effect of concept-building approach on exam performance.

I) Interview questions for the think-aloud interviews

While students are solving problems, researcher will ask only the following probing questions:

1. What are you thinking?
2. Why did you write that?
3. Is that your answer?
4. How confident are you that your answer is complete and correct? On a scale of 1-5, with 1 being very confident and 5 being not very confident, what number would you give?

If student becomes stuck, then the following probing questions may be asked:

1. What is getting in the way of you solving this problem?
2. What other information would you need to complete this problem?
3. If you could access any resource to help you solve the problem, what would you choose?
4. What would you expect this resource to be able to do for you?
5. Is there anything else you would need to be successful?

II) IRB-approved script for the think-aloud interviews

(The interviewer greets the student…., then says) "Thank you for agreeing to be interviewed for our research on how students solve bonding questions. For your participation today, you will receive $20 in the form of a gift care at the end of the interview. First I ask that you read this permission slip. *(Give time for student to read the permission slip.)* Do you have any questions? If not, please sign the two copies of the permission slip. One copy is for you to keep. Is it OK with you that we start recording? If so, I would first like to check that the recorder is working properly. *(Test recorder and play back the sentence recorded. Then restart the recorder button.)* Today is November 6, 2017 and this is interview # ……"

"As a warm up exercise to help you feel comfortable speaking aloud about what you are thinking, please assemble a S'more from the ingredients here and describe out loud what you are doing and why you are doing it. I might encourage you to explain what you are doing by asking things like 'What are you doing now?', 'Why are you doing that?', etc."

"Now let's begin. I will present you with three questions about bonding. Each question is on a separate page. Please describe aloud what you are doing as you solve each problem. You may write on each paper but please be sure to describe what you are writing and what you are doing. Any questions? Good, let's begin….."

(If and when a student gets stuck while solving a problem, the interviewer asks…) "Are you stuck right now?", "Can you describe what is not working for you?", "If you could have

access to any resource right now to help you get through this problem, what would you choose?", "What would you expect that resource to do for you?"

(When the interviewee is finished with each problem the interviewer asks….) "How confident are you that your answer is correct? On a scale of 1-5, with 1 being very confident and 5 being very not confident, what number would you give?"

(At the end of the interview)

"Is there anything you would like to say about the questions or in general how you solved them? Is there anything else you would like to say? Thank you for your help. We really appreciate your time and effort. I am going to stop the recorder now."

(Student is thanked and given their stipend for participating in the interview.)

III) The coding guide for the problem-solving approaches with example quotes

Table S1. Approach nodes, descriptions, and example quotes

Type of Approach	**Approach Description**	**Example Quotes**
Memory of an answer or related problem	The student does not follow any set of steps, or cannot explain what they doing; they just start drawing a "completed" Lewis structure.	S: Okay, I'm going to double bond the C to the O and then double bond it again. I'm just not sure if this is… and then 1, 2, 3, 4… I: So what molecule were you given? S: Uh, the CO_2. I: And what molecule have you drawn? S: Uh, an O double bonded to two different Cs. I: Okay.
Reasoning; not tied to a specific algorithm	The student tries to use the underlying principles for drawing the most preferred Lewis structure and explain the concepts behind the steps they take, but are not following any specific steps in an algorithm.	S: So, that'd be 64 plus all the Hydrogens going against the octet rule, we only need 2. (Counting). So, that would be 4 times 2, 8. So, then that'd be 72 total that it needs. It has… So, there's (Counting) 5 carbons. And only 1 oxygen with 6. Nitrogens with 5. And then 5… no 4 hydrogens with only one … so that would be 40. So, that's the 40 right there. So, that'd be 32 electrons that it shares, so I have my 2. So, that would be 16 bonds I: So, you just determined that you need to have 16 bonds in your structure? S: Yes I: Ok… So what did you just do there? S: So, there's 12 bonds already in the structure. So, it just needs… it just needs 4 more. I: So, what did you just do there? S: Put a double bond between the upper left carbon and oxygen. I: And why did you choose to do that? S: Because the oxygen would want a double bond more so… The oxygen and the carbon would want a double bond more so than the carbon and carbon. And you can't put a double bond on anywhere of the hydrogens, because they can only have 2. You put another double between the other oxygen and the carbon. And then between the carbon and carbon on the bottom so. So, this carbon… the carbon on the left of the pentagon has 4.

