INVESTIGATING HOW LEARNERS DEVELOP MODELS WITHIN SYNTHESIS MODELING

by

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(Under the Direction of Daniel K. Capps)

ABSTRACT

Central to successful modeling practice is knowing what models are; however, there is a vacancy of ideas in the literature about what to teach about the nature of models. One idea suggests teaching that models are abstractions. Synthesis modeling is an approach to learning that models are abstractions that draws on the theory of analogical learning. In synthesis modeling, learners are asked to develop a model by abstracting structure from two or more sources that share an underlying structure, but differ on the surface level. In this qualitative research, I aimed to document what it means to develop abstract models within synthesis for students. This study documented that (a) student models were categorized based on their degree of abstraction from veridical to abstract, and (b) students experienced synthesis through four manners: *Working with surface similarities, abstracting ideas, abstracting structures,* and *checking on model-source fit*.

INDEX WORDS: Models, Abstraction, Abstract Models, Synthesis Modeling, Analogical Learning

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DEDICATION

To my mother, Mrs. Zennure Karaşahinoğlu

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CHAPTER 1

INTRODUCTION

In this chapter, I present the research problem, the focus of my study, a brief review of the literature related to my study's focus, the theory guiding this study, and the valuable insights that this research contributes to the modeling literature.

Statement of the Problem

The practice of using, building, and revising scientific models (Schwarz et al., 2009), is a fundamental way scientists develop and test their ideas about natural phenomena. In the science classroom, using models is equally important as it serves as a key way for learners to develop and test their ideas about the phenomena that they encounter (Duit, 1991; Gilbert & Justi, 2016). In addition to supporting learners in developing knowledge about science, modeling is an important scientific practice to be learned (National Research Council-NRC, 2012; Schwarz et al., 2009; Treagust, Chittleborough, & Mamiala, 2002). Central to successful modeling is knowing and understanding what models are. Unfortunately, what students should learn about models is not well defined in the modeling literature (Capps, Shemwell, Lindsey, Gagnon, & Owen, 2016). This lack of definition is evident in how the literature tends to address a frequent misunderstanding about models, namely that students think that models should be copies of their referents (Grosslight, Unger, Jay, & Smith, 1991). Prevailing approaches to combating this misunderstanding include explicit instruction that models are not copies (Grosslight et al., 1991) or having students model phenomena that cannot be directly observed (Saari &Viiri, 2003).

Although such instruction has the potential to address the “model as a copy” misunderstanding, it does little to improve students’ understanding of what models are.

An alternative to teaching what models are not is teaching what they are. Models are abstractions or ideas that are pulled away from the phenomena they represent. Although it is acknowledged that models are abstract (e.g., Gilbert & Justi, 2016; Gobert & Buckley, 2000; Schwarz et al., 2009; Treagust et al., 2002), this idea had not been put to use instructionally until recently when Capps and his colleagues (2016) introduced an approach to modeling called synthesis modeling and studied its effect on student learning. Synthesis modeling is an approach to modeling where learners are asked to work from two or more instances of phenomena and develop a model by abstracting ideas and structures from those instances that share an underlying structure, but differ on the surface level. The results from Capps and colleagues’ (2016) study showed that students could learn that models are abstract, but the authors did not document how this learning unfolded.

Building on the research discussed above, I designed an investigation that focused on documenting the ways students engage in synthesis modeling. The purpose of the present investigation was to document the degree of abstraction involved in model construction and generate insights into the ways learners develop abstract models through synthesis while they work on the multiple representations of biogeochemical cycles. The investigation was conducted with a group of upper-level undergraduate students and graduate students majoring in ecology-related fields. The data used to document the ways students experienced synthesis modeling came from five interviews in which pairs of students worked together to answer a question posed by me. The interview task was to develop a model that would be broadly applicable to three different biogeochemical cycles. By drawing from the interviews, I developed five narratives to elucidate the range of ways that emerged as learners attempted to develop abstract models. With these narratives, I aimed to illustrate what it means to develop an abstract model within synthesis for the students.

Literature Review

As a homonym, the term *model* has many meanings (Mahr, 2011). Although there are a variety of ways to think about models, in science education they have been broadly conceived of in terms of mental models or conceptual models (Gilbert & Ireton, 2003). Mental models are incomplete and unstable representations that reflect learners' beliefs on a system or phenomenon (Norman, 1983). A mental model is a student's personal representation of a science idea (Tytler & Prain, 2010). On the other hand, conceptual models are thought of as simplified representations that are constructed with scientifically proven information pieces to explain a situation or phenomenon (Nersessian, 1992). My focus is on the ways learners develop abstract conceptual models. I discuss why my work focuses on one particular form of conceptual models in the following paragraphs. With this in mind, one may ask why humans use and develop models as a way of making sense of natural phenomena or systems.

Many scholars have promoted using and developing models in science classrooms (Gilbert, Boutler, & Rutherford, 2000; Gobert & Buckley, 2000; Nersessian, 2008; Penner, Lehrer, & Schauble, 1998; Schwarz et al., 2009) because models help students learn about scientific phenomena through visualization, simplification, manipulation, transformation, and mathematization (NRC, 2012). Models encourage students to actively participate in their own learning (Penner et al., 1998; Schwarz et al., 2009) and externalize their thinking (Shen & Confrey, 2007). Modeling can also create an authentic environment in which students develop and apply various scientific practices similar to those engaged in by scientists (Nersessian, 2008, 2009; Penner et al., 1998).

It is evident from numerous studies that a persistent problem impeding modeling instruction is that learners at all ages tend to think that models are copies of reality (Dogan & Abd-El-Khalick, 2008; Grosslight et al. 1991; Harrison & Treagust, 1996; Ingham & Gilbert, 1991; Lin & Chen, 2002; Ryan & Aikenhead, 1992; Tasquier, Levrini, & Dillon, 2016; Van Driel & Verloop, 1999). Compounding this problem is the lack of research on precisely defined characteristics of models that would enable learners to recognize that models are not literal interpretations.

To address the copy problem, researchers have focused on teaching learners what models are by defining them in the negative sense. This can be traced in Grosslight and colleagues' (1991) study uncovering the literal interpretation problem in middle school and high school students. Even though the researchers suggested the use of explicit instruction to demonstrate that models were not literal interpretations to address the copy problem, their study did not positively define the characteristics of models so that learners could clearly understand that models were not literal interpretations. They specified only that *models* were defined as "ideas about reality" (p. 816). However, they did not elaborate on what to teach students about models.

Similarly, addressing the copy problem, Harrison and Treagust (2000) provided students with multiple models of the same scientific phenomenon. The multiple models were not copies of the target (the domain that the students will be learning more about) because each model displayed different target features. This study concluded that teachers should discuss model meaning with students. This study, however, failed to propose a guide for teachers to convey the idea that models are nonliteral interpretations.

Later research on the same issue focused on objects that had no realistic referent (Saari & Viiri, 2003). In this research, students were provided with phenomena that had no realistic referent; thus, the opportunity for literal interpretation was removed during model development. In their study modeling was practiced in the process of learning about the properties of matter and about the changes in the states of matter. The authors argued that to learn that models are not literal interpretations, it is necessary to use different kinds of models simultaneously. This practice helped students to understand that no model is complete or absolutely right. This approach eliminated the opportunity for literal interpretation because students developed models that were clearly not literal interpretations and that had a definite source to copy. However, the study did not provide any explicit instruction to help students learn the essential characteristics that made their models nonliteral interpretations.

In another study addressing the copy problem, Lin and Chen (2002) tried to document the benefits of teaching chemistry through history. The historical materials described how scientists developed their understanding of atoms, molecules, and atomic weight tables. For example, students were asked to discuss why carbon was chosen as the reference standard of atomic weight. With the historical description of chemical concepts, students were able to learn that any element can be used as a reference. The researchers reasoned that if students could see that all of the models differed from one another, they would understand that none of them could be a literal interpretation of the particular phenomenon being investigated.

In the broader modeling literature, there are limited instances of defining what learners should know about models in the positive sense. Although they described models as incomplete and imperfect representations, Justi and Gilbert (2003) did not describe qualities that make a model incomplete and imperfect. Similarly, asking students questions related to the nature of models, Schwarz and White (2005) concluded that the recognition that models were accurate but not exact copies of their referents is required for a better understanding of models. It can be seen that the defining characteristic of what a model is was expressed in the negative sense (i.e., not exact copies). Another investigation in which researchers focused on teachers' understanding of modeling showed that knowing that models represented some aspects of phenomena and not others was the highest-level understanding about models (Van Driel & Verloop, 1999). This research showed that teachers could recognize some of the functions and characteristics of models; however, they did not mention what qualities of models provide these functions and characteristics.

As I mentioned in the previous paragraph, there are limited instances of defining an important characteristic of models to teach. With this in mind, as it is expected, little is known about guidance on conveying the idea that being nonliteral is one key characteristic of models. As an example of instructional guidance, Krajcik and Merritt's (2012) practitioner-oriented introduction to modeling practices emphasized the importance of knowing that learners tend to be too literal when it comes to thinking about models. Yet, they provided no strategy that would help teachers can promote a more appropriate (i.e., nonliteral) conception. Similarly, a well-cited work by Schwarz and colleagues (2009) argued that literal interpretation is the lowest level of understanding about the nature of models. However, the researchers did not identify what to teach students about models to help them understand that models are nonliteral interpretations. A couple of sources have alluded to positively-defined conceptions of models, but remain vague on the key characteristics of models. For example, the authors of *Taking Science to School* and *Ready, Set, Science!* defined *models* as "deliberate simplifications" (Michaels, Shouse, & Schweingruber, 2008, p. 110; NRC, 2007, p. 152). Going beyond this definition, these studies noticeably stated that error and lack of precision are important components of models. This represented a meaningful attempt to address the importance of determining the main characteristics of models so that educators can be aware of what to teach about models.

Recently, Capps and colleagues (2016) proposed abstraction, or the idea that models are removed or pulled away an idea from a source, as an important characteristic of models that students should learn. The researchers argued that abstraction is informative as it conveys more information about what models are than prominent ideas put forth in the teaching literature such as thinking of models as simplifications. As I mentioned earlier in the problem statement, defining models as abstract is not a novel idea; however, the value of teaching that models are abstractions as an important characteristic of models has been less recognized in the literature (Capps et al., 2016).

Investigating the value of focusing on teaching that abstraction is an essential characteristic of models, Capps and colleagues (2016) showed that students were able to achieve measurable gains in learning that models are abstractions, and not copies, when the modeling processes were guided around *synthesis*. In synthesis, learners are provided two or more examples of a source phenomenon, and they develop a model that would broadly represent all of the examples. Figure 1 illustrates the process of synthesis modeling.

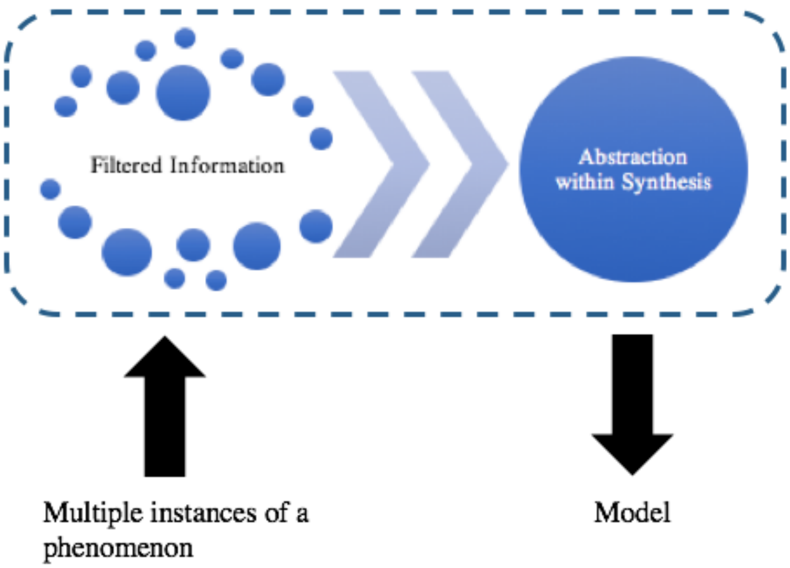


Figure 1. The process of synthesis modeling

Figure 1 illustrates that learners need to compare multiple examples that explain the same phenomenon so that they can find a common structure across them. In synthesis modeling, the researchers refer to the overall process as structure abstraction by emphasizing the importance of transformations by which a model relates to the phenomenon it represents.

Even if the way of explaining how synthesis works for learning that models are abstractions is well-posed, what it means to develop an abstract model within synthesis—inside the dashed line of Figure 1—is typically invisible to researchers, educators, and learners. By taking place inside the dashed line, this study intended to work towards understanding of what it means to develop an abstract model through synthesis. It is important to demonstrate the ways in which learners work through synthesis modeling in order to be able to start a conversation about the ideas and approaches to learning about models that can be used to organize instruction in classrooms. An instructional framework, for example, for developing abstract models helps educators with understanding of what developing an abstract model looks like for learners.

Theoretical Framework

Here, I describe how the potential for learning about abstraction described earlier is informed by the literature on analogical learning. I drew on guidance from the analogical learning literature which explains how people can learn abstract ideas by uncovering the underlying structure from a set of scenarios (Catrambone & Holyoak, 1989; Gick & Holyoak, 1980; Loewenstein, 2017; Lowenstein, Thompson, & Gentner, 1999).

