DESIGNING FOR AN INTEGRATED STEM+C EXPERIENCE

Nicole Panorkou
Montclair State University
panorkoun@montclair.edu

Toni York
Montclair State University
yorka1@montclair.edu

In this paper we present an integrated design approach for bridging content between science, technology, engineering, math, and computational thinking (STEM+C). We present data from a design experiment to show examples of the kinds of integrated reasoning that students exhibited while engaging with our design. We argue that covariational reasoning can provide strong scaffolding in making integrated connections between the STEM+C content areas.

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To integrate math and science content, science materials often simply provide graphs while math materials often merely mention science terms for context. However, these efforts do not show the ways in which students' mathematical reasoning may influence their understanding of science, or how their scientific reasoning may influence their understanding of mathematical ideas. As English (2016) argued, in STEM integration there is a need for a more balanced focus on each of the disciplines, especially mathematics which is usually underrepresented. To illustrate this reciprocal relationship between mathematical and scientific reasoning, we looked for a design approach that could honor both math and science content. Specifically, our aim was to explore the research questions: (a) What kind of design integrates science and math for students? (b) What kind of reasoning do students display as they interact with this design?

Design Framework for Integrated Learning

First, we considered the power of covariational reasoning for bridging the two disciplines. Covariational reasoning is the mental coordination of simultaneous changes in two related quantities (Carlson et al., 2002). Mathematically, covariational reasoning has shown to be a strong building block towards the introduction of functions and graphing (Confrey & Smith, 1995). In terms of science, we considered that by engaging in covariational reasoning as they actively examine the interplay of variables in natural phenomena, students would develop deeper understandings of those phenomena than they might from exploring them only in terms of cause and effect relationships. To put it another way, there is a difference between reasoning about a cause and effect relationship, for instance, the depth of the rock affects its temperature, and reasoning covariationally about a relationship, for example, the temperature is changing as the depth of the rock is changing. This study of simultaneous change exhibited by covariational reasoning presented a promising route for supporting students' development of integrated forms of math and science reasoning.

We also considered the power of digital environments for designing simulations that dynamically model abstract mathematical and scientific concepts. We hoped that exploring a simulation would provide multiple trials and rapid feedback, supporting an inquiry environment (Meadows & Caniglia, 2019). Our goal was to encourage students to use the simulation to engage in inquiry practices such as questioning, developing hypotheses, collecting data, and revising theories (Rutten et al., 2012). This use of simulations to model and interact with data is also defined by Weintrop et al. (2016) as a form of computational thinking. They describe a taxonomy of computational thinking that includes practices such as Collecting, Analyzing, and Visualizing Data as well as Using Computational Models to Understand a Concept.

Finally, we gave careful attention to the design of tasks and questioning, aiming to shift students' attention to specific elements of the model and influence the nature of their interactions with those

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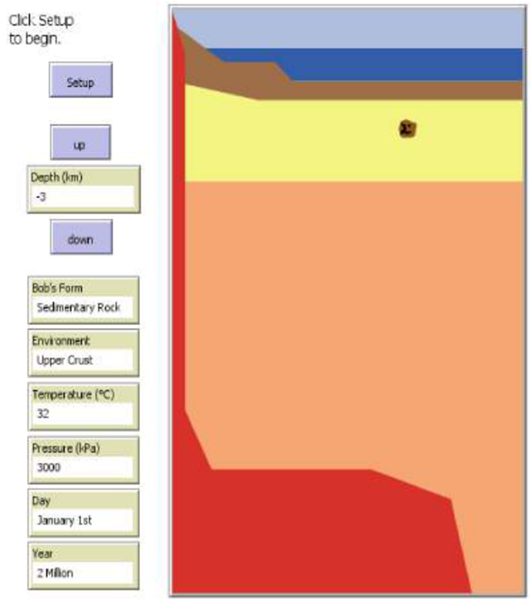
elements. The questioning was organized to encourage students to explore specific relationships, such as "What have you observed about how the temperature and pressure change as Bob moves deeper underground?" Our goal was to prompt the students to engage in some of the Carlson et al. (2002) mental actions of covariational reasoning. These include coordinating the change of one variable with changes in the other variable (MA1), coordinating the direction of change of one variable with changes in the other variable (MA2), coordinating the amount of change of one variable with changes in the other variable (MA3), coordinating the average rate-of-change of the function with uniform increments of change in the input variable (MA4), and finally coordinating the instantaneous rate of change of the function with continuous changes in the independent variable for the entire domain of the function (MA5).