		Carbon on the right has 4. All the carbons in the pentagon have 4 now. I: So, you put all double bonds. Three double bonds inside the pentagon, so that every carbon would end up making 4 bonds. S: So, there's one more. So, the only other place that you could put would be between the 2 nitrogens. I: Ok. S: Because you can't put it anywhere else, because then it would give hydrogens more than 2. And then (counting), so then the nitrogen on the far left would have 2 lone pairs to fill the octet rule. And then the 2^{nd} nitrogen will only have one, because it already has 3 bonds. And then we could shift the double bonds to form a resonance structure.
Algorithm without understanding	The student tries to use the general algorithm for drawing the most preferred Lewis structure, but either does not explain the concepts behind the steps they take or their explanations are completely incorrect.	I: Okay. Good. So you can go ahead with this one now… Can you describe what you're doing? S: Um, I'm… putting a nitrogen down, right now I'm connecting two oxygens to it, and then I'm going to connect a third one, and all the oxygens are gonna have… two of the oxygens are going to have a, um, double bond to it and one of the oxygens will have a single bond to it. So it gives nitrogen 5 valence electrons. And the oxygen connected to the nitrogen and chlorine will have a single bond to the nitrogen and a triple bond to the chlorine. And that oxygen will also get another lone pair, and the chlorine will get 2 lone pairs. I: And why did you choose to draw it that way? S: Um, every… uh, atom has the right number of valence electrons. So it doesn't have a non-zero formal charge. I: So, in this structure – you've got two double bonds between nitrogen and oxygen, you've got a single bond between nitrogen and oxygen that is then triple bonded to chlorine – S: Yes. I: Okay. Um, so you're saying they all have the right number of electrons and that they – none of those have formal charges. Is that what you're saying? S: Yes. I: So how is the formal charge calculated for any of those? S: Uh, you count up the lone pair which is 2 for lone pair and then 1 for each bond there is –

		I: Mhm. S: And then you subtract that from their total number of valence electrons that they should have. I: Okay. Okay. S: And then the answer is the, uh, formal charge. I: So, run through chlorine with me so I make sure I understand what you're thinking there. S: Chlorine has 2 lone pairs, it's, um, it would be 4 total electrons and since it has a triple bond, 3 bonds is 3 electrons so, 4 plus 3 is 7 and then chlorine has 7 valence electrons so 7 minus 7 is 0. I: Okay, and then the oxygen that's there in the middle? S: That's one lone pair so that's 2 electrons. It has a triple bond which is 3 electrons and also has a single bond which is 1 electron. So 2 plus 3 plus 1 is 6 and it – oxygen should have 6 valence electrons, so 6 minus 6 is zero. I: Okay. All right. S: I'm going to go through the rest.
Algorithm with understanding	The student tries to use the general algorithm for drawing the most preferred Lewis structure and tries to explain the concepts behind the steps they are taking.	S: The molecule is COONO2; 3 oxygen and nitrogen. All right, so for this structure that they gave me, they just connected all of them with a single bond. Chlorine needs to have 8, so only way to get that is to give three sets of lone pairs so 6. Which makes it eight. And then, this O right here has two single bonds connected to it. Which is one, two, three, four. You need four more, so two sets of lone pairs which follows the rule. And both of the oxygen right here only have on one single bond connected to it. So, it needs a second one to connect from the nitrogen which... Hold on that's wrong. I: What was wrong that you didn't like. S: Nitrogen had more than eight total. I: So you put them double bonds between oxygen and nitrogen and you ended up with… S: With 10 which does not work. I: Why doesn't that work? S: Because you can't go over 8. Ok. So, I'm going to give one double bond to one of the O's and leave the other one single. So, then nitrogen will be (counting). Nitrogen will have its octet

		rule. And then this oxygen will be double bonded. I'll give that oxygen two sets of lone pairs to follow the rule as well. And then the other O, I'll give three sets, so it can follow the octet rule as well. But then this one will be negative charge because it has seven electrons instead of six and that will work.

IV) The detailed analysis and results for the association between a student's concept-building approach on course exam performance for the POGIL course in Study 1.