The ability to perceive relational structure across multiple contexts, analogical ability, is the core of human cognition (Gentner & Smith, 2013; Hofstadter, 2001). Thus, analogical thinking has an essential place in people's everyday learning and sense making (Holyoak & Thagard, 1997). An analogy is a comparison that facilitates the mapping of systematic relations (Gentner, 1983). A good analogy uncovers common structures and helps learners draw further inferences (Gentner & Smith, 2013). Providing analogical bridges between unfamiliar ideas and knowledge that students already possess is an effective way to help students understand difficult scientific phenomena (Treagust, Harrison, & Venville 1998). Analogy can improve knowledge in three main ways: (a) abstraction—extraction of the common relational structure through similarities between multiple exemplars, (b) difference detection (contrast)—facilitating learning by contrast, alignable differences that are connected to the relational structure and occupy the same role in that structure, and (c) re-representation—substituting a more abstract relation for the specific relations in multiple analogs to improve the relational match, which occurs in perceptual as well as conceptual analogies (Gentner & Smith, 2013).

Analogical learning theory originates in studies by Holyoak and colleagues, who showed how learners could formulate abstractions by seeking the common structure within scenarios that were similar in essence, but different on the surface level (Catrambone & Holyoak, 1989; Gick

& Holyoak, 1980). In Gick and Holyoak's (1980) study, the subjects were given the two stories and told to find similarities between the two stories. In the first scenario, a general wants to find a way to capture a fortress located in the center of a country without destroying neighboring villages and detonating mines on the roads. The correct solution is to divide the army into several small groups and position those small groups at the heads of different roads so that small groups simultaneously converge on the fortress to capture it. The second scenario is about a doctor who wants to destroy a tumor in the interior of a patient's body without damaging healthy tissues around the tumor. The appropriate solution for this problem is to divide the high-intensity rays into groups of low-intensity rays and applying the rays at multiple locations around the tumor so that the rays simultaneously converged on the tumor to destroy it.

These scenarios create good external representations that facilitate abstraction by making the ideas in the stories perceptually salient. Working on the two scenarios, the participants who abstracted ideas from multiple scenarios were more apt to transfer this learning to novel situations than others who did not. The researchers concluded that analogical transfer depended on three steps: noticing (seeing the analogical connections between the source and the target problem), mapping (capturing corresponding parts of the problems), and applying (generating a parallel solution to the target problem) (Gick & Holyoak, 1980).

In light of the theory of analogical learning, Gentner (1983) argued that developing an analogy is how learners use information from one source (already known) to help resolve an unknown situation. Analogical thinking is the equivalence of perceiving common relations between a source and a target (Gentner, 1983). However, there is an issue that has been described in many cases in which learners do not completely understand a scientific analogy because human cognition, the process by which understanding is developed in learners' mind, is very sensitive to surface features of any descriptions/representations/explanations (Brown & Clement, 1987; Stavy & Tirosh, 1993). Similarly, when it comes to learning about scientific concepts, students usually focus on the surface features of multiple instances of a phenomenon instead of seeking the deep structures that define the phenomenon across instances (Goldstone & Son, 2005).

In science, students need to learn the deep structure of scientific phenomena (Schwartz, Chase, Oppezzo, & Chin, 2011). One way of facilitating deep learning is analogy making because it is all about figuring out resemblances between things that are different (Mitchell, 1993). In comparison, the process of identifying similarities and differences between two or more cases is helpful for capturing abstract structures and uncovering deep relational similarities between cases (Gentner, 1983; Gick & Holyoak, 1983; Loewenstein, Thompson, & Gentner, 2003). Applied to education, this approach has promoted learning and transfer in mathematics (Rittle- Johnson & Star, 2009) and science (Kuo & Wieman, 2015). Gick and Holyoak (1980) showed that participants who abstracted select ideas from multiple scenarios were more apt to transfer them to novel situations than participants who learned the scenarios without support for abstracting.

Gick and Holyoak (1983) also showed that if learners do not make sense of the deep structure of the phenomenon, they are not able to exhibit any transfer to problem isomorphs, multiple instances that explain the same scientific idea, with different surface features. The decision of what features should map to the target domain requires a causal analysis (Anderson & Thompson, 1989). Analogical thought should help learners abstract and map correspondences between sources and targets by using the select ideas.

Following Gentner's (2010) and Nersessian's (2008) work, Capps and colleagues (2016) called these select ideas from a source "the structure of the phenomenon" within synthesis. The researchers defined *models* as structures that are abstractions of the structure of the phenomenon they represent. They argued that abstraction represents a two-way relationship between a source phenomenon and the model of that phenomenon (see Figure 2).

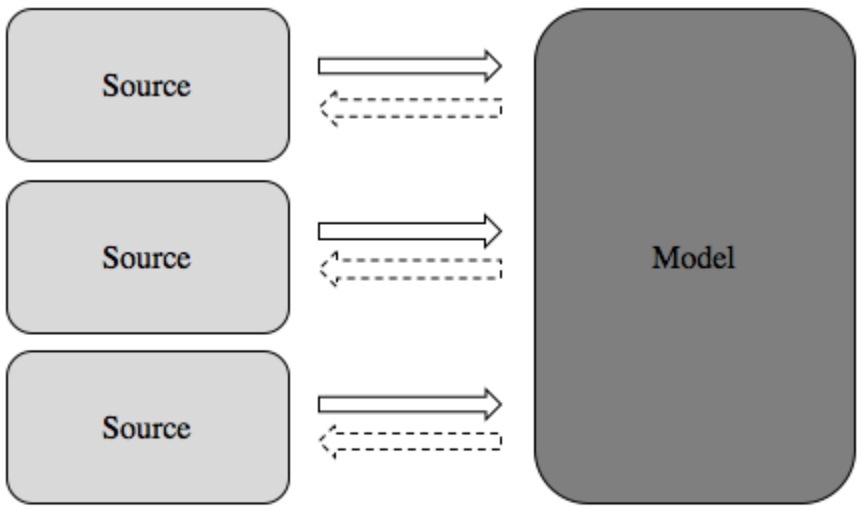


Figure 2. The relationship between sources and models through abstraction

The solid arrow illustrates the direction of the abstraction by going from the source to the model when developing a model. The dashed arrow shows the use of the model to represent a phenomenon. In their study, Capps and colleagues (2016), described these two directions in two different ways: (a) reserving abstraction to indicate the path starting from source to model and (b) using the term *transfer* to emphasize that models can be used to represent a phenomenon. According to the authors, *transferability* indicates that the model corresponds to its referent(s) under transformation as a cognate of abstraction.

Synthesis modeling is an application of the theory of analogical learning, which explains how people can learn abstract ideas by seeking the underlying structure from a set of scenarios that reflect them (Gentner 2010; Gick & Holyoak, 1980; Loewenstein, 2017). Levering analogical learning theory my interest is in how learners' understanding of the shared deep similarity between superficially dissimilar, but abstractly related examples of a phenomenon, in this case biogeochemical cycles. Because my focus, abstraction through synthesis modeling, requires comparing the three scenarios and coming up with a structural alignment, learners need to extract a principle common to the three exemplars and then transfer that principle to an emergent model. Connecting me to existing knowledge, the theory of analogical learning and its assumptions are relevant to the research problem that I investigated. This theory allows me to intellectually interpret various aspects of the phenomenon (i.e., the meaning, nature or challenges related to the phenomenon) that observed.

Research Questions

The main goal of the study focused on generating insights into the ways students developed models within synthesis modeling. Specifically, I asked the following questions:

1. How do students' models differ from one another with regard to the degree of abstraction?
2. What does it look like for students to develop an abstract model through synthesis modeling?

Key Definitions in This Study

Here, I provide operational definitions for important terms used in this study. All the definitions were drawn from the analogical learning literature. These definitions helped me describe the ways the participants worked through synthesis modeling.

Surface similarity. Gentner (1989) argued that understanding different kinds of similarity is vital to learning scientific ideas by analogy and similarity. According to her, *surface similarity* involves shared object attributes (i.e., simple descriptions of objects) rather than relational structures. Vosniadou and Ortony (1989) used the term *salient similarity*, which refers to readily accessible features of scientific concepts. Combining these two approaches, *surface similarity* in this study refers to easily accessible features shared by at least two of the different-looking sources, in this case the carbon, water, and phosphorus cycles. In the context of synthesis modeling surface level similarities are not useful as they cannot facilitate capturing a structure common to multiple sources at a deeper level. In other words, surface level similarities do not help the process of synthesis express the idea of finding key features in a combination of sources that might not be readily accessible in any one source material alone.

Abstraction of ideas. Abstraction of ideas refers to ideas that are extracted, or pulled away, from multiple sources to represent common patterns or information among the sources. These ideas resemble their referents (i.e., their sources) but they are not identical to them. Focusing on the effects of different types of similarity between source and target problems in analogical learning, Chen (1996) argued that operational ideas and features shared by the source materials could be defined as procedural similarity that facilitates the process of applying a learned solution to a target. In light of the procedural similarity concept, *abstraction of ideas* refers to the essential and relevant features (i.e., operational definitions) shared by all the sources, in this study the essential features of a biogeochemical cycle. For example, the carbon cycle depicts fossil fuels as carbon reservoirs while the largest reservoir of phosphorus is in sedimentary rocks. Calling reservoirs "holding areas" is an example of abstraction of ideas. These ideas are pulled away from the specific instances in which they are presented.

Abstraction of Structures. Based on the definition of *structural similarity* (Chen & Daehler, 1992; Gentner, 1989; Holland, Holyoak, Nisbett, & Thagard, 1986), *abstraction of structures* refers to the select information that depicts important relations among the sources that compose a phenomenon under transformation rather than direct translation. Capps and colleagues (2016) called this information *the structure of the phenomenon*. The structure which is called a model can be any form of organization. In this study, *the structure of the biogeochemical cycles* refers to the ways of substances moving back and forth between living and nonliving environments. This is the larger idea that composes any biogeochemical cycles.

Source Materials. A source material refers to the scientific concept area that describes a natural phenomenon in a certain way. In this study, I included three different sources from which students were to abstract. These were diagrams of the carbon, phosphorus, and water cycles. The diagrams described the movements of substances (carbon, phosphorus, and water) on the entire globe. The students' task was to abstract the essential features from the cycle diagrams to develop a model that would be applicable to all of the three cycles. Sources, instances, representations, cycles, and diagrams are used interchangeably to refer the materials that were given to the students in this study.

CHAPTER 2

METHODS

Here, I describe the rationale for the application of specific procedures and techniques used to identify, select, and analyze information applied to understanding the research problem. First, I provide an overview of the method that I employed in this study. I then provide a detailed description of the study design, participants, pilot study, data collection, and analysis procedures.

Given the nature of the research questions I used a qualitative approach. I selected this approach as it aligned with my purpose of focusing on the processes rather than on the product or outcomes (Merriam, 2002). The most important reason for choosing to do qualitative research is to make discoveries for the development of scientific knowledge by going beyond the known, seeing the meaning of the world from participants' perspectives, and uncovering patterns and themes (Corbin & Strauss, 2008; Patton, 2002). With this approach, I aimed to make thick descriptions of the ways in which learners followed through synthesis modeling by identifying the leading factors and reasons for any consequences and patterns noted.

Study Design

This study was organized around interviews conducted with university students. The main purpose of interviewing is to figure out what is in and on someone else's mind (Patton, 2002). The interviews in this study were unstructured, problem-based, and paired—two participants worked together on an interview task. The purpose of the interviews in this study was to explore what it means to develop an abstract model within synthesis from participants' perspectives and uncover possible patterns incorporating their experience.

I conducted the interview with students who had recently taken an upper-level ecology course. I chose these students because the topic of the interview task was designed around a course, ecosystem ecology, which was taken by all the students. A major emphasis of the course was on learning about biogeochemical cycles. Biogeochemical cycles are the circular paths of the chemical materials that pass back and forth between living and nonliving things (Odum, 1975).

In the beginning of the interviews, all the participants were told that they would be completing a modeling task. The participants were directed to study images of three different biogeochemical cycles (the phosphorus, carbon, and water cycles). Each cycle showed the major reservoirs and processes that the materials take through the ecosystem. I asked five pairs of students to think-aloud as they were developing a general model that could apply to all three cycles.

Prominently advocated by Ericsson and Simon (1993), the think-aloud method was originally developed to investigate psychological phenomena (Leighton, 2017). Duncker (1945) defined the think-aloud approach as “capturing” thought processes. Think-aloud interviews encourage subjects to articulate their thoughts as they are working on specific scenarios, concepts or a series of tasks (Leighton, 2017). Speaking allows subjects’ activity to become verbal so that the whole process can be recorded or “captured” (Duncker, 1945). During think-aloud interviews participants must think out loud in an audible way to allow recording via audio and/or video (Leighton, 2017).

There are several reasons for employing think-aloud methods in this study. The reasons are as follows:

- When engaging with a scientifically oriented question, students communicate their explanations.
- Students give feedback to each other/correct each other (idea exchanges between students).
- Dialogue helps students uncover ideas.
- The social aspect of modeling focuses on students' construction and negotiation of expressed and consensus models (Gilbert, Boutler, & Rutherford, 2000).

Another important aspect of the interviews was that the participants were interviewed in pairs. Arksey and Knight (1999) called paired interviews joint interviews in which one interviewer speaks with two interviewees simultaneously to gain both perspectives on the same phenomenon. They advocated this approach for several reasons:

- It creates an atmosphere of confidence with two interviewees;
- it compensates for an individual's gaps and memory lapses;
- it facilitates the exploration of consensus views; and
- it allows the interviewees to produce more reliable ideas and inferences.

In paired interviews, distinguishing between two participants in the audio recordings is easy; therefore, the typed transcripts provide a complete and accurate representation of how ideas developed (Highet, 2003). In this study, paired interviews offered many other practical advantages. The advantages were as follows.

- The social context of paired interviews led the interviewees to engage fully in conversation.

- The participants relaxed and became more enthusiastic about participating because they could work with someone with whom they were familiar or whose academic background was similar.
- Working with a partner required the students to verbalize their ideas and allowed the students to build on one another's ideas.
- Paired interviewing facilitated access to interactions between participants.
- One participant could clarify a point being made by the other.

