Using Models for Reasoning and Content Learning: Patterns of Bootstrapping Towards Earth Science Understandings

Ann E. Rivet, Cheryl A. Lyons, Alison R. Miller
Teachers College Columbia University, 525 W. 120th Street, New York, NY 10027
rivet@tc.columbia.edu, cal2154@tc.columbia.edu, mar2218@tc.columbia.edu

Abstract: A key aspect of using scientific models and other representations as cognitive learning tools is the reciprocal relationship between understanding the nature of models as representations, and understanding the specific concepts and phenomena that the model is intended to represent. However, challenges exist regarding how to describe and measure indicators of this reciprocity. We explored the ways in which 8th and 9th grade students utilized physical dynamic tabletop models towards developing sophisticated understandings of full scale Earth System processes. This approach allowed us to identify and describe evidence of the "bootstrapping" that occurs between understanding the model as a scientific representation, and understanding the science concepts of the represented entities, configurations, motions, and emergent phenomena in the real Earth System. We argue that this notion of bootstrapping is a productive means to conceptualize and support the development of students' epistemological understandings of both scientific models and the represented science concepts.

Introduction

One of the challenges with the current discourse in science education around scientific practices, and modeling practice in particular, is how the development of these practices interplays with the development of sophisticated target content understandings. A key aspect of using scientific models and other representations as cognitive learning tools is the reciprocal relationship between understanding the nature of models as representations, and understanding the specific concepts and phenomena that the model is intended to represent (Schwarz et al., 2009). Although the literature fully acknowledges the intertwined relationship between the two, specific attempts to conceptualize, describe, and measure how these different but related constructs evolve across students' learning continuum are still in their infancy. In particular, challenges exist regarding both how to describe and measure indicators of this reciprocity, and the conditions under which the interplay between students' understanding the nature of models as representations (a key aspect of modeling practice) and robust conceptual understanding developed through working with such models is most productive for learning.

Our work attempts to frame this important intersection of practice and conceptual learning. Specifically, we sought to address the following question: what is the nature of the relationship between students' demonstrated content understandings and the sophistication of their analogical reasoning around representative models? We articulated a progressive analogical reasoning construct to describe the ways in which students develop in their ability to conceptualize more abstract and generalized understandings of both models as representations, as well as concepts and phenomena that are represented in specific models. Through in-depth interviews and written assessments, we explored the ways in which 8th and 9th grade students utilized physical dynamic tabletop models towards developing sophisticated understandings of full scale Earth System processes. This approach allowed us to identify and describe evidence of the "bootstrapping" that occurs between understanding the model *as* a scientific representation, and understanding the science concepts *of* the represented entities, configurations, motions, and emergent phenomena in the real Earth System (Carey, 2004; Kurtz, Mao & Gentner, 2001). We argue that this notion of bootstrapping is a productive means to conceptualize the development of students' epistemological understandings of both scientific models and the represented science concepts, and should be further explored and supported through instructional approaches and other cognitive tools embedded in science learning experiences across the K-12 continuum.

Conceptual Framework

Challenges Particular to Earth Science Learning

Science is about developing understandings and explanations of phenomena of the natural world. To the greatest extent possible, much of science education involves giving students direct experiences with such phenomena. Yet it is not possible to bring many of the important phenomena of Earth Science into the classroom setting for students to explore. Key Earth system processes, such as eclipses, ocean currents, and differential heating of the atmosphere, are beyond a students' tangible grasp. The most common way to address this challenge is to make extensive use of a wide array of representation types across the Earth Science curriculum (Kastens & Rivet, 2010), including conceptual models. Conceptual models are defined by the

National Research Council (NRC, 2012) as diagrams, physical replicas, mathematical representations, analogies and computer simulations that are simplified structural, functional, or behavioral analogs for the phenomena being represented, and can be used to generate explanations and predictions. Specifically, we focus our research on dynamic tabletop models that change or move. Research has found that such models are engaging for students, and have the ability to mirror the use of models in authentic science practice to both represent and develop new understandings (Neressian et al., 2003). However, there are known challenges with using such models in classrooms, including documented cognitive leaps of scale and rate, and instructional approaches that are often focused on the details of the model rather than on students' use of the model to develop understandings of the represented Earth System. To address these challenges in support of Earth Science learning, there is a need for greater understanding of how exactly students interpret and reason with physical models, and what kinds of supports (from the teacher, instructional materials, and the model itself) are most effective in guiding students' use of such models towards deep understandings of the Earth.

