Aligning Undergraduate Science Curricula With Three-Dimensional Learning

By Jeffrey Radloff, Brenda Capobianco, Jessica Weller, Sanjay Rebello, David Eichinger, and Kendra Erk

Recent science reform advocates for the inclusion of engineering design to teach science and represents a shift to so-called three-dimensional (3D) learning. This shift often requires science instructors to adapt their current curriculum to integrate 3D learning. To support this shift, the current study illustrates the collaborative development and use of a rubric for aligning existing curriculum with new reform. Collaborators include three undergraduate science content course (i.e., biology, chemistry, and physics) instructors who used the tool to adapt their current curriculum. In this article, we outline the phases of tool development and showcase its implementation by the chemistry content course instructor to integrate a rocket design task. Successes and considerations are discussed as they relate to science teacher education and professional learning.

The Next Generation Science Standards (NGSS) portray science and engineering as a set of collective disciplinary core ideas (DCIs), science and engineering practices (SEPs), and cross-cutting concepts (CCCs; NGSS Lead States, 2013). Together, these three strands support what is called “three-dimensional” or “3D” learning (Duncan & Cavera, 2015; Krajcik, 2015). This framework represents a marked difference in the way science is taught (Ford, 2015). In addition to previous inquiry-based practices, K–12 science teachers must now understand how to employ and adapt engineering design to teach science (Cunningham et al., 2018).

While novel to science reform, engineering design–based science instruction shares several features with inquiry-based teaching (Fortus et al., 2004). As portrayed in the NGSS, inquiry and design are linked closely through a set of interdisciplinary concepts and practices (see Appendices F and G in NGSS Lead States, 2013). Additionally, both are context driven, iterative, and social endeavors (Pleasants & Olson, 2019). However, the purposes and goals of science and engineering are quite divergent (Eekels & Roozenburg, 1991). Science focuses on exploring and understanding the natural world through continuously asking and answering questions (Irzik & Nola, 2014), while engineering aims to improve the world through developing and optimizing solutions to design problems (Lewis, 2006).

In the K–16 science classroom, engineering design is an effective and equitable method of science instruction (Brophy et al., 2008; Silk et al., 2009). Engaging students in design-based science instruction often leads to increased science learning (Bethke Wendell & Rogers, 2013; Cunningham et al., 2020) and attitudes (Lie et al., 2019). Design-based science instruction also engages students in collaborative decision-making and reflection (Wendell et al., 2017), “21st-century skills” that underlie 3D learning and are essential for STEM careers (NGSS Lead States, 2013; National Science Teaching Association, 2020).

Science course instructors and teacher educators must reevaluate and reorganize the way they meet the demands of the NGSS (Pellegrino et al., 2014). This includes the redesign of core undergraduate science courses for preservice teachers to include engineering concepts and practices in support of 3D learning. For science instructors, the integration of the NGSS requires not only the development of new curricular units that address DCIs, SEPs, and CCCs for both science and engineering but...
also the alignment of novel instructional activities with 3D learning. Yet, instructors lack practical tools to help them meet these goals.

In this article, we outline the process a group of university science instructors took to map DCIs, SEPs, and CCCs with course-related engineering design–based science learning experiences, then describe how this process and the related 3D learning matrix help instructors facilitate 3D learning. We illustrate the steps we took as a collective group of science teacher educators and profile a science instructor’s curricular attempts with using the matrix. This case is profiled as an exemplar for other college science educators to consider when mapping the NGSS with their current curriculum.

Context of our work

This initiative is part of a large-scale, multiyear, nationally funded project that examines the impact of an engineering design–based approach on preservice elementary science teachers’ understanding of engineering practices. In this project, university science and science education faculty jointly reorganize their respective course objectives, learning experiences, and corresponding assessments to address NGSS standards and 3D learning. The course instructors include one faculty member from each of the biology, physics, and chemistry departments. The science instructors work in concert with the science methods instructor to develop a progression of standards-based engineering design experiences that are later used in the methods course as a platform for reflection on students’ developing understanding of design. A materials science engineering instructor provides insightful feedback on accurate representations of engineering for each task. The chemistry course instructor implemented an antacid rocket design task focused on acid-base chemistry and chemical reaction rates. The physics instructor engaged students in a locker alarm task focused on energy transfer, and the biology instructor implemented a compost task that emphasized decomposition and matter flow within ecosystems (Radloff et al., 2019).

FIGURE 1

Initial 3D learning matrix.