Feasibility Study

Prior to the study, I piloted the interview task with six colleagues from my research group to determine how participants might interpret images of two different biogeochemical cycles—Carbon (C) and Phosphorus (P)—and to establish whether or not the images provided the proper amount of information to complete the task. Pilot studies are important in that they highlight the different elements of the observation and interview techniques and clarify whether or not those techniques are appropriate or problematic (Shkedi, 2005). The subjects were asked for feedback to identify ambiguities related to the cycles. Conducting the pilot study provided helpful information: It gave advance warning about whether or not the interview protocol was realistic and workable, and it allowed the researcher to see if proposed interview materials, in this case the cycle diagrams, were inappropriate or too complicated. In addition to this, the pilot study provided an opportunity to collect preliminary data.

The pilot phase demonstrated that images of cycles were similar in terms of the type of cycling materials, which are classified as elements (C and P), and the arrows that show the flow of materials. Because the participants were provided with the two cycles, they tended to make a copy of the diagrams. Moreover, participants asked for brief explanations about the cycle images to figure out what was going on in each cycle. The participants realized that they were more familiar with the phosphorus cycle than the carbon cycle.

After the pilot study, I added an image of the water cycle as the third cycle. With this addition, the interview materials included the carbon cycle (gas and mobile), phosphorus (solid and less mobile), and the water cycle (liquid and relatively mobile). I made this change to avoid any problems with copying because when learners encountered multiple scenarios explaining a similar scientific idea, they had to transfer the essential ideas to their models instead of copying the source materials. The second change after the pilot involved adding a caption to the cycle images to briefly explain each cycle.

Participants

Using a convenience sampling approach, I recruited five pairs of students (undergraduate and graduate) to participate in the study. Participants came from the same university in the southeastern U.S. and had similar disciplinary backgrounds. All students were recruited from the same ecosystems ecology course. The participants voluntarily took part in the interviews. Participants received a $10 gift certificate to a local coffee shop for their willingness to participate in the study.

Table 1 displays the participants' pseudonyms, gender, class standing, and department. I assumed that the students were familiar with basic ecological concepts such as biogeochemical cycling and scientific practices, like modeling, given their advanced standing in their majors and the fact that they had just taken an ecosystems ecology course which focused on both biogeochemical cycles and modeling. However, I made no assumption about the depth of their knowledge in these areas, given their different experiences and interests within their field. For example, some of the participants were graduate students who were engaging in ecological research that pertained to biogeochemical cycling, while others were undergraduates with far less experience with the topic. The aim of this study was not to compare the content knowledge of one group of students to that of another instead it was to describe what it means to develop an abstract model for these students.

Table 1.

Participant Information

Pseudonym	**Gender**	**Class Standing**	**Department**
Calina	Female	Ph.D. Candidate	Forestry & Natural Resources
Frank	Male	Senior Undergraduate	Biology
Henry	Male	Senior Undergraduate	Biology
Jade	Female	Ph.D. Student	Ecology
Jane	Female	Ph.D. Student	Forestry & Natural Resources
Kate	Female	Senior Undergraduate	Ecology
Kacy	Female	Ph.D. Student	Ecology
Mabel	Female	Senior Undergraduate	Ecology
Sabrina	Female	Ph.D. Student	Forestry & Natural Resources
Sergio	Male	Ph.D. Student	Forestry & Natural Resources

Data Collection

The data were collected in the spring and summer semester of 2017 for this study. The primary data source was the audio- and video-recorded unstructured interviews. Additional data sources were copies of participants' work including both photographs of the models that they produced on white boards and physical copies of the models that they drew on scratch paper.

Conducting the interviews. All 10 students agreed to participate in an interview in which I asked them to develop a general representation applicable to all the three biogeochemical cycles. I provided students with the pictures (diagrams) of the phosphorus, carbon, and water cycles. Each picture had a caption briefly explaining the phenomenon. I asked the participants to look through the cycle diagrams and think aloud while working on their models. I only interrupted the interview to ask/answer some questions and remind the students of the task. After giving the students scratch paper, pens, a large whiteboard, and dry erase markers to develop their models, I conducted all five paired interviews in person by using the same interview protocol and materials for each interview to ensure consistency in the data collection. The interviews took between 35 and 60 minutes (from shortest to longest the duration of the interviews in minutes were 38:19, 37:29, 44:05, 36:45, and 58:01 respectively). I audio- and video-recorded each interview, and took some pictures of the students' drawings during the interview. I was granted permission from each participant to record the interview on a voice recorder prior to the interview. Participants were informed that they might withdraw from the interview at any time. Other than to ask for clarification or remind the students of the task, I did not intervene in the conversation after students began the task. Ethics approval was granted by the University of Georgia Institutional Review Board (IRB) in May 2017 (see Appendix A).

Data Analysis

The purpose of the first research question was to categorize participants' models in terms of the degree of abstraction. In order to answer this question, I looked at each pair's model and described the features the models contained, the degree to which the models were abstract, how the models differed from each other, and how the models were similar to each other. This descriptive analysis categorized the models in terms of *ideas, structures,* and *the ways of representing the phenomenon* (see Table 2). My goal was to describe the degree of abstraction involved in the synthesis modeling activity. I was interested in how students transferred certain critical relations from the source materials—in this case, the three biogeochemical cycle diagrams—to their final models.

Table 2.

Criteria for Model Descriptions

Criterion for Categorization	**Definition for the Criterion**	**Example**
Ideas	Individual ideas that are pulled away from the sources	Calling the materials (P, C, and H_2O) inputs
Structures	Further inferences drawn from the essential ideas in the sources	Showing the exchange of materials between biotic and abiotic environments of the Earth
Ways of representing the phenomenon	Mediums (i.e., symbols, figures, or words) the participants use the convey their way of thinking about models	Using box-and-arrow diagrams to represent the spheres

My process for analyzing the models began with looking through the students' models to see the characteristics that were common in each final model. I determined three key characteristics in the students' models: (a) ideas (individual ideas that are pulled away from the sources), (b) structures (transformation of individual ideas), and (c) the way of representing the phenomenon (symbols/figures/words that are used in models).

For the *ideas*, I examined the individual ideas from the source materials that were directly or indirectly included in the models. The *structures* included further inferences drawn from the essential ideas in the sources (Capps et al., 2016). The focus was whether the participants might construct a new structure and transfer certain critical relations from the sources to their model. By looking at *the way of representing the phenomenon*, I described what kind of medium the participants used to convey their way of thinking about abstract models. At the end of the analysis, I aimed to make a distinction between the different models developed by the five groups of students through the descriptions of the degree of abstraction.

To answer the second research question, I began by process coding (Saldaña, 2013) the interviews to reduce the raw data into short phrases that captured the main idea of participants' turns of talk so I could extensively and quickly access data related to my second research question from a larger segment of data in the interviews. In coding the interviews, I reduced critical pieces of the interview, related to abstraction, into pithy sentences capturing the main idea of the responses of the participants with no interpretation. I reduced turns of talk into short phrases beginning with the gerund form of the verb used by the participant (Saldaña, 2013). I wrote all the phrases alongside the transcripts (see Table 3 for an example of gerund-based phrases).

Table 3.

Gerund-Based Phrases

A Participant's Response	**A Gerund-Based Phrase**
Henry: You couldn't really necessarily call these life cycles because some of these are abiotic factors.	Arguing that because of some abiotic factors, the cycles cannot be called life cycles

After reducing the responses into the short phrases, I read through each phrase to look for similarities and differences within each transcript. I then used this process to pick out notable phrases and begin a list of codes that assigned an essence-capturing and summative attribute for a portion of the reduced data. These codes were emergent as they arose from the data. Table 4 displays some examples of the codes.

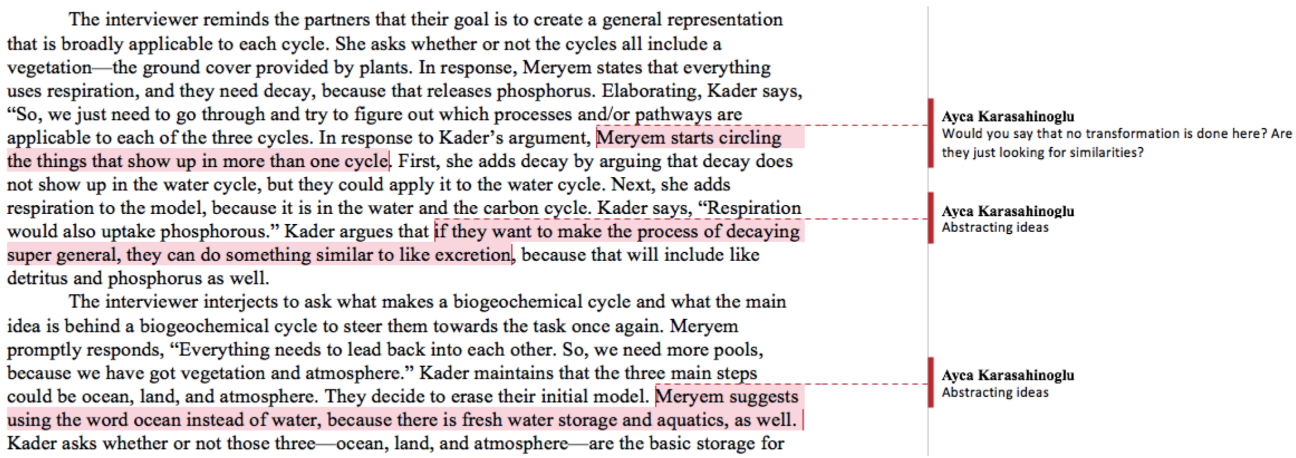
Table 4.

Some Codes from a Sample Interview Transcript

Participants' Responses	**Gerund-Based Phrases**	**Emergent Codes**
Frank: We could just say, life source, water. Umm. Okay, so – or do you mean from land to ocean? For atmosphere to land – oh, runoff. There's runoff common in everything [every cycle]. So, this could be reversible as well.	Pointing out that there is runoff common to every cycle, which can be reversible in the model.	Looking for common features
Henry: Well, technically it ends up in the – largest storage of water is in the oceans, does the ocean play a role – it does, in both of them [C and P], actually –	Pointing out that water ends up stored in oceans and noting that oceans also play a role in C and P cycles.	Looking for common features
Frank: So, instead of I guess giving names to everything, we could just say like, these general terms like resources – reservoirs – reservoirs – sinks – right. And – what else?	Suggesting using general terms such as resources, reservoirs, sinks instead of giving names to everything in the model.	Generalizing ideas
Frank: We could super simplify it and say, it's a cycle of energy, water, and gases through land, ocean, and atmosphere.	Suggesting simplifying the model and saying it is a cycle of energy, water, and gases through land, ocean, and atmosphere.	Generalizing ideas

Next, I developed a coherent and readable narrative—a descriptive retelling—for each pair. Here, my goal was to obtain a sense of how the participants' experiences developing abstract models originated and evolved during the synthesis modeling task. Each narrative described how some participants were able to get nearer to developing abstract models while some of them could not make progress with their models in terms of abstraction. In developing the narratives, I first grouped the phrases using the emergent codes as the main idea connecting them. Next, I developed paragraphs connecting the phrases into a coherent story related to the code. I took care to keep the phrases in chronological order based on the original interview transcripts. I kept these narratives as close to the data as possible. I tried to minimize the hazard of bias in representing the evidence and the order in which ideas, concepts, actions, meanings emerged in the interviews (see Appendix B, C, D, E, and F Interview Narrative Summaries).

The last step was to uncover the major themes related to the ways the participants experienced synthesis modeling. To do so, I compared the five narratives to identify notable patterns based on my second research question that aimed to answer the question of what it looks like for students to develop an abstract model through synthesis modeling. I searched for similarities and differences across the narratives to establish the themes. The comparison that I made to develop the themes involved interpretation rather than summative attributes that I mentioned earlier in the process of coding. The process of theme development was an iterative process that required reading through each narrative, over and over again, interpreting the narratives, drawing out temporary themes, and checking these themes against all the narratives, until my thesis advisor and I had reached a consensus on a common set of themes. These discussions took place weekly over a period of a couple of months. Figure 3 displays an early phase in the process in which I developed the themes from the narratives.


The interviewer reminds the partners that their goal is to create a general representation that is broadly applicable to each cycle. She asks whether or not the cycles all include a vegetation—the ground cover provided by plants. In response, Meryem states that everything uses respiration, and they need decay, because that releases phosphorus. Elaborating, Kader says, "So, we just need to go through and try to figure out which processes and/or pathways are applicable to each of the three cycles. In response to Kader's argument, Meryem starts circling the things that show up in more than one cycle. First, she adds decay by arguing that decay does not show up in the water cycle, but they could apply it to the water cycle. Next, she adds respiration to the model, because it is in the water and the carbon cycle. Kader says, "Respiration would also uptake phosphorous." Kader argues that if they want to make the process of decaying super general, they can do something similar to like excretion, because that will include like detritus and phosphorus as well.

The interviewer interjects to ask what makes a biogeochemical cycle and what the main idea is behind a biogeochemical cycle to steer them towards the task once again. Meryem promptly responds, "Everything needs to lead back into each other. So, we need more pools, because we have got vegetation and atmosphere." Kader maintains that the three main steps could be ocean, land, and atmosphere. They decide to erase their initial model. Meryem suggests using the word ocean instead of water, because there is fresh water storage and aquatics, as well. Kader asks whether or not those three—ocean, land, and atmosphere—are the basic storage for

Ayca Karasahinoglu
Would you say that no transformation is done here? Are they just looking for similarities?

Ayca Karasahinoglu
Abstracting ideas

Ayca Karasahinoglu
Abstracting ideas

Figure 3. An early phase in developing the themes

The themes that were derived from the narratives were based on the ways the students either abstracted or did not abstract ideas and structures to develop the models in their interviews. For example, purposefully using a general term (i.e., calling the process of decay *excretion*) to refer to some of the components of the cycles was one way the students abstracted ideas. That was persistent across each of the groups. This action was termed "abstracting ideas" (see Figure 3). In this case, the theme meant drawing out relevant and important ideas and concepts shared by all three biogeochemical cycles and redefining these ideas and concepts. In the results section I present each of the themes that arose from the narratives and describe the variation in the ways these themes were expressed across the groups using illustrative examples from the five groups to show this variation.

