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You Are What You Assess: The Case for Emphasizing Chemistry on Chemistry Assessments

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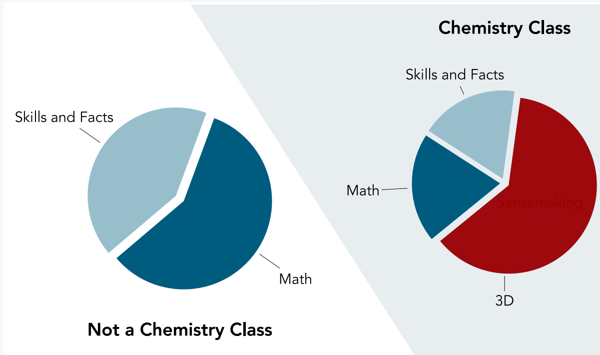

ABSTRACT: What we emphasize and reward on assessments signals to students what matters to us. Accordingly, a great deal of scholarship in chemistry education has focused on defining the sorts of performances worth assessing. Here, we unpack observations we made while analyzing what "success" meant across three large-enrollment general chemistry environments. We observed that students enrolled in two of the three environments could succeed without ever connecting atomic/molecular behavior to how and why phenomena happen. These environments, we argue, were not really "chemistry classes" but rather opportunities for students to gain proficiency with a jumble of skills and factual recall. However, one of the three environments dedicated 14−57% of points on exams to items with the potential to engage students in using core ideas (e.g., energy, bonding interactions) to predict, explain, or model observable events. This course, we argue, is more aligned with the intellectual work of the chemical sciences than the other two. If our courses assess solely (or largely) decontextualized skills and factual recall we risk (1) gating access to STEM careers on the basis of facility with skills most students will never use outside the classroom and (2) never allowing students to experience the tremendous predictive and explanatory power of atomic/molecular models. We implore the community to reflect on whether "what counts" in the courses we teach aligns with the performances we actually value.

KEYWORDS: *Testing/Assessment, Curriculum, First-Year Undergraduate/General*

■ INTRODUCTION

What we emphasize and reward on assessments operationalizes what we really care about. If most of the points in a course may be earned by performing disaggregated skills and factual recall, that course is about skills and facts, regardless of what the syllabus or instructor says.[1−5] Indeed, gaps between the rhetoric used to justify the importance of courses and the performances awarded on exams have led to the perspective that there exists a "hidden curriculum" defined, in part, by the strong implicit messages sent by assessments.[6]

The central role of assessments in defining what "success" means in a course has led many chemistry education scholars to consider the sorts of performances that *should* be assessed. Early work focused on "problem-solving" found that students were perfectly capable of "plugging and chugging" their way to a numerical answer without understanding the physical meaning of that answer.[7−10] This informed calls for the inclusion of more open-ended "conceptual" problems on exams and fewer close-ended "algorithmic" tasks.[7,11] Unfortunately, ambiguity surrounding what "conceptual" means,[12] how "open-ended conceptual tasks" should be integrated into assessments, and what positive outcomes come about by emphasizing such problems has limited the practical impact of the problem-solving literature.

More recent scholarship has sought to define what we want students to know and be able to do with sufficient precision to inform research and practice. For example, we[13−17] and others[18,19] have drawn on the construct of 3-dimensional (3D) learning[20,21] to describe science learning as blending large-grain core ideas (e.g., energy, bonding interactions) to engage in science practices (e.g., developing and using models, argumentation) as framed by crosscutting lenses (e.g., cause and effect, patterns). Aligning prompts with specific core ideas, science practices, and crosscutting concepts gives researchers and instructors a fair degree of control over how they want to realize and assess "doing science" in their context. How students might be productively engaged in 3D performances in

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the context of college-level general[22,23] and organic chemistry[24−26] remains an active area of research in the field.

Given the large quantity of assessment-related studies published by the chemistry education research community, one would hope that the sorts of performances that determine student success in chemistry courses would trend more toward "doing science" and less toward "performance of disaggregated skills". Indeed, Matz and colleagues found that an increased emphasis on 3D tasks on exams was a signature of chemistry and biology transformation efforts at Michigan State University.[27] Unfortunately, there is little information on the sorts of tasks that populate chemistry exams nationwide. Without such information, when studies report on "improved exam scores" or "improved course grades", the field has little context by which to judge what that means.