<table>
<thead>
<tr>
<th>Name of Design Task Semester Implemented By:</th>
</tr>
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<tbody>
<tr>
<td>Identify Problem Share &amp; Develop Plan Create &amp; Test Communicate &amp; Feedback Improve and Retest</td>
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<table>
<thead>
<tr>
<th>Crosscutting Concepts (Fill in with “X” and describe how addressed.)</th>
<th>Patterns</th>
<th>Cause &amp; Effect Mechanism and Explanation</th>
<th>Scale, Proportion, and Quantity</th>
<th>Systems and System Models</th>
<th>Energy and Matter</th>
<th>Structure and Function</th>
<th>Stability and Change</th>
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<tbody>
<tr>
<td>Emphasis on...</td>
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<tr>
<th>Disciplinary Core Ideas (Copy and paste from NGSS)</th>
<th>Earth and Space Science Standards</th>
<th>Life Science Standards</th>
<th>Physical Science Standards</th>
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<td>Emphasis on...</td>
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| DCI/SEP Connections | SEP/CCC Connections | DCI/CCC Connections | Performance Expectation |
Goals of the 3D learning matrix

The goals of the 3D learning matrix include the following: (a) Align those experiences with 3D learning; (b) help course instructors assess and reflect on the implementation of their design experiences; and (c) modify and refine curriculum to align with these constructs (e.g., targeted assessments). The instructors identify which DCIs, SEPs, and CCCs are emphasized in each respective design task and map these constructs with their instructional activities. Figure 1 illustrates the initial matrix.

Developing the 3D learning matrix

There were three distinct phases in our collaborative work. The first phase focused on the science instructors creating and pilot-testing their engineering design–based tasks for their respective courses. The second phase emphasized instructors reflecting on their experiences and operationalizing their work together. The last phase entailed the instructors collectively mapping and coordinating their design experiences to the NGSS framework and with one another’s course. By doing so, the instructors, as a team, provided a standards-based, well-coordinated, progressive series of content-rich courses for preservice elementary science teachers. What follows is a description of each phase.

Phase I: Development of course-based design tasks

The first phase involved the instructors developing an understanding of engineering design while creating design-based tasks for their course. This entailed initially reading literature on the nature of engineering design (e.g., Lawson & Dorst, 2013), engineering pedagogies (e.g., Capobianco et al., 2013), and research in engineering education (Crismond & Adams, 2012; McDonnell, 2015). The project team met on a biweekly basis to discuss its review of literature, share ideas for plausible design-based experiences, and outline instructional activities for different design tasks. During this time, the course instructors reviewed and decided on a model for engineering design that aligned with the project goals, their personal conceptions of design, and their tentative ideas for design-based tasks in their courses (see Figure 2).

Each instructor focused on different entry points for developing engineering design tasks. The chemistry instructor integrated a design experience that emphasized the practices of conducting investigations and testing a toy rocket propelled by antacid tablets. The physics instructor integrated a design experience related to simple circuitry that involved multiple iterations of design of a locker alarm. The biology instructor created a design task that connected with existing lessons using modeling in the context of decomposition (see Radloff et al., 2019). Some instructors modified existing design tasks from previous projects, while others developed original ideas. Underpinning each design experience was a focus on how the tasks aligned with the Using Principles of Design to Advance Teacher Education (UPDTE) model for engineering design and thus placed emphasis on engineering practices (see Figure 2).

Phase II: Operationalizing SEPs across courses

As the course instructors began to implement their design tasks, they continued to meet and discuss how they were engaging students with engineering practices to learn science. Specifically, they reflected on which SEPs were addressed by each design task and to what extent. Initially, the instructors identified several SEPs for their design tasks. The chemistry instructor, for example, described
her capstone rocket task as addressing eight SEPs. After completing the 3D learning matrix, she quickly recognized four SEPs that were the most relevant. These SEPs were then classified as either primary and secondary or more or less emphasized by each design task created by the instructors. Individual instructors used the matrix during this time to scaffold their conversations, focusing on the use of a common “three-dimensional” language.

**Phase III: Mapping and coordinating SEPs, DCIs, and CCCs across courses**

The next step was to augment the instructors’ design experiences by addressing DCIs and CCCs. First, SEPs were mapped across all courses to showcase which SEPs were addressed by the larger project. Then instructors mapped their DCIs and CCCs, as well as those intersections between constructs (e.g., connections between DCI and SEP, SEP and CCC, and DCI and CCC). Based on the results from this work, the instructors established relevant performance expectations (PEs) or the overarching goals of a given unit of study (Appendix F; NGSS Lead States, 2013). This exercise helped instructors recognize and make connections between the engineering- and science-related constructs (DCIs, SEPs, and CCCs) embedded in their design tasks relative to their lesson objectives.

Results from the matrix were analyzed and converted into Venn diagrams that summarized each task as it related to 3D learning (Houseal, 2015). In the next section, we illustrate an example of a Venn diagram using the chemistry instructor’s rocket task.