Limitations and Delimitations

One of the limitations of unstructured paired interviews is that it can be easy for the interviewer to get involved and to become subjective. The interviewer must drive the interview but should not get too involved in the discussion. Otherwise, it is possible that the interviewee will give the answer/product/reaction that the interviewer seems to expect. The second limitation to this kind of interview is that it may be possible to lose track of the focus of the conversation and allow it to go off topic. It might become costly in terms of time and usefulness for both the interviewer and the interviewee. Moreover, one participant might dominate the conversation, while another might prefer to stay quiet.

As one delimitation, I narrowed my focus to senior undergraduate and graduate students with an ecology background as this population was easily accessible, and I designed the interview task for biogeochemical cycles. Another delimitation was the targeted literature because the studies in my literature review were in the English language.

CHAPTER 3

RESULTS

In this chapter, I report on the findings of this study. The findings are organized by the two research questions.

The Degree of Abstraction in the Final Models (RQ1)

Here, I describe the degree to which the groups' models were abstracted from the three biogeochemical cycles. As mentioned earlier, I refer to abstraction as a way of sense making in which a significant new structure is created—a structure that is pulled away from the sources rather than structures or ideas based on surface features. My intention, here, is not to evaluate which model is correct or complete in terms of the functions or characteristics of models as these judgements depend on the goal of the modelers (i.e., the aspect(s) of the phenomena the groups intend to represent). Instead, I distinguish between the different models developed by the five groups based on their degree of abstraction. As I mentioned in the data analysis section, each group's model was evaluated in terms of the features that were taken out from the sources, the structure, and the way it represented the source phenomena. Table 5 shows each of the groups' final models along with a brief description of the model that I generated.

Table 5.

Model Descriptions

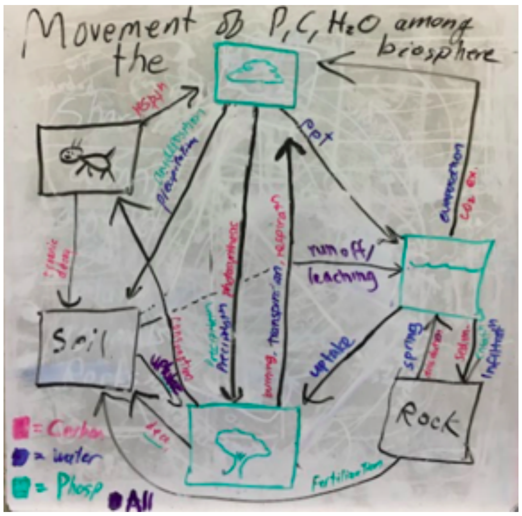
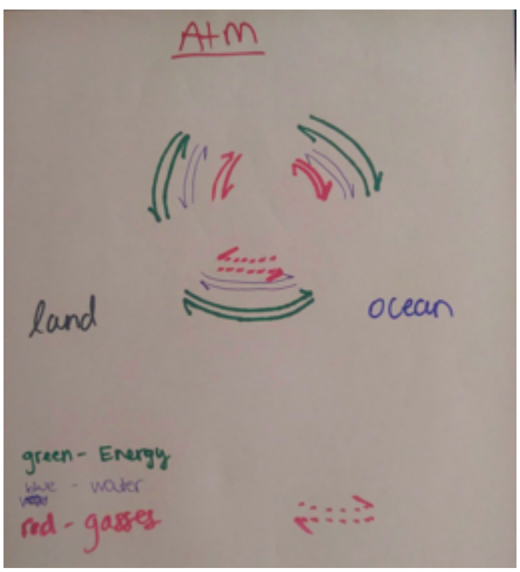
Pair	Final Model	Description
Pair 1		• Includes source-specific details • Covers several features: soil, atmosphere, rock, animals, plants, and water • Combines surface features from each of the sources into one representation • Focuses on the source-specific pathways (i.e., decay, respiration, and precipitation) rather than the back and forth movement of materials
Pair 2		• Covers three spheres that are apparent in the three cycle diagrams: atmosphere, land, and ocean. • Makes connections between spheres through source-specific materials (phosphorus, carbon, and water) • Refers to carbon and phosphorus as energy and gas, respectively • Shows reversible and nonreversible interactions between spheres

Table 5. (cont.)

Model Descriptions

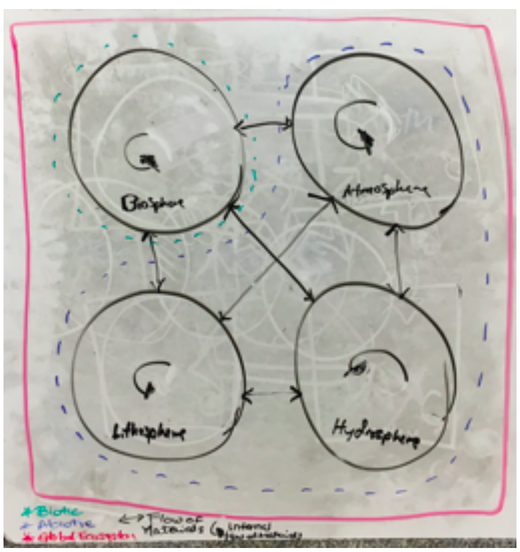
Pair	Final Model	Description
Pair 3		• Covers the four spheres: atmosphere, land, water, and organisms which are not very explicit in the water cycle • Makes connections between spheres through source-specific processes—such as decay, sediment, and respiration • Calls some commonalities (precipitation, burning, and weather) abiotic processes in general • Bridges all the spheres with two-way arrows • Includes a lot of surface level features
Pair 4		• Covers four spheres: atmosphere, lithosphere, hydrosphere, and biosphere • Shows the flow of materials between biotic and abiotic environments • Classifies spheres into abiotic and biotic in a global ecosystem • Includes internal cycles for each sphere • Eliminates any source-specific details • Develops a structure general enough to be applied to any biogeochemical cycles

Table 5. (cont.)

Model Descriptions

Pair	Final Model	Description
Pair 5		• Covers four spheres: atmosphere, lithosphere, hydrosphere, and biosphere • Shows the exchange of materials (back and forth movement) between biotic and abiotic environments of the Earth • Includes fast and slow cycles • Calls fast and slow cycles biotic and abiotic, respectively • Eliminates source-specific fluxes, pools, and processes • Calls the materials inputs • Combines information that cannot be apparent in any of the cycles • Develops a structure general enough to be applied to any biogeochemical cycles

I grouped the models in three descriptive categories: (1) veridical, (2) revisionary, and (3) abstract. Each category is explained below.

1. Veridical: Models categorized in this group included surface features that were apparent in any of the source materials--the carbon, phosphorus, and water cycles. The students combined these features from the three source materials in one representation and did not transform the features in any way. In other words, they created a literal representation of the source materials that symbolize the phenomenon.

2. Revisionary: Models categorized in this group were simplified and slightly generalized. The models included some abstract features; however, those features were not enough to show the structure and the relations across the three cycles. The models included both abstract features and surface level features at the same time. This was the reason for considering those models neither a copy of the cycle diagrams nor an abstraction of the structure. For example, Pair 3 took out the four main reservoirs from the cycle diagrams—water, land, ocean, and organisms (see Table 5 for an image of the model). However, they used some surface level features that were not applicable to all three cycles to show the relations among the four main reservoirs. Those models partially draw core ideas away from the cycle diagrams.
3. Abstract: Models in this category showed the cyclical relations that composed the biogeochemical cycles. The students expressed important operational features shared by all of the biogeochemical cycles (i.e., biotic and abiotic factors, biosphere, lithosphere, and hydrosphere) in their final model. More importantly, models in this category could explain the structure common to all the biogeochemical cycles.

Figure 4 shows the degree of abstraction in the groups' final models. The positioning of the colored diamond near the top of the figure shows approximately where each group was located along the continuum from veridical to abstract. One group, Pair 1, included the carbon, water, and phosphorus cycle separately in one representation. In addition, the representation depicted surface level features that were source-specific. Their approach was to make one representation that included all the cycles rather than one that could stand in for each of the cycles. Thus, Pair 1's model was grouped in the category of veridical.

Pair 2 and 3's models were classified under the same category; revisionary, however their location along the continuum was different. Pair 2 was located closer to the veridical end of the continuum, as it included the three main spheres—atmosphere, land, ocean—which were apparent in the cycle diagrams and source-specific materials (i.e., water) that flow back and forth between the spheres. Pair 3 was located closer to the abstract end of the continuum, as it covered all the four essential spheres, including land, water, atmosphere, and organisms (see Table 5 for the image of the model). It is important to note that Pair 3's model is more abstract than Pair 2's model because Pair 3's model uncovered a larger idea that materials cycle between living and nonliving environments by including organisms that are not apparent in all of the cycles. In addition, the spheres were linked to each other through a few abstract features (i.e., biotic and abiotic processes). The other connections among the spheres were made with the surface level features (i.e., decay and autotrophs). These important differences made the model of Pair 3 relatively more abstract than the model of Pair 2.

The models of Pairs 4 and 5 were grouped in the same category, abstract. The degree of abstraction did not differ considerably between these two models. Both of the models depicted the general structure that comprise biogeochemical cycles. That is, the models had no surface level features from any of the cycle diagrams. The pairs were able to take out the essential features from the three cycles to construct the structure to represent the larger idea behind the phenomenon.

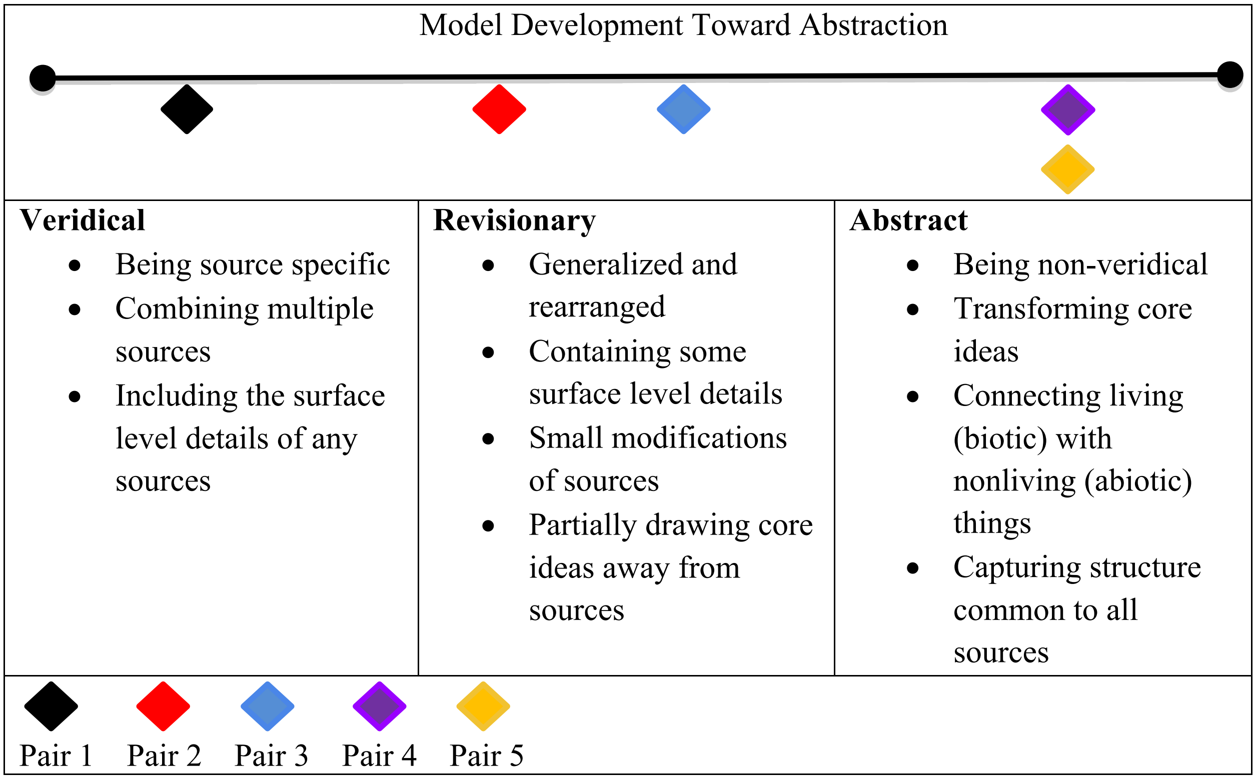


Figure 4. The degree of abstraction in the final models

The Ways the Learners Follow through Synthesis (RQ2)

Here, I describe the ways the participants engaged in synthesis modeling through a comparative analysis of the five narrative summaries developed from the interviews. Through an analysis of the data, four themes arose. The themes were: *Working with Surface Similarities, Abstracting Ideas, Abstracting Structures,* and *Checking on Model-Source Fit*. The themes are listed and defined in Table 6. In addition, I describe variations within the themes that are elaborated on through the quotes and images in the text.

Table 6.

The Ways the Participants Follow Through Synthesis

Themes	Definitions	Variations within Themes
Working with Surface Similarities	Focusing on easily accessible features of the cycle diagrams which are unhelpful and irrelevant to developing a model within synthesis	● Looking at each source material separately and adding something specific from any of the three cycles to the emergent model ● Focusing on the shared features that are apparent in the source materials and combining them into one representation ● Strictly sticking to the source materials
Abstracting Ideas	Taking away the essential features shared by all three sources of biogeochemical cycles	● Drawing out relevant and important features shared by all three sources and redefining them
Abstracting Structures	Extracting and transferring the structure common to all of the cycles, which represent the phenomenon	● Capturing the structure by looking for what connects the source materials to each other ● Transferring the structure to a final model
Checking on Model-Source Fit	Making sure that the features and structures that compose the emergent models apply to all the source materials or any biogeochemical cycles	● Checking the features and/or structures against the source materials ● Checking whether or not the final models overgeneralize the features and/or structures ● Checking whether or not the final models map to cycles beyond source materials.