"Success" in a chemistry course could represent substantive engagement in predicting, explaining, or modeling phenomena in terms of atomic/molecular behavior, or it could simply represent facility with arithmetic and a good memory for polyatomic ion names. This commentary was borne from observations made while examining what "success" meant in three large-enrollment general chemistry learning environments. These three environments were each enacted at large research-intensive universities in the Midwest and represent how thousands of students per year experienced a general chemistry course. Here, we will unpack what we observed and argue that "success" in general chemistry should be defined by intellectual work authentic to the chemical sciences.

WHAT "SUCCESS" MEANT IN THREE GENERAL CHEMISTRY ENACTMENTS

As part of a more extensive study relating learner and learning environment characteristics to student explanations, we sought to characterize the intellectual work required for success in each of three general (i.e., introductory) chemistry contexts. The characteristics of each learning environment are not the focus of this commentary, so we will simply call these courses *Learning Environment A*, *Learning Environment B*, and *Learning Environment C*. Assessment emphasis was characterized using the "3-Dimensional Learning Assessment Protocol" (or 3D-LAP).[28] The 3D-LAP specifies criteria an assessment item must satisfy to have the potential for eliciting evidence that students can connect core ideas to phenomena via engagement in science practices. Note that the 3D-LAP can only detect the *potential* to elicit use of knowledge; other studies on *actual* student responses must be done to determine the extent to which this potential is realized.

Box 1. Codes Describing Assessment Tasks Given in General Chemistry Courses During the F19 and Sp19 Semesters

Math	Perform a calculation, use a mathematical representation, or derive a relationship to obtain an answer
3D	Predict, explain or model phenomena in terms of atomic/molecular behavior
Other	Neither; usually the execution of a skill (*e.g.*, nomenclature, electron configurations) or recollection of a fact

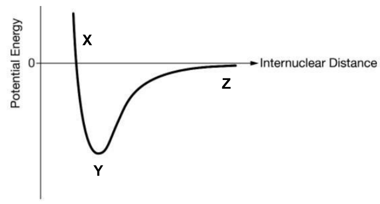
Summative assessments used as part of two-semester general chemistry enactments in each context were collected for analysis. First-semester exams analyzed were administered during the fall of 2019. Second-semester exams analyzed were administered during the spring of 2019. Due to the sudden pivot to remote instruction brought about by the COVID-19 pandemic, exams given during the spring of 2020 are likely not representative of the status quo for any learning environment. Institutional Review Board approval was obtained for this data collection effort.

Two authors (R.L.S. and L.J.S.) independently coded the items contained in each assessment using the 3D-LAP. Tasks

Math Modeling Task

Consider a system of two atoms with a stable interaction between them (the atoms are stuck in the bottom of the potential energy well). The potential energy curve for this system is shown below. What would happen to the system for the potential energy to change **from Y to Z**?

I. A third atom from the surroundings would collide with the system.
II. Energy would transfer from the surroundings to the system.
III. Energy would transfer from the system to the surroundings.
IV. The interaction between the atoms in the system would be formed.
V. The interaction between the atoms in the system would be overcome.



a. I, II, and IV
b. I, II, and V
c. I, III, and V
d. I, III, and IV
e. II only

Mathematical Thinking Task

For the process of mixing urea (NH_2CONH_2) and water, ΔH for the system is positive, ΔS for the system is positive, and ΔG is negative. Which of the following statements are correct for this process?

I. The urea-urea and water-water interactions are weaker than the urea-water interactions that are formed when the two are mixed.
II. The urea-urea and water-water interactions are stronger than the urea-water interactions that are formed when the two are mixed.
III. The solution (formed after mixing) has higher entropy than pure solute and pure solvent because more arrangements are possible.
IV. The solution formed (after mixing) has lower entropy than pure solute and pure solvent because less arrangements are possible.
V. Urea does not dissolve in water.
VI. Urea dissolves in water.

a. I, III, and V
b. II, IV, and VI
c. I, IV, and V
d. II, III, and VI
e. I, III, and VI

Figure 1. Two tasks from our data set that fulfill 3D-LAP criteria for potentially engaging students in using mathematical skills to connect big ideas to phenomena. The correct answer selections are indicated in blue.

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were assigned one of three mutually exclusive descriptors (described by Box 1). A total of 758 individual items were characterized. The two coders agreed on the coding of 93% of these responses, with a Cohen's Kappa of 0.87. Following independent coding, the authors met and reached a consensus on the assignment of all codes. Consensus codes for all characterized assessment items and a discussion of disagreements in coding are appended to this manuscript as Supporting Information.