Modeling Practice

There is a distinction made in the literature between models (particularly conceptual models) and modeling practice. The practice of modeling, as described by Schwarz et al. (2009), is a weaving together of both the active engagement with the elements of modeling, and the understanding of the rationale and norms that guide the practice, referred to as *meta-modeling knowledge* (Schwarz & White, 2005). Meta-modeling knowledge includes understandings of how models are used, why they are used, and what their strengths and limitations are. Thus simply working with physical representations is claimed to be insufficient for students to develop an understanding and appreciation of modeling practice. Rather, it is through this combination of engagement with and knowledge of modeling, that students develop a more robust sense of how science works and the nature of the knowledge that science produces (Schwarz et al., 2009).

One of the persistent questions around the conceptualization of students' development of science practices in general, including modeling practice, is the nature of the reciprocal relationship between developing understandings of the practice itself and understandings of the specific scientific concepts engaged through the practices. Researchers have argued that models and the real world phenomena that they represent exist as a dialogic: it is through analyzing phenomena one can glean insights into the potential elements, relations, operations, and rules that govern and constrain the model; while concurrently, the model allows for the generation of new explanations and predictions regarding the targeted phenomena (Schwartz et al., 2009). The National Research Council (2012) goes further to state that developing an understanding of models and their role in science can help learners construct and revise their own mental models of phenomena, which in turn results in more robust reasoning and a deeper understanding of science concepts. However, as strong as this claim is in theory, there is scant evidence to illustrate such reciprocity in actual student learning. Due in part to measurement challenges, science practices such as modeling are often examined and evaluated in the abstract, apart from the disciplinary content focus in which the modeling practice is embedded. Therefore the question still remains regarding the nature of the conceptual and epistemic science learning and meaning making that is gained through engagement with modeling practices around targeted concepts and phenomena under study.

Learning from Models: Analogical Reasoning

In light of these challenges we were interested in exploring further the nature of how students come to understand the 'representation-ness' of models, and how the models are understood to serve as analogies for phenomena that are too big, too slow, or too intangible to be observed directly. To shape our thinking, we drew heavily from the literature on analogical reasoning, and in particular the work of Dedre Gentner. Gentner's structure mapping framework for analogy (e.g., Gentner, 1983) focuses the process of establishing a structural alignment between a familiar source (in this case, a physical model in front of students) and an unfamiliar target (such as a large-scale Earth process like atmospheric circulation or subduction at plate boundaries). Gentner's framework distinguishes among different forms of similarity that may exist between the source and the target, and articulates a set of implicit rules for mapping knowledge about the source onto the target. This and other educational research demonstrates how the power of analogy comes from the relationships between objects rather than from the attributes of objects themselves, and that the most powerful analogy-derived insights come from the existence of higher-order relations such as causality that correspond between the source and the target.

Building from Wilson's (2005) approach to construct modeling, in our work we identified three key levels of analogical reasoning regarding the correspondences and non-correspondences between models and the Earth System that frame an increasingly sophisticated way that students may come to use models to develop robust understandings of Earth Science concepts and phenomena (see Figure 1). To illustrate these three levels, we describe the reasoning that students may engage in around an exemplar model of the phases of the moon (Figure 2). In this model, a basketball is placed on a stand in the front of the room, with a small plastic doll taped to a point about half-way between the top and the mid-line, oriented so it is facing the classroom. A bright light is placed to the side of the basketball. The instructor then moves a smaller yellow lacrosse ball around the basketball, at a sufficient angle so that the light from the lamp continually illuminates one side of the yellow ball as it moves around the basketball. Using this model, we describe the three levels of reasoning about correspondences and non-correspondences shown in Figure 1 that we believe users of this model would engage in while coming to better understand the target phenomena, that of the observed phases of the Moon from Earth.