Each of these themes are described and justified in separate subsections below. The superscripts in the text point to where in the narrative summaries this information was drawn (see Appendix B, C, D, E, and F Interview Narrative Summaries). As representative examples of what the specific processes explained under each theme look like, I provide quotes from the interview transcripts in the text and screenshots from the video records. The quotes are meant to be representative of the essential idea of the positions taken and the ideas advanced in the interviews.

Working with surface similarities.

Initially, all of the groups attempted to develop their model by looking for shared features common to all three cycles. As there were no features that were common to all three sources, the students ended up combining similar features they saw in at least two of the sources into one representation. The similar features from the cycle diagrams were not useful or relevant to the synthesis modeling task. The main reason for this was the fact that these features were not applicable to the three cycles. Having importance to one or two of the cycles, the surface level features were insufficient to represent the larger idea behind biogeochemical cycles. The tendency, to focus on shared surface level features, was most obvious early in the process for a majority of the groups as they began to develop their models. Despite this tendency, the groups recorded very slight variations in working with surface level features. In the following paragraphs, I present the variations across the groups.

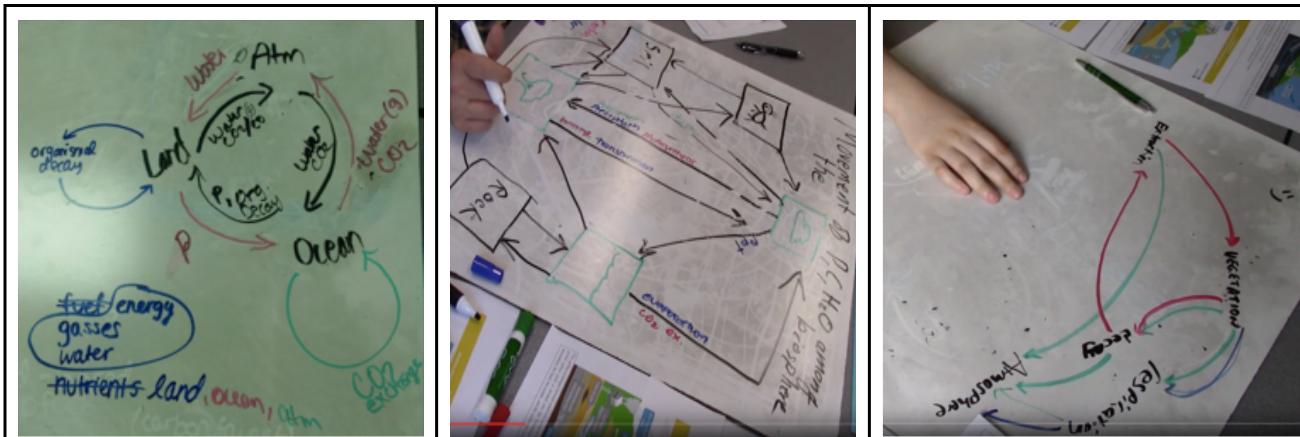
The groups looked at the features that were apparent in the cycle diagrams. They selected these readily accessible features (e.g., vegetation, respiration, transpiration, and fossil fuels) common to two or three of the cycles together and tried to construct their general model from these features [Jane and Sergio: Lines 33,34,58,59,83,84,96,97; Kate and Mabel: Lines 4,8,12,25,26,44,45,82,83,84; Kacy and Jade: Lines

[36,37,38; Sabrina and Calina: Lines 28,29] An example of the results of working with surface similarities can be seen in the following conversation where Kate and Mabel were discussing the similarities between the C and P cycles.

> Kate: *I'm going to write out vegetation. Vegetation.*
> Mabel: *So, we have vegetation, and then, we have respiration and decay. So, I guess we could have like respiration – so, respiration and then decay. Because decay can also release phosphorous, because that's the thing with like the triangle <?> and all that.*
> Kate: *Because respiration would also involve like the transpiration.*
> Kate: *So, respiration, transpiration. Okay, wait.*
> Mabel: *I guess, going back to like – we could have extraction be one of the steps for like – okay – for fossil fuels and phosphorous?*
> Kate: *Cool, that sounds good.*
> Mabel: *For phosphorus, extraction goes into vegetation, because it uses fertilizer.*

The features that I underlined in the quote denote easily observable features in all of the cycles. What they did was to take out readily accessible features from the diagrams that they were given, and then, trying to put them together into one representation instead of creating a structure common to all three cycles.

Figure 5 explicitly demonstrates that even though some participants could determine the essential features, such as atmosphere, water, and land, that composed the biogeochemical cycles, they were not able to extract the ideas. The reason for this was that they borrowed some features directly as connectors, such as decay, respiration, CO_2 exchange, etc., from the source materials to make a connection among the main features. As can be seen in the image of the initial model Pair 1 developed in Figure 5, the group took out some important features from the cycle diagrams, including land, atmosphere, and ocean. They then tried to make a connection among these features through the surface level ideas (organismal decay) that were apparent in the cycle diagrams. Even though the group made sense of where the substances were cycling, they showed that organismal decay is the only pathway that leads the substances to cycle on land, which is an accurate description for the way the carbon and phosphorus cycle, but it does not apply to the water cycle.



Pair 1	Pair 2	Pair 3

Figure 5. Connecting the features (i.e., soil, atmosphere, and ocean) from the cycles with the surface level pathways (i.e., organismal decay and respiration)

Another example of the variation in working with surface similarities was that participants stuck to the source materials while they tried to determine the important features in the cycle diagrams. [Jane and Sergio: Lines: 85,86,87,88,89,101,102,103,111,112,113,114,115,126] In other words, some students made a decision on what to retain and what to eliminate from their model by looking at the features the cycle diagrams explicitly presented. An example of this was observed in the following conversation between Sergio and Jane.

> Sergio: *How does carbon get to the ground from the atmosphere?*
> Jane: *Are there carbon fixing bacteria? No, that's nitrogen, I'm confusing it. Anyway, we should stick to what's on here* [cycle diagrams].
> Sergio: *It's not on here* [cycle diagrams], *so let's leave it off*.
>
> Sergio explained more how and why they strictly adhered to the cycle diagrams:
>
> *I would say, if I may step in on that, I would say, yes, because what we were asked to do was to take these three models* [cycle diagrams]. *We were not told to evaluate which ones were important. The interpretation therefore is if they were included in the three models* [cycle diagrams], *it should be considered given that they are important, because that's what we were asked, to take what was on here* [cycle diagrams] *and make it into a single*

model. Therefore, it's irrelevant as to what the process actually is, it was on these sheets of paper [cycle diagrams], *so it's on here* [their final model].

The underlined statements in the quote indicates that the group did not use information from the sources to uncover and map a structure common to all three cycles, but rather they looked at the features that were readily presented in the cycles, copied them, and then, combined them into one representation without any further elaboration.

As one more variation in working with surface similarities, some groups worked on surface level features in a slightly different way in which they tried to add some features that are very specific to one or two of the cycles. [Frank and Henry: Lines 22,23,44,45,46,59,60; Kacy and Jade: Lines 40,41; Sabrina and Calina: Lines 24,25,40,41; Kate and Mabel: Lines 109,110,111] That is, the cycle diagrams had a few features that were characteristic of any cycle, such as a self-feeding cycle of phosphorus being reused over and over again (i.e., phosphate moving quickly through plants and animals). The groups were not able to develop a structure that would be broadly applicable and transferable to all three cycles due to looking at the cycles separately and focusing on some cycle-specific features. An example of this was observed in the following conversation between Henry and Frank.

Henry: *And then the same thing [vegetation] for phosphorous. I feel like it's the – this would be a phosphorous faucet and the thing is that the phosphorous doesn't go into the atmosphere. It stays within land and the ocean, so the runoff leads to phosphorous being deposited into the ocean, and then, it just goes back and forth through vegetation. So, like we would eat the veggies, get the phosphorus, and then eventually – right – it would go back into the ground.*
Frank: *So, how would we…?*
Henry: *I would say that we should have just a circle of phosphorous just being reused – reused, so phosphorous doesn't increase or decrease? Is that basically what it's saying?*
Frank: *Yeah, so, what we could do is have a lateral cycle for phosphorus rather than up and down.*

The quote above shows that the group looked at the cycle diagrams separately. They tried to include one characteristic of the phosphorus cycle that is not valid to the water cycle. This served as an inhibitor to abstraction, pulling the key features away from the cycle diagrams.

Abstracting ideas.

In this section, I explain how the performance of the groups in the abstracting of ideas differed from each other during synthesis modeling. To do so, I draw on the theory of analogical learning that posits learning abstract ideas can be supported by uncovering the underlying structure from a set of instances of a phenomenon. The theory argues that seeing the connections between sources, capturing corresponding parts of the sources, and creating a common structure that fits a novel situation are the main three steps in analogical learning.

Although all of the groups started by working with surface level similarities, some groups moved beyond these commonalities by abstracting the essential features from the three cycle diagrams. Once the group realized that they could not simply combine surface level similarities, they tried to pull relevant and applicable features away from the source materials. For some groups, this transition happened quickly, in a matter of minutes, whereas for others, it took between 20 and 30 minutes. For example, at the beginning of the interview Kacy and Jade began by looking at the big ideas across the different cycle. [Kacy and Jade: Lines 3,4,5,6,7,8,9,10,11] The quote below marked their successes in abstracting, or drawing key features away from the cycles.

> <0:00:43>Jade: *Right, so I guess like when I first go to through this like comparing and contrasting here and finding similarities, if we're going to make something that's representative of all of these cycles and even like nitrogen, that's a different cycle, like I just look for things in common. So, like, they all have a pretty similar setup with a few different details. Like these have soil layers; this one doesn't, but they all have like atmosphere, and they have like land, water, and then a soil layer, and they all talk about different processes and they all have arrows. And as you said, more scientifically, sources and sinks. But, yeah, if I was looking for something general, I think that I would like to see what's in common and then how you could make it so that you can adapt it to*

whatever you might, you know, whatever you – elements you might be interested in or even water.

<0:01:40>Kacy: *The idea is to have pretty much like one land soil air and then try to incorporate the three in one image, right? So, maybe, we can start with like some processes that could happen at the same time, you know, like because, for example, some of the – kind of, how do you say when things get back into the atmosphere, kind of like that release of – there are some that go together, right, like the – like some of these.*

As can be seen in this interchange, the first thing they effortlessly figured out was looking for what makes a model representative of all of the cycles, even the nitrogen cycle that was not provided as source material for the interview. As Jade said, the cycles had a very similar system with a few different details. Elaborating, she argued that the general model that they wanted to develop can be adapted to whatever elements they worked on. This was where she considered the model as abstraction, the structure that were taken out from the sources. They explicitly stated that the general model should be applicable to any kind of biogeochemical cycles. This showed that the group began to see that there was a common structure across the cycles to represent the big picture of the phenomenon.

The essential features that cut across the cycles were not apparent at the surface level in any of the cycles. On the contrary, another group spent a great amount of time coming up with a few abstract ideas that were pulled away from the cycle diagrams. Because this group looked at the cycles separately in the beginning of the interview, they were not able to consolidate the underlying structure to all of the cycles for a while. [Frank and Henry: Lines 2,3,4,5,6] After approximately 23 minutes, Henry and Frank made a great effort to shift their approach from being cycle-specific to thinking in a more general and abstract way in terms of the interviewer's revised prompt, which asked them to make a representation that would work for all biogeochemical cycles. [Frank and Henry: Lines 63,64,65,66,67] The slightly revised prompt was not much different from the initial direction for the interview task which was to develop a representation that will work for all three biogeochemical cycles. The only difference seemed to be that it referred to all biogeochemical cycles instead of the three of them. It was only after this that Frank and Henry began generalizing ideas from the three cycles was presented in the quote below.

> <0:23:16> Frank: *So, instead of I guess giving names to everything, we could just say like, these general terms like resources – reservoirs – reservoirs – sinks – right. And – what else? Fuels. And then, I guess, <Inaudible>.*
> Henry: *There's always air, water, earth, and then – air, water, earth, like those are the three main –*
> Frank: *...we could super simplify it and say, it's a cycle of energy, water, and gases through land, ocean, and atmosphere.*

Frank and Henry made a major change in their thinking when they were pushed to think about all biogeochemical cycles. Before that, they stuck to the three cycles and thought about them separately. Basically, they dived into the cycles separately and took out a couple of features that seemed to be important in their perspectives (i.e., atmosphere is the key source for the water cycle, whereas rocks are key sources of phosphorus and carbon cycles).

In general, groups articulated some features in the cycles by using more or less general terms and definitions. Henry and Frank: Lines 14,15,34,35,53,54,55,67,70,71,72,75,76; Jane and Sergio: Lines 6,7,8,16,17,18,28,29,30,31,32,62,63,64; Sabrina and Calina: Lines 46,60,61,66,67,68,69,70,80; Kate and Mabel: Lines 11,28,29,30,33,35,36,40,41,51,52,58,59,65,66,67,68; Kacy and Jade: Lines 5,6,24,25,26,27,28,29,72,97,98,105,106,107,108,113 The operational definitions for the essential features in the cycles did not contain any considerable variations in the narratives. All the groups had a tendency to define their own terms to represent the essential features from the cycle diagrams. By doing so, the groups showed that they captured the main idea behind biogeochemical cycles by pulling the important features away from the particular sources. These were essential features that cut across the cycles that were not apparent at the surface level in any of the cycles. As an example, the quote and the image below marked one of the groups' successes in abstracting, or drawing key features away from the cycles, and set the stage for further abstractions.