**Using the matrix to map the antacid rocket task**

Table 1 illustrates the rocket task’s alignment with the matrix. In this task (a capstone project in the chemistry content course), students collaboratively apply their knowledge of acid-base chemistry and reaction rates to test and optimize the propellants for a “fun, child-friendly, and safe” toy rocket. Following the investigation, students modify an “unsafe” rocket safety manual to summarize and reflect on their findings. The main learning objective of this design task is for students to demonstrate how to plan and carry out chemistry-based design and experimentation.

When developing their propellant mixtures, students work in small groups to evaluate different mixtures of acids and bases, including vinegar, baking soda, a popular antacid tablet, and water. The groups then create testing procedures and test and evaluate the performance of their rockets (e.g., by speed of reaction or height of rocket flight). After evaluating their findings, students redesign or adjust their propellant mixtures and retest before summarizing their results in their safety manuals.

In Table 1, the task name is in the top left (Rocket Task), the SEPs are in the top row (Appendix F; NGSS Lead States, 2013), and the design phases from the project design model are in the far-left column (see Capobianco et al., 2018). The instructor marked the SEPs that were more emphasized (i.e., primary) with a “P” and those less emphasized (i.e., secondary).

### TABLE 1

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<td>Create and test</td>
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<td>Communicate and give feedback</td>
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<td>Improve and retest</td>
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</table>

**Identify the problem**

- **Primary (P)**

**Share and develop plan**

- **Primary (P)**

**Create and test**

- **Primary (P)**

**Communicate and give feedback**

- **Primary (P)**

**Improve and retest**

- **Secondary (S)**
with an “S.” After she distinguished the SEPs, the instructor then identified which design phase corresponded to each SEP (i.e., where each “P” and “S” appears in Table 1).

In this task, the instructor identified the primary practices of planning and carrying out investigations, analyzing and/or interpreting data, and engaging in argumentation from evidence during design phases of sharing and developing a plan, creating and testing, and communication and feedback, respectively. This table highlights the students’ experimentation and evaluation as they developed and tested their rocket propellants. To clarify, teachers evaluated each rocket launch ($n = 12$ per group) in real time. She noted the secondary SEPs of constructing scientific explanations and design solutions and obtaining, evaluating, and communicating information during phases of communication and feedback and improve and retest, respectively. These were represented by students summarizing and reflecting on their results in their rocket safety manuals.

Next, major DCIs and CCCs were isolated. As described, the task addressed matter and energy flow in ecosystems. This emphasis on energy flow in ecosystems was reflected through the DCIs and CCCs (see Table 2).

After identifying related DCIs, SEPs, and CCCs, the chemistry instructor then pinpointed the intersections between them (e.g., connections between DCIs and SEPs and between DCIs and CCCs). To demonstrate these intersections meant isolating the distinct lesson activities that addressed each juncture (see Table 3). The design phases identified in Table 1 may help instructors identify the relevant lesson activities that demonstrate the intersections between threads of three-dimensional learning while also emphasizing the use of design.

This information was then converted into a three-dimensional learning Venn diagram and legend (see Figure 3). The larger circles provide the DCIs, SEPs, and CCCs; the middle area denotes the PE; and the outer areas represent the intersections between threads. Design phases have been mapped for SEPs.

**Discussion**

The 3D learning matrix represents a robust and practical approach to promoting reflection among university science instructors about how to align their existing efforts with 3D learning. Faculty can reflect on their design experiences by documenting where DCIs, SEPs, and CCCs are present and identifying areas where lesson activities can be improved or modified. In this way, the matrix promotes an awareness of how instructors are integrating engineering design to teach science (Ford, 2015; Krajcik, 2015; Cunningham et al., 2018).

By connecting instructional activities with three-dimensional learning, the matrix can also be used to highlight areas within design tasks where instructors may provide design feedback and implement assessments (Wendell et al., 2017; Wendell et al., 2019), as well as develop or refine

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**TABLE 2**

Mapped DCIs, CCCs, and SEPs for the rocket task.