3D tasks were those items that met 3D-LAP criteria for potentially engaging students in using core ideas to engage in science and engineering practices as framed by crosscutting lenses. Notably, a 3D task might require mathematical or representational skills; see Figure 1 for two examples of such tasks taken from our data set.[29]

These items require students to use a mathematical representation to connect core ideas to a phenomenon. The "Math Modeling Task" asks students to use a representation of potential energy vs internuclear distance to explain how and why an attractive interaction between two atoms is disrupted. The "Mathematical Thinking Task" requires students to recognize how free energy changes relate to enthalpy and entropy changes and to explicitly connect this relationship to a phenomenon (urea dissolving in water). We selected multiple-choice questions for inclusion in Figure 1 to highlight that 3D prompts can be (and are) given to large-enrollment classes. Both prompts shown in this figure were given to approximately 2500 students.

"Math" and "Other" tasks required the use of skills or factual recall but did not satisfy all 3D-LAP criteria; that is, these prompts could not provide evidence of students' use of core ideas to predict, explain, or model phenomena. Common "math" problems included dimensional analysis, calculation of the enthalpy change for a reaction, and prediction of how a change in one ideal gas law parameter would affect another parameter. Common "other" problems included drawing (or selecting) Lewis structures and determining electron configurations and nomenclature.

In Figure 2, we report the percentage of points on midterm examinations dedicated to tasks that have the potential to elicit evidence of 3D performances, decontextualized math skills, and other competencies across the three learning environments under study. Students enrolled in *Learning Environment A* (n = 2450 in F19 and 950 in Sp19) took common assessments throughout both semesters. Likewise, students whose general chemistry experience occurred in *Environment B* (n = 950 in F19 and 550 in Sp19) took the same midterm exams. Students enrolled in *Learning Environment C* (n = 1300 in F19 and 1050 in Sp19) were engaged in a common midterm assessment during F19. However, each section of *Environment C* had different examinations for the remainder of the tests examined. Each examination given is represented by a separate bar in Figure 2.

A Pearson's χ^2 test indicated a significant and substantive relationship between learning environment and assessment emphasis ($\chi^2(2)$ = 136.74, p < 0.001, Cramer's V = 0.45). Posthoc analysis of the results of this test showed a strong positive association between *Environment A* and exam emphasis on 3D items (Figure S4 in the Supporting Information). Indeed, it is apparent from Figure 2 that *Learning Environment A* placed substantial emphasis on students explaining how and why atomic/molecular phenomena occur on all first-semester assessments (32−42% of points) and most second-semester assessments (14−57% of points). Interestingly, 3D Learning was more consistently emphasized on first-semester exams than on second-semester exams in *Learning Environment A*. The third midterm administered during the second-semester included relatively few questions that required students to connect big ideas to phenomena explicitly, while the first midterm given during that same semester had the greatest emphasis on 3D performances of any exam in our data set. By contrast, *Learning Environments B* and *C* dedicated little to no points to items characterized as 3-dimensional in either semester of instruction. For midterm examinations 2 and 3 given during the first-semester course,