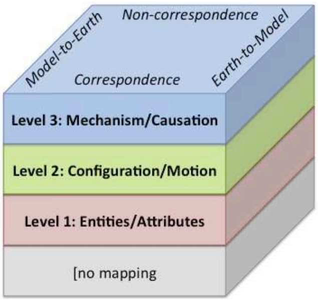

Figure 1: Levels of students' analogical reasoning between a physical model and the Earth System

Figure 2: Model of the phases of the Moon

The first, and most basic, level of analogic mapping has to do with identifying and understanding the correspondences and non-correspondences between entities in the model and entities in the Earth System. By 'entities' we are referring to both specific object mapping and mapping of the characteristics of those objects. In the example, reasoning about correspondences and non-correspondences at the entity level would include identifying and naming the basketball as representing the Earth, the yellow lacrosse ball as representing the Moon, the bright lamp as representing the Sun, and the doll as representing an observer on Earth. Likewise, non-correspondences at the entity level would include noting that the Earth is not actually orange like the basketball, that the lamp is much smaller than the real Sun, and that the stand holding the basketball has no correspondence to any entity in the real Earth System.

The second level of reasoning that users of this model would engage in involves considering either the configuration or arrangement of entities with respect to each other in the model as corresponding to similar configurations of entities in the Earth System, or the motion of entities with respect to other objects in the model as corresponding to similar motions of objects in the Earth System. For example, students may begin to reason that the motion of the yellow lacrosse ball around the basketball may correspond to the motion of the moon around the Earth. Non-correspondences of configuration or motion would also be recognized, including the fact that the motion of the moon in orbit around the Earth is considerably slower than the motion of the yellow ball in the model. Similarly, the basketball is not rotating in the model, whereas in the Earth System the Earth would be rotating concurrently to the moon orbiting around the planet.

The third and most sophisticated level of reasoning involved recognizing the phenomena as it emerges or develops in the model and identifying the cause or mechanism which drives that phenomena, and mapping that mechanism or cause such that it corresponds to the same mechanism or cause in the real Earth System. In the example, students would recognize that the doll on the basketball was observing the illumination of the yellow ball change as it orbited the basketball, resulting in 'phases' of the yellow ball at different times. This emergent phenomena of 'phases' corresponds to the phases of the moon that we observe on Earth, and the mechanism causing those phases in the model corresponds to the similar mechanism in the Earth System related to the orbit of the moon around the Earth with respect to the position of the Sun.

The dimensions of the construct include not only the vertical additive levels of mapping with increasing sophistication, but also the additional dimension of mapping both correspondences and non-correspondences at each level. As every representation is by definition some form of simplification or abstraction of actual real world phenomena, we believe fluency in reasoning around models includes both a conceptualization of a model's similarities and differences to the phenomena being represented. It is important for students to recognize not only the affordances but also the limitations of models, as the nature of the inherent approximations and assumptions of each model limits its range of validity and precision of predictive power (NRC, 2012). Thus in our construct, as well as throughout our assessments of students' reasoning, analogical mapping of both correspondences and non-correspondences played a prominent role.

Bootstrapping Between Modeling Practices and Analogical Reasoning

Given the conceptualized reciprocity between modeling practice and analogical reasoning around models, it then becomes important to consider the implications of this claim for describing and identifying observable characteristics of this relationship in students' science learning. We take up the notion of "bootstrapping" as a productive lens to consider the nature of this relationship. Bootstrapping is a frequent metaphor used in the literature to refer to the process of "using theory to constrain data and using data in turn to constrain, refine, and elaborate theory" (Koslowski, 1996, p.281). It builds from the uniquely human capacity for learning and using representative symbols and relations between them, and the ability to integrate across distinctly different representational systems (Carey, 2004). The metaphor is thus a way to help explain how a learner is able to achieve conceptual endpoints that far transcend where she is starting from, particularly through the creation of successively new and more powerful mental representations. This process of conceptual bootstrapping is not additive, in the sense that the development along any single dimension or representational system does not logically follow a successively cumulative linear fashion. Rather, progress within such a reciprocal relationship is marked by co-concurrent development across two or more systems, with the sophistication of intermediate steps in each progression exceeding what would be anticipated if addressed in isolation.