> Sabrina: *So, it seems that this* [pointing out the arrow on the upper left in their model] *is commonly – precipitation/deposition among these* [the atmosphere and land in the phosphorus cycle]*, let's see – let's look at the carbon cycle, so we have precipitation for the water cycle.*
> Calina: *We can just call it inputs.*
> Sabrina: *Okay.*
> Calina: *This* [pointing out below the earth's surface] *one is always the slow cycle. Right? I feel like we can do something – we can have like something branch off into the biotic cycle from here* [Earth's surface]*, but I don't feel like this* [below Earth's surface] *part ever is really part of the fast cycle.*
> Sabrina: *Yeah, so what describes this* [below Earth's surface]*? Is this like slow migration? Transformation? I'm thinking of like for water it's slow migration because it's moving through the aquifers and things like that.*
> Calina: *It's kind of like a holding area.*
> Sabrina: *Reservoirs? We could just say that.*

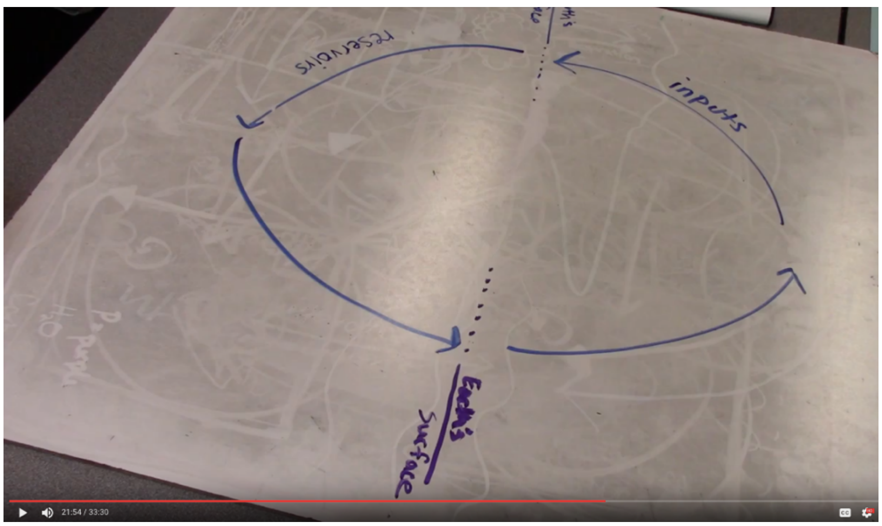


Figure 6. The way Sabrina and Calina pulled a couple of important features away from the sources: (a) inputs and (b) reservoirs

The quote above demonstrated that the pair looked at the phenomenon in a more stripped-down form, avoiding the surface level features that would make the model development within the synthesis difficult. The most important reason for the participants to follow that approach in abstract model development was to realize that models should be applicable to all three cycles rather than specific to any of the cycles. When the participants struggled with features that were particular to one or two of the cycles but were not apparent in the other cycle(s), they started making their own operational definitions and even coining some general terms/words that could tie the particular features together to represent the links and relations in their final model (i.e., inputs, holding areas, and reservoirs). As can be seen in Figure 6, Sabrina and Calina tried to develop a structure that would be applicable to all three cycles. The structure sufficiently depicted how inputs and outputs between underground and above ground move through the slow (abiotic) and fast (biotic) cycling. This structure can be adopted to show how a substance flows through the compartments of Earth—how a biogeochemical cycle works globally.

Abstracting structures.

Only two of the groups were arranged the abstract ideas they had generated into a model capable of explaining all the sources. [Sabrina and Calina: Lines 4,5,6,7,45,46,83,84,85; Kacy and Jade: Lines 15,16,47,48,49,53,54,55,56,58,59] These two groups tended to think that some of the specific features from the source materials would be lost if the goal was to capture the structural alignment across the three cycles. The groups were able to figure out that the three cycle diagrams had a similar set up with some different details. By doing so, the groups were able to move forward focusing on the underlying structures of the cycles. This only occurred once the students began linking the abstract ideas they had generated in a way that tied the different cycles together. The students had mostly let go of any source-specific surface level features and began to think of the model in terms of the essential features and the structure that composed biogeochemical cycles.

This was evident when the groups realized that the model should not have any specifics; instead, it was meant to represent the bigger ideas and structures behind the biogeochemical cycles. Thus, the model they created should not be a copy of any of the cycles; instead, it should represent the key features (structure) of all the cycles.

Both groups that developed an abstract model had a similar way of organizing their model with a few distinctions. For example, the model that Sabrina and Calina developed depicted the cycle of inputs and outputs between underground and above ground through slow (abiotic) and quick (biotic) cycling, whereas Jade and Kacy represented the flow of materials between biotic and abiotic environments through four spheres (lithosphere, atmosphere, hydrosphere, and biosphere) in a global ecosystem (see Figure 7). The starting point for both groups was looking for what connects all of the cycles and trying to find a way to link them to each other without going into any specific cycles.

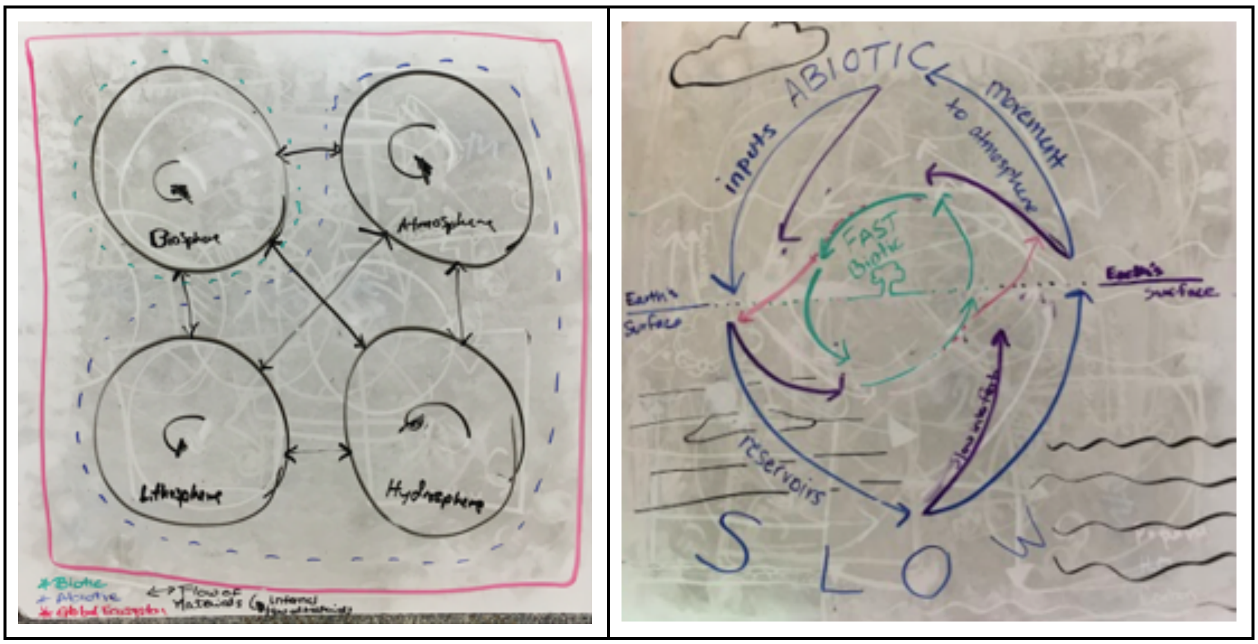


Figure 7. Kacy and Jade's model (on the left) and Sabrina and Calina's model (on the right)

To demonstrate what the model that was considered as the structure of the phenomenon looks like, an example was presented in Figure 8 and in the quote in the following paragraphs.

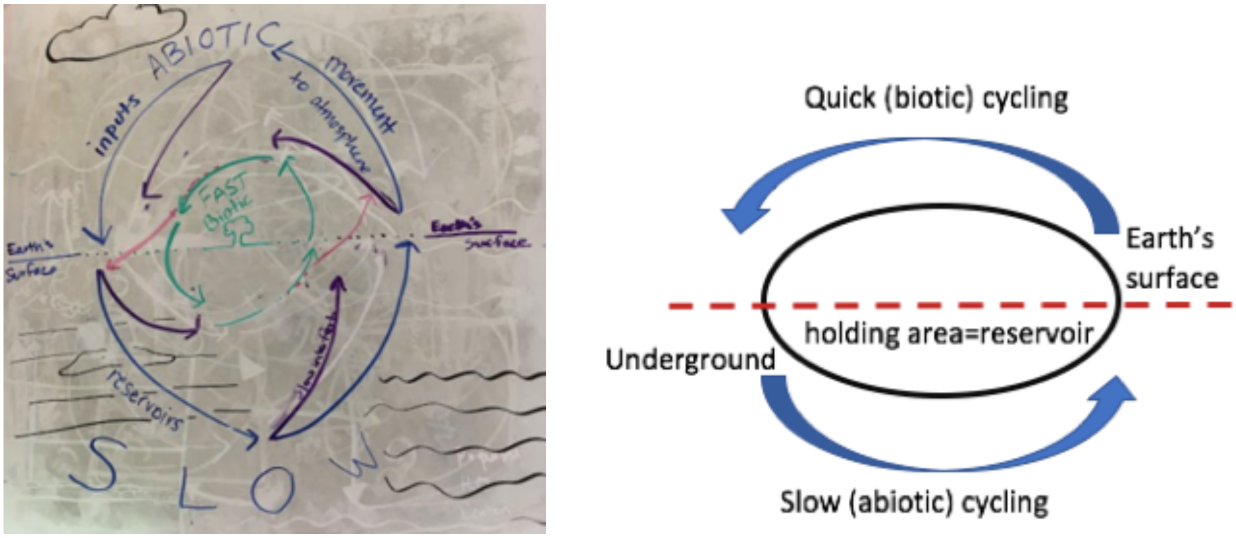


Figure 8. A final model representing the structure of the phenomenon (on the left) and its simplified version by the author (on the right)

Figure 8 shows that the group used some abstract ideas (i.e., slow and fast cycling, biotic and abiotic factors, inputs, reservoirs, holding area, and Earth's surface) to make a connection between all of the cycles. The group was able to seek and take out the features that were applicable across the cycles rather than focusing on the features that were apparent in the cycle diagrams on the surface level. They then could develop a framework on which to put those features that were pulled away from the source materials together in their final model to represent the phenomenon on a deeper level.

> Calina: ...*if you extremely simplified it, you would have one arrow going up and one arrow going down and like maybe a few undergrounds*.
> ...
> Calina: *I'm wondering if we can focus on slow and fast cycling.*
> Sabrina: *Well, I was trying to find the common ground between the cycles*.
> Sabrina: *Right, and so, we had a lot of arrows that aligned, and I was going to simplify it down to the ones that overlapped, and you do lose some of your specifics in there, but that's fine if they don't apply across all models* [cycle diagrams].
> Calina: *Well, we could have like ocean and then land over here* [drawing that on a paper]. *I mean, I don't know if we necessarily – I think we would label it like slow cycling and fast cycling, because to me that's what I see is like the connector between them* [cycle diagrams] *all, right?*
> Calina: *Yeah, I think that this should – we should maybe make it not so much like land and water so much as like Earth's surface.*

Sabrina: *So, it seems that this* [pointing out the arrow on the upper left] *is commonly – precipitation/deposition among these, let's see – let's look at the carbon cycle, so we have precipitation for the water cycle.*
Calina: *We can just call it inputs.*
...
The interviewer: *Can you explain why your model is powerful to represent all of the biogeochemical cycles?*
Calina: *I like that while it* [their final model] *doesn't necessarily have the specific fluxes and pools, it* [their final model] *gives a more general idea for how the cycles work globally, which I like. And, I think the connections between the fast and the slow cycle are some of the things that people lose sight of when they're thinking about biogeochemical cycles, so I like that we highlighted that.*

An important aspect of this conversation was that the features and ideas that they discussed and included in their final model were not readily accessible in any of the cycle diagrams; instead, the group dived into the cycle diagrams, extracted the key features, and represented them in an abstract way (i.e., inputs and the fast and quick cycling). Another aspect of the way the group experienced synthesis modeling was that they did not attempt to copy any of the features in the cycle diagrams, which fits perfectly into the main learning objective of synthesis modeling.

Checking on model-source fit.

Throughout the entire interview the groups regularly checked their final model against the different cycles to make sure that the features and/or structures from the source materials were applicable to all three cycles. [Frank and Henry: Lines 8,9,10; Jane and Sergio: Lines 48,49,50,51,52,67; Kate and Mabel: Lines 53,62,72,113,114,115,116; Sabrina and Calina: Lines 76,77,78; Kacy and Jade: Lines 27,28,29,101,102,103,104] This checking appeared to have been supported by the synthesis process as it occurred across all of the groups. It likely occurred as each of the cycle diagrams was readily available to the groups while they worked on generating their models.

The groups recorded considerable variations in checking the model for fit: (1) checking features against the cycles, (2) checking whether or not final models overgeneralize features and/or structures, and (3) checking whether or not final models map to cycles beyond source materials. An example of the first kind of variation in checking the model-source fit was observed in the following conversation between Henry and Frank.