We also considered connecting the dynamic representations of relationships in the simulation with the graphing of those relationships. This connection was found to advance students' conceptions of graphs of functions as a representation of coordinated change (e.g., Ellis et al., 2018). Students often fail to connect graphs with the covariational relationships they represent (Moore & Thompson, 2015), therefore, beyond simply describing and then having students graph these relationships, our goal was to ask them to use the simulation to collect data and graph these relationships. Our conjecture was that by engaging in these kinds of reasoning and practices as they interacted with our design, students would construct their own conceptual bridges in the context of an integrated STEM+C experience. In this paper, we present this design approach by providing an example using the phenomenon of the rock cycle, which is part of a larger collection studying science phenomena (e.g., Basu & Panorkou, 2019; Zhu et al., 2018).

An Example of Integrated STEM+C Design From the Rock Cycle

The earth science concept of the rock cycle describes the cyclical changes rocks experience due to the earth's thermal energy. Like many natural phenomena, the rock cycle involves multiple variables. By identifying relationships such as the increase in temperature and pressure as depth below ground increases, we conjectured that covariation can be used as a link to integrate science and math. To encourage students to investigate for themselves how these quantities covary in the rock cycle, we developed the Bob's Life simulation. The Bob's Life simulation (Figure 1) models the life of a rock named Bob near the sea on a volcanic island as he experiences different rock cycle processes and takes on different forms. The student controls Bob's depth in 1-km increments to investigate the behavior of the model. The simulation provides immediate visual feedback as the animation shows Bob moving and changing his form.

Though we used real geological data (e.g., Becerril et al., 2013) as a starting point to describe Bob's path, these relationships are not always perfectly linear in the real world and can vary widely in real environments (e.g., de Wall et al., 2019). However, by sacrificing a certain amount of scientific realism, we were able to design the relationships between Bob's depth and the temperature and pressure to be piecewise linear functions with planned regions of friendlier numbers for students to graph. For example, in the Upper Crust environment we selected the numbers such that for each 1 km Bob moves down the temperature increases by 8 °C and the pressure increases by 1,000 kPa. This design choice maintains the scientific integrity of the model while creating an accessible data set for middle school students to investigate. The Bob's Life simulation is thus a simplified model of real-world processes designed to have useful pedagogical features (Weintrop et al., 2016).



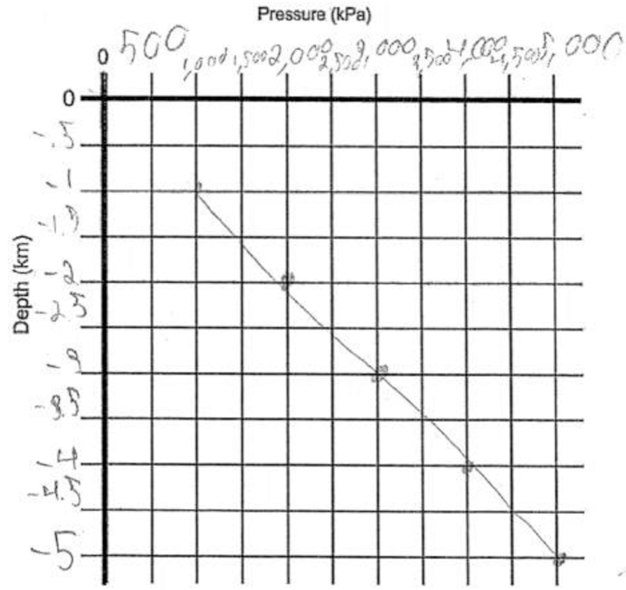


Figure 1 (left): The Bob's Life Simulation Interface
Figure 2 (right): Michael's Graph of Depth and Pressure

Students' Forms of Integrated STEM+C Reasoning

We focus on a whole-class design experiment (Cobb et al., 2003) in a middle school classroom and present episodes from a single pair of students, Laura and Michael, to illustrate examples of students' integrated reasoning as they interacted with our design. We adapted the Carlson et al. (2002) framework to identify episodes that illustrate students' covariational reasoning. We also remained open to students' use of other forms of reasoning, such as multivariational reasoning (Kuster & Jones, 2019) and computational thinking practices (Weintrop et al., 2016). At the same time, we examined how our design seemed to influence this reasoning by investigating the dialectic relationship between design and learning.