Bootstrapping in our case refers to the ways in which students recognize and make meaning of similarities and differences between the physical model as a representation and their understanding of the full scale Earth System, in order to generalize and abstract to broader science principles. This perspective also promotes the perspective of conceptual models as cognitive tools (Brown, Collins & Duguid, 1989). For example, the more a learner are able to recognize and use the "tool" (conceptual model) of convection to explain both real world phenomena and tangible representations, the better she is able to understand both what the concept of convection stands for in the abstract, as well as the nature of an increasing array of instances and phenomena where the concept of convection is an appropriate explanation. The iterative movement between partial insights gleaned through the consideration of the "representation-ness" of physical models and the particular analogical similarities and differences between models and real Earth phenomena results in the development of more sophisticated models that account for previously unrepresented structures or behaviors, and thus enhanced conceptual understanding (Nersessian & Chandrasekharan, 2009).

However, evidence of this bootstrapping between models and conceptual scientific understanding is still minimally described in the literature. Missing are robust accounts of what students look like as they are productively (and not so productively) engaged in this process of learning. Such characterizations are needed in order to inform instructional strategies aimed to support students' effective engagement with and use of models across phenomena, as well as the nature of assessment tasks to evaluate and inform modeling practice and robust conceptual understandings. Our work aims to address this need by exploring the following research question: What is the nature of the relationship between students' demonstrated conceptual understanding and the sophistication of their analogical reasoning around physical models of full-scale Earth System phenomena?

Methods

Setting and data sources

The two-year study examining the nature of students' analogical reasoning around Earth System models was conducted in partnership with three 8th and three 9th grade Earth Science teachers in schools outside of a large city in the Northeastern US, which reflected a range of demographics and achievement levels. In Year 1 of the study, teacher used models as part of their typical Earth Science instruction. In Year 2, they incorporated specific instructional strategies to support students' reasoning around models (see Rivet, et al. 2013).

We developed parallel assessment activities around three Earth Science topics: phases of the moon, the cause of the seasons, and differential sorting in depositional environments. Teachers addressed each of these topics at various times across the year in lessons spanning 1-4 class periods, utilizing their own selected array of models and other representations in each lesson. For our assessment activities, we featured a researcher-run 3D dynamic model of the Earth System process that we developed, set up in the front of the room for students to observe (e.g., see Figure 2). A pre/post written assessment consisting of 20-22 short answer and multiple-choice items was developed for each topic. Items were crafted to elicit students' understanding of either a correspondence or non-correspondence between the assessment activity model and the targeted aspect of the Earth System, at one or more levels of the analogical reasoning construct. Additionally, individual videotaped interviews with selected target students from each teacher were conducted after each posttest administration to further elicit more detailed explications of their reasoning and content understanding. These interviews involved asking students to elaborate on their understanding and reasoning around a selected group of 6-8 posttest items for each topic. During these interviews, students were provided with a miniature version of the model used for the written assessments and told that they could use the model at any time to help them explain or figure out an answer. Further information about the assessment instrument design, including sample questions, is described in detail in Rivet & Kastens (2012).

Data collection and analysis

The assessments activities were administered in a pre/post format to all of the sections of each of our partner teachers in both Year 1 and Year 2 of the study, for a total of 357 consenting participants. As we were interested in understanding the relationship of assessment items as reflecting the proposed construct rather than student gain, we examined both the pretest and posttest together in the same data set. Therefore, the total number of cases considered was 707, with 323 cases from year 1 and 384 cases from year 2. An expanded outcome space was used to map each item response made by the student to a particular level of the construct. A kappa calculation of .84 for moon, .86 for seasons, and .90 for deposition provided a strong sense of inter-rater reliability. Prior analysis (Rivet, et al., 2013) demonstrated that the three assessments were generally comparable at measuring student reasoning around the levels of the construct, providing validity for claims drawn by looking across assessments in the three different topic areas.