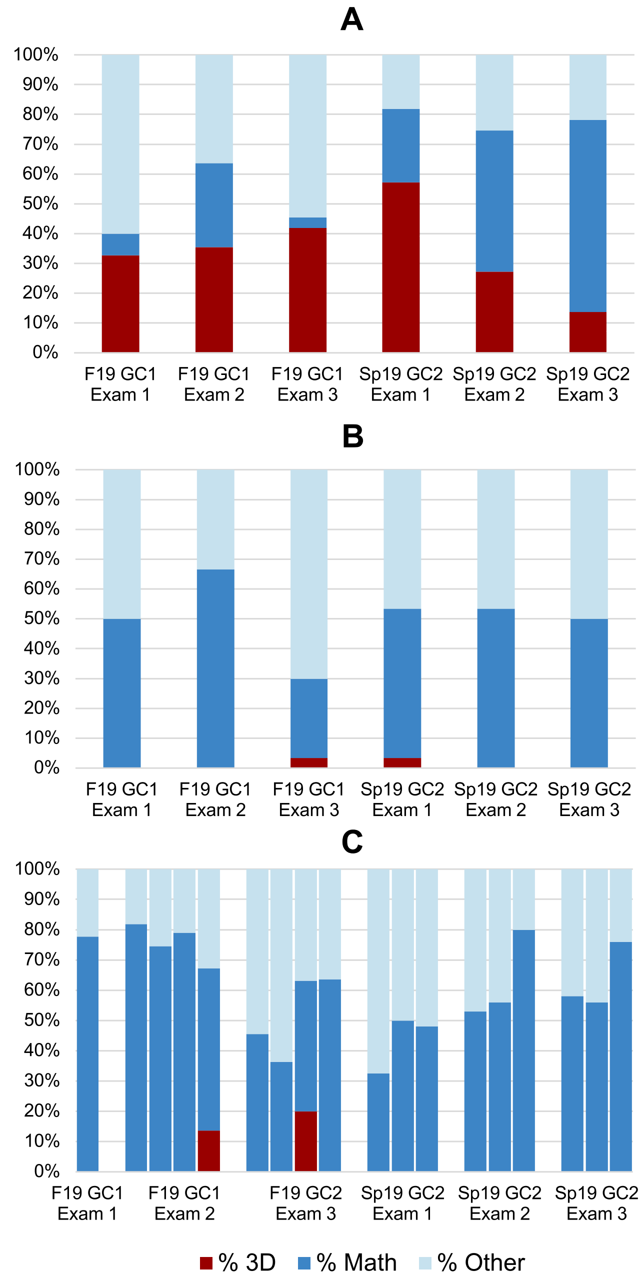

Figure 2. Percentage of points on midterm examinations given across three learning environments that had the potential to elicit evidence of 3D performances, decontextualized math skills, and other competencies. GC1 represents the first semester of the general chemistry sequence while GC2 represents the second-semester course. Each bar represents a distinct exam form.

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one section of *Environment C* included one item coded as 3-dimensional. This item accounted for 14% of the total points on midterm 2 and 20% on midterm 3. Virtually all points on exams given during the second-semester course in both types of environments failed to meet the 3D LAP criteria for having the potential to elicit evidence of 3D performances.

Given that 3D performances were not emphasized on midterms in *Learning Environments B* and *C*, one might reasonably wonder what was assessed on exams given in these courses. It seems, judging from the codes summarized in Figure 2, that the answer to this was often "decontextualized math". More than half of the points on midterms 1 and 2 given in *Learning Environments B* and *C* during the F19 semester were tagged with this code. Indeed, one of the midterm 2 forms administered to *Environment C*-enrolled students dedicated 79% of points to items that required students to perform mathematical skills. Assessment focus on "math" continued unabated in second-semester courses: Most *Environment B* and *C* midterm 2 and 3 forms analyzed dedicated 50% or more of their total points to math problems. Relatedly, midterm 3 given as part of the second-semester course in *Learning Environment A* can be accurately characterized as a math test, given that 65% of points on this test were allocated to assessing "math" and only 14% had the potential to elicit evidence of 3D performances.

INFERRING PRIORITIES FROM ASSESSMENT EMPHASIS

We have intentionally told the reader nothing about *Learning Environments A−C* apart from the performances emphasized on midterm exams given in each context. Our purpose was to strip away all other aspects of the curricular activity system at each study site and point out what can be inferred solely from what was assessed. *Learning Environments B* and *C*, from our perspective, are not chemistry classes. One could succeed perfectly well in either of these courses without ever connecting core chemistry ideas to causes for phenomena on high stakes assessments (which make up >45% of students' grades). By contrast, students with inequitable access to precollege mathematics preparations would (and have) performed inequitably on such assessment tasks.[30−32]

Learning Environment A placed substantial emphasis on 3D tasks (14−57%), though executing calculations and performing skills also received a large share of points. From assessment emphasis alone, it appears that *A* required engagement in authentic disciplinary work (i.e., 3D performances) far more frequently than *B* and *C*. Success in *A* required that students connect large-grain ideas to causes for chemical phenomena. However, executing 3D performances was not sufficient for success in *A*; skills and calculations were allotted a larger share of points than 3D tasks on all but one midterm examined.