> Henry: *Okay. So, I guess the first thing that I would do is look at what are the sources of each cycle, exactly. So, it seems to me that for the water cycle, that it's coming mostly from the atmosphere, the water that's stored in the atmosphere, and then it's cycled through to land and then underground, and then back to the atmosphere. So, the atmosphere is definitely one of the key – what do they call those? Basins?*
>
> Frank: *Like the source of resources – okay.*
>
> Henry: *Yeah, so the atmosphere is a key source, and then, it's also prevalent in the carbon cycle. But, I don't know about the phosphorus cycle, where does that mostly come from?*
>
> Frank: *Good point on the atmosphere being a key source, but I think with phosphorus and carbon, it would be best to start with a rock formation over time and start with like the buildup of biofuel from years and years of decay–and like carbon energy in there. This is short term, for instance, burning – even animal death, very short term. But what's not short term and is the biggest source of energy for everything is coal, oil, and gas. So, to build a model, I guess it would be best to start with each cycle's main source.*
>
> Henry: *So, atmosphere would definitely be at the top.*
>
> Frank: *Would that be for all of them or just for water cycle?*

This quote above shows students struggling when they attempted to combine surface features from the cycles. Here, the availability of the three cycles appeared instrumental in Henry's questioning of whether the atmosphere should belong in the model. When the idea of the atmosphere arose, Henry acknowledged that it was part of the carbon and water cycles; however, when he checked the idea against the phosphorus cycle he questioned whether it was relevant.

Checking the fitness of the model also appeared instrumental in helping students recognize when they had gone too far, eliminating important features that were relevant to all three cycles. Here again, the ability to map the model on the different cycles helped students realize they may have overgeneralized or pulled the model too far away from the cycles. An example of this can be seen in the following quote from Kate's and Mabel's conversation.

> Kate: *Well, what would emission have to do with like atmospheric phosphorus?*
> Mabel: *Because it's going into the atmosphere from the organism.*
> Kate: *Well, it's going into the land first, but then, the abiotic processes turn it into the atmosphere.*
> Mabel: *Oh, you're right; you're right.*
> Kate: *Yeah, I think – I mean respiration would work but we'd have to be specifically talking about autotrophs. So, we could turn – or we could do like respiration, but like have a note like autotrophs only.*
> Mabel: *Then that would leave out heterotrophs which are kind of a big part of the other cycles.*
> Kate: *Yeah. But, that's what I'm saying is like, I mean we could do like autotrophs but then just like – I guess that would be the only thing that would have to change.*
> Mabel: *I guess. I guess.*
> Kate: *Either that or we have to switch this to just autotrophs.*
> Mabel: *We could switch it to autotrophs, but that's the <Inaudible>, that's the other thing where it's like we're – basically for the – what was I going to say? Umm, it's like we're cutting out a pretty major part of all three cycles, the heterotrophs, for the sake of simplicity.*

The quote above is an example to illustrate what checking whether or not the final models overgeneralize or overlook the features and/or structures looks like. It can be argued that checking the model for fitness was also important in leading the group to realize that they tried to disregard some key features (i.e., heterotrophs) that seemed to be relevant to all three cycles. In other words, mapping the model on the different biogeochemical cycles made the group feel uncertain about whether or not they might overgeneralize, or ignore the features that might be worth representing in their model.

Finally, there was evidence of groups checking whether their model (abstraction) mapped to cycles beyond the three they had been given. For example, after Mabel and Kate agreed that their model should not be a direct reflection of any referents, they began thinking about whether or not the model could represent the nitrogen cycle and how it would need to be adapted to do so.

> Mabel: *So, what I think that means is basically you don't have any specifics on a cycle, but you have commonalities that you can, like <u>general things you take from all of them that would be applicable</u> and that you could, <u>if you wanted to take this model and then throw nitrogen at it, it would fit.</u>*
> Kate: *...I do not know what else to add, kind of, to make it more, kind of, self- explanatory without going into a specific cycle.*
> Mabel: *...tell me about <u>how you would adapt this for the nitrogen cycle</u>.*

CHAPTER 4

DISCUSSION

In this chapter, I discuss the significance of my findings in light of what is already known about the research problem, and, how my research contributes valuable insights to teaching, learning, and research in science education.

Synthesis as a Way of Dealing with the Copy Problem

With my two research questions, I aimed to address the well-documented problem of thinking that models are copies of the reality (Dogan & Abd-El-Khalick, 2008; Grosslight et al. 1991; Harrison & Treagust, 1996; Ingham & Gilbert, 1991; Lin & Chen, 2002; Ryan & Aikenhead, 1992; Tasquier, Levrini, & Dillon, 2016; Van Driel & Verloop, 1999). This is one fundamental barrier that learners face when developing models.

Particularly noteworthy in the findings of the first question was that there was considerable variation in abstraction in the final models across the groups. Student models were categorized based on their degree of abstraction from veridical to abstract (see Figure 9).

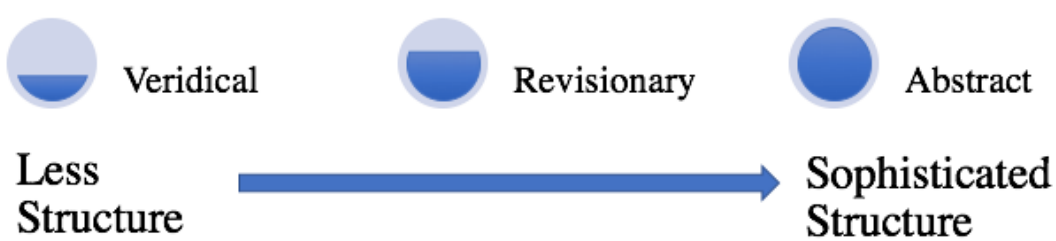


Figure 9. Variations in abstraction in the student models

Veridical models were developed by identifying surface level features of two or more sources. Instead of transforming ideas from the cycles, the students ended up copying the features that are apparent in any cycle diagram. A model that was developed in such a way would not work because the features that were specific to the cycles limited the applicability of the model. This model was also unable to convey key features about the biogeochemical cycles.

Slightly more abstract models were the revisionary models. When students developed partially abstract ideas, which did not show the structure across the multiple representations of the phenomenon, their model could not sufficiently support cross-representation transfer between the sources and the final models. Because these revisionary models include both abstract ideas and surface features from the sources, it is difficult to consider them either a copy or an abstraction of the phenomenon. Those kinds of models are incomplete in terms of presenting key features and connections between these features.

The most abstract models were developed when learners stayed with all three sources in developing a structure to represent the phenomenon, the structure that was taken out from the multiple sources was incorporated into the phenomenon. Where the learners view the sources simultaneously, their performance in synthesis by abstracting ideas and structures is remarkably more effective than those who work on one or two of the sources separately.

According to Chen and Daehler (1992), Gentner (1989), and Holland, Holyoak, Nisbett, and Thagard (1986), structure is the select information that helps learners show the main relations among the sources of a phenomenon through transformation. In the case of developing abstract models in this study, having sophisticated structures, abstract models could incorporate in all the three sources. In other words, the model depicted important relations among the sources (i.e., the movement of substances between living and nonliving components of the entire globe). This would indicate that the presence of multiple representations of the phenomenon facilitates the way in which learners develop a structure which is abstraction by pulling the essential features away from those representations. Schwartz (1995) and Schwartz and colleagues (2011) also reported that multiple representations of a phenomenon helped students generate understanding that was more abstract. One reason to exploit different-looking instances (also known as source materials) of a phenomenon in synthesis modeling is to take advantage of the multiple sources that have an underlying structure that leads learners to avoid copying. This study indicated that having students with multiple representations was sufficient enough to push them toward abstraction, a sophisticated structure, even though some students insisted on a literal interpretation of what they saw on the surface level in the sources.

My second research question investigated how learners experience synthesis modeling by focusing on the process rather than the products. This research question, along with recent research by Capps and his colleagues (2016) begins to reveal the most desirable characteristic of models and the ways learners experience synthesis modeling.

My second question extended previous work that dealt with the copy problem (Grosslight et al.,1991; Harrison & Treagust, 2000; Lin & Chen, 2002; Saari & Viiri, 2003) by investigating what developing an abstract model through synthesis modeling looked like for students. The results of this study clearly showed that the synthesis modeling was experienced through four manners, illustrated in Figure 10: *Working with Surface Similarities, Abstracting Ideas, Abstracting Structures,* and *Checking on Model-Source Fit*.

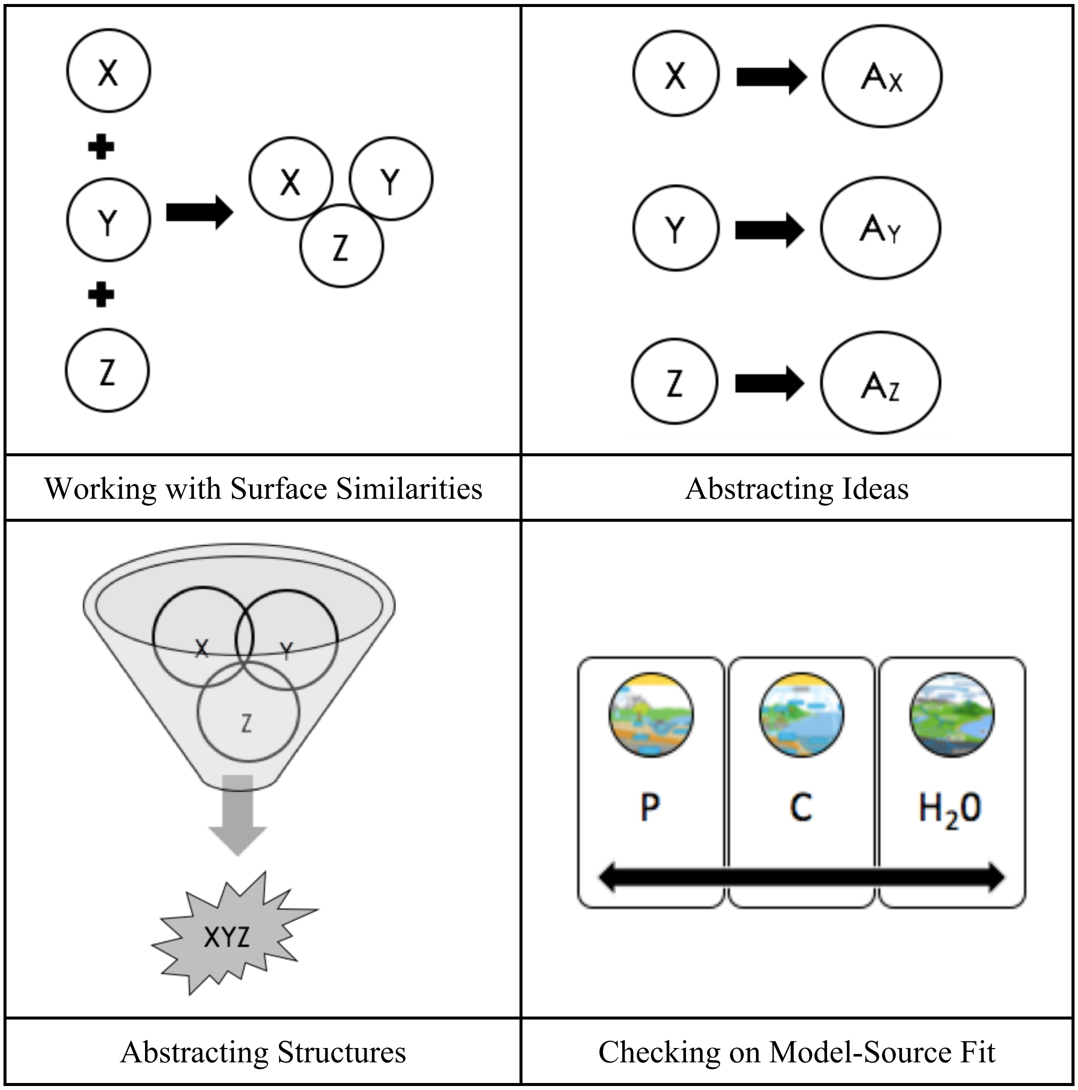


Figure 10. Schematic of four manners the students follow through synthesis

When learners began to work with surface similarities, they tended to mirror what they saw in the source materials. Looking at the similarities that were apparent at the surface level across the cycles, learners did not extract the essential ideas from the sources to construct a structure. The lack of commonalities across the three cycles acted as a constraint against surface level thinking. They realized that the surface level features from the cycles did not help them capture the structure common to all the sources because there were no surface level features that were applicable to all of the representations of the phenomenon.

In light of the observations presented in the previous paragraph, I would say that the presence of multiple instances during a process of model development might support learners in recognizing that their final models do not have to resemble the instances on the surface level. Lin and Chen (2002) also reported that when students realized that all of the models differed from one another, they could easily understand that none of the models would be a copy of the particular phenomenon.

As another important observation, the students who moved beyond working with surface level features tended to seek the key features to develop an abstraction. There were two kinds of abstraction that I identified in this study, *abstraction of ideas* and *abstraction of structures*. Abstraction of ideas generally precedes the abstraction of structures. Here, I go back to one argument that I mentioned in the literature review. This argument was that models included select information from a source under transformation rather than a direct translation of any phenomena. Following Gentner's (2010) and Nersessian's (2008) work, Capps and colleagues (2016) called this select information from a source "the structure of the phenomenon." The researchers defined *models* as structures that are abstractions of the structure of the phenomenon they represent. This explains why extracted key features from the sources were transformed into structures.

The findings demonstrated that students who worked on key features common to all sources could use information that were provided in the sources in an effective and logical way to the mapping of abstract select ideas rather than randomly using information pieces to develop a literal representation. As students talked over abstract ideas that they pulled away from the multiple instances of the phenomenon, they began to look for a structural alignment across the multiple instances. The abstract ideas served as a mediator to facilitate structural abstractions that can explain any kind of representation of a phenomenon. In this case, it is worth emphasizing that the ability to perceive the structure across multiple contexts requires drawing further inferences, rather than reproducing the representation that are provided as sources (Gentner & Smith, 2013; Hofstadter, 2001).

These results confirmed the theoretical assumptions that students learn about abstract ideas and the transfer of these ideas through the steps including noticing (seeing the connections), mapping (capturing corresponding parts), and applying (generating a structure) as I discussed in the section of the theoretical framework (Gentner & Smith, 2013). At this point, it is important to indicate that the purpose of this study is not to test the validity of the theory of analogical learning, but rather to improve our understanding of the mechanism by which learners interact with abstract ideas, similarities, differences, and analogies as a way of sense making.