With parameters estimated using R software, the assessment data was analyzed using a Rasch modeling approach for polytomous data. This approach provides an estimate of student ability and test item difficulty, both of which can be approximated based on the overall performance of a given sample of students on an instrument (Wilson, 2005). A Cronbach's alpha of .81 was established for the multidimensional analysis across the three topics, and the expected *a posteriori* (EAP) was 0.84 for moon assessment items, 0.82 for seasons, and 0.80 for deposition. Ability estimates were calculated for each student on every test they completed to determine their proficiency score in relation to the difficulty of the items. The average ability estimate for moon posttests was 0.51, or about a level 2 non-correspondence, 0.25 for seasons (level 2 correspondence), and -0.35 for deposition (level 2 correspondence). For each posttest, the students' ability estimate was utilized to assign a level of analogical reasoning based on our construct. Levels were determined by taking the average ability estimate score from the two adjacent levels, which produced a threshold score. For example, the threshold score was calculated by averaging the mean score of level 1 correspondence (1c) and mean score of level 1 non-correspondence (1n) within a topic. This average score established the cut-off point for a student to receive either a level 1 correspondence or level 1 non-correspondence score.

Of the 357 students included in the above analyses, 29 were identified as target students for further examination. These target students had completed all six tests (except for one group of six students from year 1 that did not receive a seasons pretest) and had participated in at least two interviews from the three topics. The students' demographics are outlined in Table 1. In examining the ability estimates of the target students' posttests in comparison to the overall data set, these students appear to be representative of the larger student population included in this study.

Table 1: Target student demographics.

Target Student Demographics (n_{total} = 29 students, n_{year1} = 16 students, n_{year2} = 13 students)						
School	MS1 = 11	MS2 = 8	MS3 = 2	HS1 = 8		
Teacher	T1 = 8	T2 = 8	T3 = 5	T4 = 3	T5 = 2	T6 = 3
Level	Lower = 1		General = 20		Advanced = 8	
Gender	Female = 11		Male = 18			

The target student interviews were transcribed and analyzed along several dimensions, including the robustness of their articulated conceptual understanding of the causal mechanism driving each of the modeled Earth phenomena (moon phases, seasons, and deposition). Student responses in each interview were rated on a scale from weak to excellent. Weak understanding included descriptions of relative motions or configurations of entities in the Earth System, but no connections to causes or mechanisms of the emergent phenomena. A good understanding was rated when there was a single cause or preliminary mechanism given, whereas an excellent understanding indicated the influence of multiple coordinated factors on the resulting phenomena. The specific criteria for each level were tailored to the particular content focus of the interview. Each target student received a single rating score for each topic based on their responses across questions in the interview. We then compared target students' content scores from the interviews with their posttest analogical reasoning level ascertained from the written assessment for each topic. These ratings were categorized to identify clusters of students that shared similar profiles of content understanding and analogical mapping across content areas.

Findings

Overall, there were a few observed trends across the target student group focused on in this analysis. First, based on the analogical mapping proficiency scores calculated by the assessments, none of these students were found to reason only at the lowest measureable level, that of only being able to map correspondences between the model and the Earth System at Level 1: Entities and Attributes. Everyone in this group was also able to at minimum reason around both correspondences and non-correspondences at this level for every topic. The Moon assessment demonstrated the greatest range of proficiencies along the construct, with four students demonstrating proficiency at only Level 1 correspondences and non-correspondences, and eleven students demonstrating proficiency at mapping non-correspondences at Level 3: Causation and Mechanism, the most sophisticated reasoning measured on the written assessment. The other two assessments, focused on seasons and deposition, were more challenging for students. None of the students in this group were found to consistently demonstrate proficiency at Level 3 for either of these two topics. That is not to say that they did not occasionally respond accurately to assessment items targeted to these levels. Rather, with respect to the whole student population who completed these assessments, the target students were not the most proficient at sophisticated Level 3 mapping in the seasons and deposition assessment activities.

We identified four clusters, or profiles, of the relationship between the sophistication of students' analogical reasoning around science models and their content understanding as articulated during the interviews. Each of these profiles is described in detail below.

Profile 1: "Level 1" Mapping with Weak Content

The first pattern that emerged were a relatively small group of target students (3 of the 29, or 10%) whose average proficiency rating on each of the three assessments indicated overall ability to articulate correspondences and non-correspondences only at the "Level 1: entity and attribute" stage of the construct map. These students also demonstrated limited understanding of the science concepts under study consistently across the interviews. The combination of relatively weak content understandings and limited proficiency at identifying and articulating the relationship between the model and the Earth System phenomena is to be expected as students are just beginning to develop fluency with both the science concepts and modeling practice. We would consider such students to be near the beginning of a progression that describes this kind of learning. What is also of note in these groups of students is the consistency of their typical responses across topics, both in terms of mapping between the model and the Earth System and the sophistication of their descriptions of the science phenomena itself. Unlike other profiles identified, described in more detail below, students' performance in both the three posttest assessment tasks and the two or three interviews they participated in was consistently near the lower end of both the content and the analogical mapping scale.