<table>
<thead>
<tr>
<th>Disciplinary Core Ideas (DCIs)</th>
<th>Crosscutting Concepts (CCCs)</th>
<th>Science and Engineering Practices (SEPs)</th>
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</thead>
<tbody>
<tr>
<td>PS1.B. Chemical Reactions: Chemical processes, their rates, and whether or not energy is stored or released can be understood in terms of the collisions of molecules and the rearrangements of atoms into new molecules, with consequent changes in the sum of all bond energies in the set of molecules that are matched by changes in kinetic energy. (HS-PS1-4),(HS-PS1-5)</td>
<td>Cause and Effect: Change in reactants affects products in a chemical reaction (e.g., rocket propellants, launches).</td>
<td>Plan and Carry Out Investigations (P): Different acid-base combinations can be used to propel the toy rocket, some better than others.</td>
</tr>
<tr>
<td>ETS1.C. Optimizing the Design Solution: Criteria may need to be broken down into simpler ones that can be approached systematically, and decisions about the priority of certain criteria over others (trade-offs) may be needed. (secondary to HS-PS1-6)</td>
<td>Scale, Proportion, and Quantity: Balanced chemical equations corresponded with teachers’ choices for concentrations of reactants.</td>
<td>Analyze and/or Interpret Data (P): Different acid-base combinations lead to different performance results that may or may not meet design criteria.</td>
</tr>
<tr>
<td></td>
<td>Structure and Function: Acid/base reactions produce specific products based on chemical structures.</td>
<td>Engaging in Argumentation Using Evidence (P): Choices for improving propellant mixtures are based upon quantitative performance results.</td>
</tr>
</tbody>
</table>
their assessments for stronger alignment with science standards. More broadly, the matrix offers a potential form of accountability for adopting three-dimensional learning in science courses for preservice teachers and undergraduate students in general. This application was evident in the chemistry instructor’s responses to identifying the intersections between DCIs, SEPs, and CCCs.

The matrix can also be used by college science instructors seeking to collaborate. In addition to mapping instructors’ individual design tasks, the matrix can be used to document, connect, and scaffold three-dimensional learning across multiple science content courses (e.g., chemistry, biology, and physics). While the chemistry design task was used as a capstone project, multiple smaller tasks may be implemented within and across courses to address and engage students in engineering design differentially (e.g., introduce certain SEPs or the design process) to build students’ understanding over time. In this way, the matrix is a tool that can be used to examine trends in learning progressions among students as they move from one course to the next. Correspondingly, it could also be used to scaffold and track learning across multiple design tasks within the same course.

Aside from these practical applications, the matrix offers an entry point into the interpretation and adoption of standards between instructors (Ford, 2015). In the UPDATE project, the matrix offered instructors a common “anchor” and language that could be revisited and explored as needed (Capobianco et al., 2020). For example, the instructors who participated in the UPDATE project held varying interpretations of both the engineering design process and SEPs when they started to develop their design tasks. Likewise, the PEs associated with the rocket task did not directly include the SEP involving planning and carrying out investigations. However, when mapping how the PEs fit together within the phenomena and the storyline associated with experimenting with and designing the toy rocket propellants, that SEP emerged as a primary practice. The rocket task represented an authentic investigation in which the other primary practices (i.e., SEPs 4 and 7) were embedded.

Finally, the matrix supports a practical approach to organizing and sharing peer feedback among faculty, both in person and remotely. Ongoing face-to-face collaborative meetings with colleagues helped us develop and hone our initial understandings of engineering, engineering design, and 3D learning (Capobianco et al., 2020). The onset of the pandemic required that we relocate our conversations to an electronic platform, and after that point, the implementation of the rocket design task and corresponding meetings took place remotely. Throughout this time, the matrix served as a shared foothold for us to return to our original objectives for curriculum reform and innovation grounded in 3D learning. In sum, we learned that applications of the matrix afford both synchronous and asyn-

|| Performance Expectation(s) | DCI/SEP Connections | SEP/CCC Connections | DCI/CCC Connections |
|-----------------------------|---------------------|---------------------|---------------------|
| HS-PS1-5. Apply scientific principles and evidence to provide an explanation about the effects of changing temperature or concentrations of the reacting particles on the rate at which a reaction occurs. | Students work collaboratively to plan and investigate (e.g., reinforce/apply) their knowledge of acid-base chemistry through creating a method of propulsion for a toy rocket. | Students collect evidence and make arguments about how to improve their propulsion systems (e.g., when combining chemicals to propel their rockets; cause and effect). | Students manipulate concentrations of chemical reactants when developing their propulsion systems (e.g., scale, proportion, quantity tied into acid-base chemistry). Students apply their knowledge of acid-base chemistry when choosing their propellants (structure and function; cause and effect). |
| HS-PS1-6. Refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium. | | | |

Note. CCC = Crosscutting Concepts; DCI = Disciplinary Core Ideas; SEP = Science and Engineering Practices.
chronous professional development.

Conclusion
As three-dimensional learning with engineering continues to be adopted and practiced by K–12 science teachers, college science instructors must be equipped to do the same. Science faculty must have the knowledge of and associated tools for integrating science and engineering practices in concert with core disciplinary ideas and crosscutting concepts. By using the 3D learning matrix, college science instructors gain the skills and knowledge necessary to shift and reorient their understanding, curriculum, and teaching to meet the demand for high-quality, reform-based science instruction.

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References


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