At the start of the design experiment, students were asked to freely explore the simulation. We included this free play to build students' interest and to encourage them to begin using inquiry practices (Rutten et al., 2012) as they interacted with the simulation and described what they noticed. During this time, we asked Laura about what she had noticed so far:

> Laura: I'd say, there's a rock named Bob, and you can control his depth. And if you go, the deeper you get, his form changes, his environment changes, his temperature, the pressure that's being put on the rock, the day, and the year change.

Laura's reasoning shows that the free exploration of the simulation offered a constructive space for her to both inquire into the behavior of the model and also to reason about how the rock's form, environment, temperature, and pressure change based on its depth. She coordinated changes in the variable she controlled, Bob's depth, with several other variables that were also changing simultaneously, illustrating MA1 reasoning. We would also argue that she exhibited multivariational reasoning since she was able to coordinate multiple variables at the same time.

After the free exploration, Laura was asked to use the simulation to investigate how the temperature and pressure change as Bob moves deeper underground. She responded that "the deeper you go, the more pressure's being put on it" and "the lower Bob goes in depth, the higher the temperature increases." Her responses show that she coordinated the direction of change of Bob's depth with the direction of change in pressure and temperature, engaging in both MA2 and multivariational reasoning. Immediately after giving the latter response, she used the simulation to illustrate by moving Bob several kilometers lower and pointing at the increasing number in the temperature readout. Laura's action shows that she used the simulation to understand what is changing and how it is changing in the model, illustrating a form of computational thinking.

Next, we asked students to collect data and graph the relationship between the variables. When asked to describe the numerical relationship in his graph (Figure 2), Michael said, "I got 1, as Bob moves 1 km deeper underground, the pressure increases by 1,000 kPa, because each km you go deeper, is 1,000 pressure compacted on Bob." Even though Michael's graph visually appears to be a falling line, his response shows that he viewed this as representing the increase in pressure as Bob moved deeper. This is evidence of MA3 reasoning as well as an indication that he might have been imagining his graph as an emerging record of this covariational relationship rather than a static shape (Moore & Thompson, 2015). This also shows that our design supported Michael in using computational thinking practices of collecting, analyzing, and visualizing data.

At the end of the experiment, students were asked to find intermediate values on their graphs. For example, we asked Michael to state the depth at which Bob would experience 4,500 kPa of pressure. Michael stated, "I think it's 4½ km underground." He explained that this is "Because 4 km underground is 4,000, and every .5 is 500, so if you do 4.5, that's going to be 4,500." Earlier, Michael had also observed, "1 km underground is 1,000, and if you add a .5 that's 500 more so that's 1,500." This shows that Michael had not only noticed that the pressure changed by a certain amount for each 1-km step, but that he had also used his graph to see that he could describe this relationship in terms of steps of .5 km. Michael's observation that "every .5 is 500" is an example of MA4 because it shows that he was reasoning about the rate at which pressure was changing for equal incremental changes in Bob's depth. It also shows that he used his graph as a second model to understand the relationships, illustrating computational thinking.

Conclusion

In response to RQ (a), we believe that this experiment has shown how our design approach can be used to develop integrated STEM+C instructional modules that have a more *balanced focus* (English, 2016) on each of the disciplines. This work supports our assertion that covariational reasoning can serve as a bridge to integrated STEM+C learning. Guided by the task design and questioning, students explored and explained the model's behavior in terms of both rock cycle processes and mathematical relationships. In response to RQ (b), the analysis of students' reasoning showed that they developed a sophisticated understanding of the science content which included identifying the factors that influence the rock cycle and constructing relationships between the involved variables. Students reasoned covariationally at various levels (Carlson et al., 2002) as they interacted with our design. We have also shown that students displayed multivariational reasoning (Kuster & Jones, 2019) and engaged in computational thinking practices (Weintrop et al., 2016). In the future, we plan to continue refining this integrated design framework with the rock cycle module as well as other modules that use covariational reasoning to build conceptual bridges between science and math. We also plan to explore other topics, such as probability and statistics, which might also be able to play the same bridging role that covariation plays in our Bob's Life simulation and investigation design.

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