One student who fit this profile, Stephanie, demonstrated proficiency at mapping between the model and real Earth System only at a Level 1 during the written assessment, and no higher than a Level 2 during the interview. For example, during the Moon Phase interview she said that the model was like the phases of the moon because "as the moon revolves around, it should show the changes." Epistemologically, such comments reflected a common perception amongst students in this profile that the model "shows" the science concept that it is intended to represent, without indicating clearly what that science concept was or how the model represented that idea. Stephanie did not make any statements to suggest why we see phases beyond explaining that it relates to the revolution of the moon around earth. She showed similar limitations for the topic of seasons. Her poor content knowledge and limited mapping ability did not deter Stephanie from using the physical model to communicate, as she was observed using the physical model to illustrate both accurate and inaccurate conceptions about the entities in the real Earth System and the relative motions of these entities.

Profile 2: Medium Proficiency for Content Understanding and Analogical Mapping

A second profile that emerged from the target student analysis was that almost a quarter of these students, 24%, were generally in the middle in terms of both sophistication of mapping the correspondences and non-correspondences between the model and the real Earth System, and the robustness of their content understanding. This pattern also reflects the ability level achieved by the majority of students in the larger study. As students are moving through the Earth Science curriculum in middle and high school, there is evidence that they have a better understanding of both the ways that scientific models represent, and can be used to understand, specific Earth Systems phenomena than they did in the lower grades. Specifically, they generally characterize the phenomena under study in terms of spatial relationships between entities, and are able to accurately identify and describe Level 2: Configuration and Motion correspondences between the model and the phenomena. However, these students still struggle with characterizing the non-correspondences of motion or configuration in the model, and are limited in their explanations of the mechanism behind emergent phenomena across topics. We consider this an appropriate "stepping stone" understanding (Wiser, Smith & Doubler, 2012) as students develop increased fluency with both modeling and Earth System understandings.

One student who fit this profile, Robert, demonstrated consistent Level 2 mapping and good, but not excellent content knowledge. During the seasons interview, Robert attributed the changing seasons to the tilt of the Earth's axis in different positions in its revolution around the sun, but did not explain more sophisticated aspects such as the effect that the changing angle of light has on the amount of solar energy received at a point on Earth. Robert was able to explain his mapping between the real Earth's revolution and tilt and that of the model, but illustrated tilt inconsistently using the physical model. During the deposition interview, Robert explained how the attributes of sediment might influence settling rates but conflated density and size. Robert never used the physical model for deposition, in contrast to the seasons model which he used frequently.

Profile 3: Robust Content and Mapping Fluency

A rather surprising result of our analysis was the finding that over 40% of the target students (12 of the 29 interviewed) demonstrated robust content understanding of the science concepts across the three topics, and relatively high sophistication in terms of their ability to map correspondences between the model and the real Earth System in the assessment activities. As described earlier, the assessments for the seasons and deposition topics were limited in the extent to which evidence of Level 3: Causation and Mechanism correspondences, and particularly non-correspondences, was measured. There was also observed a relative range of both mapping proficiency and robustness of content explanations in this group. However, when looking across the three topics on their posttest and post-instruction interview responses, it was evident that a majority of our target students were able to demonstrate both modeling and conceptual understanding with an appropriately expected level of sophistication given the population.

One student, Emily, demonstrated both strong knowledge of each topic and a strong ability to explain how the model illustrated the real system at various levels. Emily did not use the physical model provided during the interviews frequently; however, she did use it to communicate sophisticated ideas and demonstrate Level 3 mapping.