Figure S1 shows the mean performances for Exams 1-4 for abstraction and exemplar learners. Statistical significance was tested with a mixed ANOVA on students' exam 1-4 scores, with concept-building approach as a between-subjects variable and exam number as a within-subjects variable.[1] Mauchly's test indicated a significant violation of sphericity ($W = .65$, $p < .001$), so within-subjects effects (exam number and concept-building*exam number) are reported with Greenhouse-Geyser corrected degrees of freedom and *p*-values ($\varepsilon = .82$). The overall advantage for abstraction learners was not significant (F (1, 79) = 2.78, MSE = 612.39, p = .10, $\eta_p^2 = .034$). There was no interaction with exam number (F (2.45, 195.68) = 1.30, p = .277), but performance levels differed across the exam number, F (2.45, 195.68) = 60.26, $p < .001$, $\eta_p^2 = .430$. We also conducted an ANOVA on the cumulative final exam scores. Abstraction learners (M = 74.37, *SE* = 2.17) scored nominally but not significantly better than exemplar learners (M = 72.12, *SE = 3.19*) (F = .353, p = .554).

[1] In our previous research comparing exam performance of abstraction and exemplar learners (e.g., Frey et al., 2017), we included ACT/SAT Math as a covariate to control for differences in math between these two groups of learners. In the current study, we examined self-reported ACT Math or, for those only reporting SAT Math, the corresponding ACT Math score based on concordance tables (Dorans, 1999), and found that math scores did not differ between abstraction (M = 27.55, SE = .44) and exemplar (M = 27.04, SE = .36) learners in this sample (F < 1). Thus, the analyses we report do not include math as a covariate. Nonetheless, we did conduct analyses with math as a covariate (reducing our sample to the 47 abstraction learners and 23 exemplar learners who reported a math score), and the results did not change.

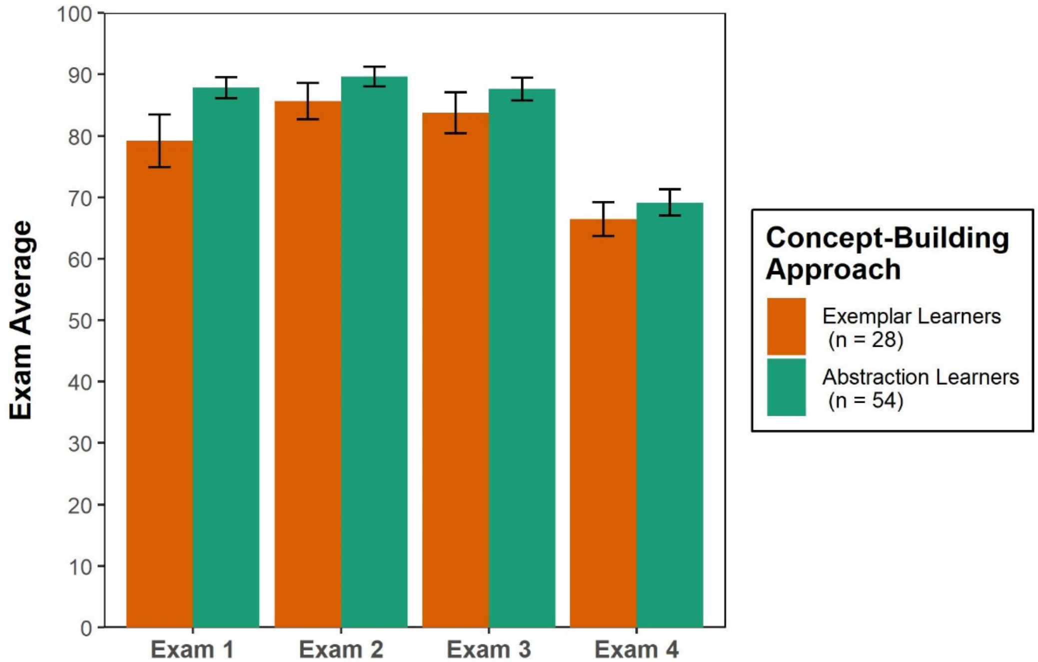

Figure S1. The mean performances for each exam for abstraction and exemplar learners. Error bars represent Standard Error of the Mean.