We are uncertain whether *Environment A* struck an appropriate balance of 3D items, math items, and other items; no literature base provides insight on the extent to which assessments should emphasize 3D items relative to other types of tasks. Despite this, it seems reasonable that we should dedicate a substantial chunk of course points to assessing 3D learning if we care about this sort of intellectual work. Course transformations that report assessment emphasis typically dedicate 35−55% of points on high stakes assessments to 3D items, which seems like a "substantial chunk" of total points to us.[27,29]

At this point, the reader may be thinking that we are opposed to assessing skills. This is not the case. Skills, mathematical and otherwise, are certainly needed to engage in the disciplinary work of chemistry. For example, using Lewis structures as models to explain differences in boiling point requires that one draw a Lewis structure.[33,34] However, the skill of "Lewis structure drawing" is not inherently meaningful. If Lewis structures are never used as models, it is difficult to defend their incorporation into a curriculum. Instead, we argue for progressing away from assessing skills in isolation and toward applying these skills to predict and explain phenomena.

LET'S ASSESS AND SUPPORT PERFORMANCES THAT MATTER

Atomic/molecular models allow us to understand aspects of our existence that are otherwise unintelligible and design solutions to pressing problems. Indeed, the mRNA vaccines that serve to protect much of the world from COVID-19 were enabled by advances in lipid nanoparticle packaging:[35] chemistry in action! If we want our students engaged in "doing chemistry", then they should explain how and why things happen in terms of atomic/molecular behavior and design products and processes for defined functions. A great deal of work remains to be done regarding how all learners can be effectively supported in authentic performances by learning environment and assessment features. For example, it is unknown what task and learning environment features give the message to chemistry-enrolled students that the goal of a given activity is "figuring out" rather than "learning about". However, we can say with no reservations that environments which *never* (or almost never) ask students to connect big ideas to why phenomena happen (e.g., *Environments B* and *C*) have little chance of engaging said students in "doing chemistry". We find it tragic that thousands of students march through a "chemistry" course without ever having the chance to experience the tremendous predictive and explanatory power of atomic/molecular models. Relatedly, it is challenging to defend gating access to STEM professions based on how well someone can perform a set of disconnected skills they will never need to use again.

Practical Considerations for Integrating 3D tasks into Chemistry Courses

Three-dimensional assessment tasks should be a part of learning environments designed to coherently emphasize connecting big ideas to how and why phenomena happen. We strongly suspect that the legion of papers describing student difficulties with connecting atomic/molecular behavior to observable events (e.g., emergent properties of metals,[36] gas behavior,[37,38] phase changes[39]) sampled students enrolled in environments similar to *B* or *C*; that is, sampled students were likely never supported in reasoning about phenomena in terms of atoms and molecules. Students are undoubtedly capable of explaining phase changes,[40] acid−base reactions,[22] emission spectra,[41] and dissolution[42] if appropriately supported. Indeed, one can find examples of impressively sophisticated models for explaining evaporation and condensation constructed by fifth-grade students engaged in a model-focused curriculum.[43] Stated succinctly, our students are all capable of making sense of the world in terms of atomic/molecular behavior if we signal that this is important and provide appropriate support in all aspects of the learning environments we enact.

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It must be acknowledged that creating learning environments focused on connecting core ideas to phenomena is a nontrivial undertaking. There are suites of materials for general chemistry,[44,45] organic chemistry,[46] and laboratory courses[47−50] that attempt to coherently emphasize aspects of scientific practice. However, these are best considered “curricular overhauls” rather than “curricular tweaks”. Indeed, ongoing work in our groups suggests that tweaking instructional practices in an otherwise traditional course does not effectively support students in explaining phenomena. One could envision (at least) two paths toward more 3D chemistry learning environments: (1) a sudden “paradigm shift” in which one adopts and refines an existing evidence-based curriculum such as Chemistry, Life, the Universe, and Everything,[44] or (2) a slow evolution of the status quo where instructional and assessment materials emphasize ever-more opportunities for students to predict, explain, and model observable events using ideas such as energy and bonding interactions. Regardless of whether sudden transformation or slow evolution is more tractable in a particular context, the central point of this commentary is that *change is sorely needed* in some general chemistry enactments. We simply cannot continue forcing students to march through a gauntlet of decontextualized skills and facts and try to pass this off as chemistry. Such a course misrepresents the power of the chemical sciences as a discipline and selects students for continuation in STEM based on often irrelevant proficiencies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c00532.

Supporting Information overview (PDF)

Criteria for assessment items tagged as “math” (PDF)

Codes for assessment tasks (XLSX)

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Notes

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