Profile 4: Consistency of Analogical Mapping Ability with Variable Content Understanding Across Topics

Seven students in our target group (24%) did not fit into any of the three prior categories. Four of these students (14% of the total group) demonstrated an interesting pattern in that the sophistication of their analogic mapping between the model and the Earth System demonstrated through the written assessment was consistent across topics, yet during the interview they displayed vastly different levels of conceptual understandings of the science phenomena under study. Three of these students were proficient at the Level 2 mapping, however demonstrated excellent understanding of either moon or seasons phenomena but poor understanding of deposition. One of these students showed a similar trend in terms of content, but mapped at the lowest level across the written assessments.

One student, Sarah, demonstrated poor mapping consistently despite variations in the robustness of her content knowledge across the topics. Sarah demonstrated Level 1 mapping along with poor knowledge of deposition. For Moon Phases, Sarah was able to explain verbally, and with the aid of a physical model, what the causes are for the phases of the moon. However, she was not able to map between the model and real Earth for more specific questions relating to particular configurations of the model and how these mapped to real phases. For questions such as these, Sarah struggled to explain her reasoning.

Outlier Examples

The three students who did not fit into any of the above categories showed unique patterns of mapping and content understanding across the three topics. One student consistently mapped at the mid to upper range of ability levels for a Level 2, but demonstrated poor content understanding across the board. A second student demonstrated consistently excellent conceptual understanding across topics, but performed at the lowest level of analogical mapping consistently across the assessments. The third student in the group showed a pair-wise trend: excellent content understanding of moon and high sophistication of mapping; a level 2 mapping ability on seasons (no interview); and a lower conceptual understanding of deposition with proficiency of analogical mapping on this assessment at a Level 1. To our surprise, this was the only student out of the 29 target students interviewed who showed this trend.

One example of a student in this group is Michael, who showed difficulty applying the knowledge he had of the causes of the seasons to a model, both on the written assessment and during the interview. This student never used the provided physical model of seasons during his explanations, and when describing how the model was like the seasons, he gave a response that was only at a Level 2, stating "the earth goes around the sun and it is rotating [like] the ball orbiting around the [basketball], the seasons change in different areas." However, throughout the interview Michael showed that he understood more sophisticated aspects of the causes of the seasons including the influence of the tilt of Earth on the angle of sunlight, which he explained affected the amount of sunlight an area received.

Discussion: Bootstrapping Towards Conceptual Understandings

The analysis of target student profiles illustrates some significant characteristics that demarcate the evolving reciprocal relationship between understanding Earth System models *as* scientific representations, and understanding the science concepts *of* the represented entities, configurations, motions, and emergent phenomena in the real Earth System. First, it is notable that none of the target students included in the analysis were capable of mapping at any significant level without robust content understanding as well. Our findings demonstrate that it is not the case that analogical mapping is a generalized and transferrable context-independent skill. If it were, it is possible that we would have observed students engaged in sophisticated analogical reasoning while also demonstrating weak conceptual understanding. Rather, our data support the claim that analogical reasoning only exists *in the context of the phenomena and concepts that are being reasoned about*. This indicates that the power of bootstrapping between representations and phenomena to develop robust conceptual understandings must begin with at least some limited understanding of the phenomena under study to initiate the bootstrapping process.

A second important trend observed in this analysis is that the sophistication of analogical mapping around models and the robustness of students' conceptual understanding co-vary across the profiles. Overall 22 of the 29 target students (over 75%) were consistent in terms of falling into either a "low mapping/low content", "medium/medium", or "high/high" profile. This finding in particular supports the claim that increased sophistication in modeling practice and increased sophistication of conceptual scientific understanding do indeed co-vary, and exist together in a reciprocal developmental relationship. This lends support to the power of considering bootstrapping as a productive mechanism to describe the relationship between developing modeling and conceptual understandings.

This research points to both specific recommendations for instruction and curriculum design, and areas in need of further research. By recognizing the nature of the reciprocal relationship between content understanding and modeling practice, this work encourages curriculum and instruction to avoid teaching science concepts and modeling practices as separate knowledge domains. Additionally, the profiles themselves illuminate the nature of both students' engagement and use of models and the sophistication of their conceptual reasoning at each of these levels. Such information can be used by teachers to help assess and support student learning within and across content areas. Next steps in this work include further analysis of science classroom environments engaged with robust model use, with the aim of understanding the various ways that instruction can influence the relationship between students' modeling practices and concurrent development of science content understanding.

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