One issue that was raised in the theoretical framework was whether or not learners understand scientific analogies out due to being sensitive to surface features of any representations (Brown & Clement, 1987; Goldstone & Son, 2005; Stavy & Tirosh, 1993). In other words, learners can better solve a target problem when it covers equivalent versions of a source problem with a familiar situation. However, whether or not people learn abstract principles of a scientific concept is measured by their ability to solve any problems in an unfamiliar domain (Goldstone & Son, 2005). That means learners should be able to sensitive to the shared abstract features of the source and target to make an effective transfer between them.

One possibility is that Goldstone and Son (2005) are right and that students usually focus on the surface features of multiple instances of a phenomenon when they learn about scientific concepts. One may ask the question of what encourages learners to focus on the underlying structure of phenomena. In this regard, the possible interpretation of the results in this study may be that abstraction within synthesis modeling is aided by the presence of the different representations of the phenomenon. The availability of the different-looking instances during the whole process of model development provides learners with something that they could map their final model onto. These instances, multiple representations (sources) of the phenomenon that are available for students during the synthesis, also provide students with a chance to be sure that their structure (abstract model) can fit any sources of the phenomenon.

Toward a Hypothetical Framework for Teaching That Models Are Abstract, Not Exact Copies of Their Referents

I now consider the four themes that I drew from the narratives together and propose a framework for synthesis modeling to provide educators with guidelines for understanding of what it means to develop abstract models to help learners make sense of a phenomenon on a deeper level. Figure 11 condenses the four themes from the results into a general framework for a pedagogical way of helping learners understand that abstraction is one of the valuable characteristics of models to deal with the copy problem. This model aims to transfer the ways learners experience synthesis modeling from the specific context of this study, biogeochemical cycles, to other contexts in science curriculum. In this framework, developing abstract models has two main functions: explanation and evaluation.

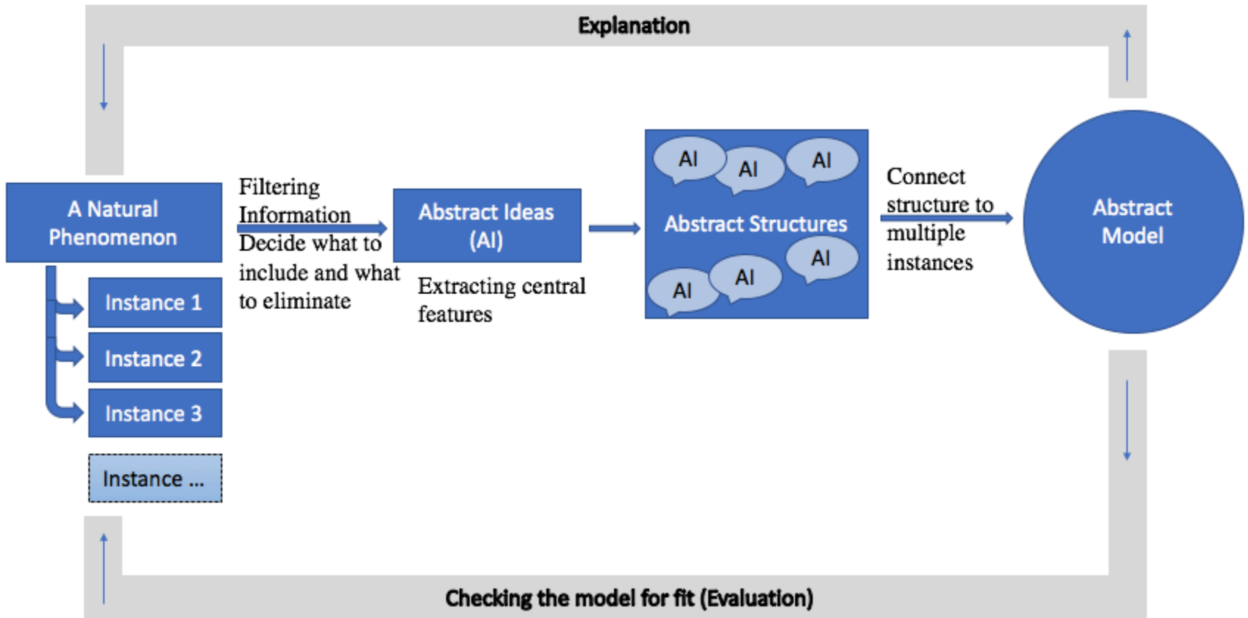


Figure 11. A hypothetical framework for teaching that models are abstract

The function of explanation provides a way of understanding how a system or phenomenon works in general because the abstract model is expected to represent the larger ideas behind the system or phenomenon rather than copying any of the sources that explain scientific phenomena. One important aspect of this function is that students can explain any kind of representation of the phenomenon. This representation does not need to be provided as source during the synthesis. In other words, student models should be adapted to any representations related to the same phenomenon.

As a second function, the abstract model development facilitates the way in which the students revisit each of the representations of the phenomenon that they try to explain through synthesis. The purpose of bidirectional relationship between the multiple instances and the final model is to check the model for fitness. That is, it is valuable that making sure that the features that are included in the model are applicable to each of the representations of the phenomenon. This function also helps student avoid copying any sources by eliminating the chance of covering surface level features in the model. The main reason is that the surface level features do not help students pull the structure away from the sources within synthesis.

In light of the ways students experienced synthesis modeling in this study, in this framework I propose that the synthesis modeling requires elaborating on different-looking instances that explain the same phenomenon. This elaboration is as follows:

- looking at the instances at a deeper level;
- taking out the key features from the sources;
- generating abstract ideas through these features;
- seeing how connected the ideas are;
- developing a structure by using the relations among ideas;
- mapping the structure onto a model;
- checking the model back and forth for the fitness to each of the representations; and
- revising the model, if needed.

Here, I go back to an argument in the literature that practitioner-oriented introduction to modeling practices emphasized the importance of knowing that learners tend to be too literal, when it comes to thinking about models (Krajcik & Merritt, 2012). The researchers did not provide any strategy that would help educators promote a more appropriate (i.e., nonliteral) conception. In regard to the framework I proposed in this study, the findings confirm that synthesis can support students in looking beyond surface level similarities to develop an abstract model. What it means to develop an abstract model rather than a replica can be taught students by using the framework that was derived from how the students experienced developing abstract models within synthesis—the main focus of this work.

CHAPTER 5

IMPLICATIONS, CONCLUSION, and DIRECTIONS for FUTURE RESEARCH

Implications

This study provides important insights into how learners experience synthesis modeling. If we are to help learners understand that models are not copies of the reality, we will need some ways to support this learning. Synthesis modeling is one of the ways in which educators can deal with the copy problem. According to the results of this study, what it means to develop an abstract model for students is as follows: (a) understanding the key features that connect all sources and take these features out from the sources; (b) using an all-purpose language to define key features common to all the sources; and (c) evaluating the wide applicability of final models to all the sources (i.e., any biogeochemical cycles).

In order to foster learning that models are abstractions, teachers could help learners:

- uncover key features that compose a phenomenon;
- hold a more holistic understanding of scientific concepts to see a larger picture;
- make sense of the idea that a model is an abstraction rather than a replica;
- understand that abstract model development needs to draw upon more than one source of a phenomenon;
- realize that there are desirable characteristics of models that often need to be quite different from sources beyond the preceding similarities and differences between the sources.

There should be greater emphasis on helping educators make sense of how to teach that models are abstractions and of how students experience the synthesis approach in classrooms. Specific professional development focused in facilitating learning that models are abstractions can provide science educators with a focus on how the abstract nature of models can be explained through the synthesis modeling approach and on how the synthesis modeling can interact with instruction of any subject and student learning. Focusing instruction on learning what models are will support students in understanding crucial aspects about the nature of science which is key in helping learners achieve a level of scientific literacy which is needed to become a critical consumer of scientific information.

Finally, this work investigating the experiences of the students within synthesis modeling will begin a conversation about the fundamental ideas and approaches to learning core ideas about what models are that can be used to organize instruction.

Conclusion

The central question I engaged with in this study can be summed up as follows: what does it look like for students to learn through synthesis modeling? I believe that this is a very important question for science learning and teaching. Reform movements in science education have placed a strong emphasis on modeling as a key scientific practice at the primary and secondary levels (e.g., NGSS Lead States, 2013). As promising as modeling instruction seems to be, there is much that we still do not understand about it. As an example, we still do not know how to address the longstanding problem that learners tend to see models as copies of the phenomena they represent (Grosslight et al., 1991) and there is a vacancy of ideas about what students should learn about models that make them something other than copies. As a step toward answering the central question, I built on Capps and colleagues' (2016) suggestion that abstraction could be one such idea about models worth learning and described the ways the students experience developing abstract models within synthesis. I think that understanding these ways could help science educators support the key purpose of using and developing models in science classrooms. With the hypothetical framework that I proposed in this study, I tried to put more emphasis on the students' experience developing abstract models, how learning in synthesis occurs, and how to facilitate learning.

Synthesis modeling can support learners in understanding that models are abstract by:

- engaging learners with different-looking instances that share an underlying structure, but differ on the surface level;
- taking learners from surface-level thinking to abstract thinking;
- minimizing the opportunity for copying sources of a phenomenon;
- providing learners with the opportunity for checking the applicability of their model.

As the main contribution of this study, abstraction is just one fundamental characteristic of models, and synthesis is a single approach to convey this idea to cope with the copy problem. Needed is research on other informative ideas about what to teach about the nature of models along with viable instructional approaches that can support both teachers and students in better understanding of the fact that models are abstractions.

I hope that this work will provide insight for educators to organize instruction in science classrooms. For instance, in argumentation, a core idea is that arguments consist of claims, evidence, and reasoning (Erduran, Simon, & Osborne, 2004). This idea can be used as a framework for teaching argumentation (McNeill & Krajcik, 2012). Absent a set of core ideas at this level, there is a danger that modeling pedagogy could be unfocused and therefore unsustainable. Furthermore, focusing instruction on learning that models are abstractions will support students in understanding crucial aspects about the nature of science which is key in helping learners achieve a level of scientific literacy which is needed to become a critical consumer of scientific information.

Directions for Future Research

An important direction for future research is to investigate how the degree of similarity and complexity of representations of phenomena affects the process of synthesis modeling. This investigation would provide empirical evidence on whether there is a relationship between the scope of abstraction, which is the main objective of synthesis modeling, and the degree of similarity and complexity of the instances that explain the same phenomenon.

Another direction for future research is to examine the importance of content knowledge within synthesis modeling. It is assumed that content knowledge in the disciplines has an impact on the ways in which learners interpret scientific phenomena. Investigations in this area would allow us to better understand (1) whether students with a different level of content knowledge exhibit different patterns in synthesis modeling and (2) how content knowledge influences the understanding of essential ideas and pathways.

A third direction for future research is to examine whether learners' understanding of models affects the way of developing models. Such an investigation would provide insight into whether having an idea of what a model is could account for performance in developing abstract representations of any scientific phenomena through synthesis modeling.

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APPENDICES

Appendix A

IRB Approval Letter

The University of Georgia

Phone 706-542-3199

Office of the Vice President for Research
Institutional Review Board

APPROVAL

May 3, 2017

Dear Daniel Capps:

On 5/3/2017, the IRB reviewed the following submission:

Type of Review:	Initial Study
Title of Study:	Synthesis Modeling as a Way of Thinking About the Nature of Models in Biology
Investigator:	Daniel Capps
IRB ID:	STUDY00004653
Funding:	None
Grant ID:	None
Review Category:	Exempt 2

The IRB approved the protocol on 5/3/2017.

In conducting this study, you are required to follow the requirements listed in the Investigator Manual (HRP-103).

Sincerely,

Dr. Gerald E. Crites, MD, MEd
University of Georgia
Institutional Review Board Chairperson

310 East Campus Rd, Tucker Hall Room 212 • Athens, Georgia 30602
An Equal Opportunity/Affirmative Action Institution

Appendix B

Jane and Sergio's Interview Narrative Summary

Jane and Sergio's Narrative

As the group begins the task, Jane suggests getting the essential ideas and components from the cycles. She is thinking about the variables that are affected, such as water and ground storage, and about the factors that go between those variables are, when it comes to modeling. Jane then states that for any of the cycles she looks at where the water is, where the carbon is, where the phosphorus is, and where they are stored. She adds that there are stocks (sources) and flows in the system like a ground stock, an ocean stock, and an atmospheric stock, and there are flows between them.

Jane begins drawing three square blocks to represent clouds, water, and trees on a white board. She says that the initial model including the atmosphere [clouds], the water, and the surface [trees] represents the water cycle. Next, Sergio suggests doing the same drawing for the other two cycles. Jane reminds him that they will have one model. In response, Sergio says, "Right, the idea is to have a single, let's just say, three square block flow charts of inputs and outputs for all of them at the same time." Jane says that she used three square blocks (atmosphere, water, and surface) because they are common in all of the three of the cycles—water, carbon, and phosphorus storage in the atmosphere block. The pair decides to call the tree, clouds, and water blocks a terrestrial living system, an atmosphere system and an aquatic system, respectively.

Sergio recommends making a Venn diagram rather than using square blocks to show where atmosphere, aquatic, and terrestrial systems intercept. Jane wonders why they would want to combine the systems. Sergio responds that he was interpreting square blocks that they drew in the first place as things that are stored in the atmosphere, things that are stored in the land (rocks, cliffs, etc.) and things that are stored organically. Immediately, Jane says that she was thinking more geographically about what the things cycling are rather than categorically—abiotic or biotic. Agreeing with his partner, Sergio argues that their initial model isolates each system from the other. He then wonders if there are situations when different systems blend. Jane responds that she is trying to define the boundaries between the systems and argues that the three systems represent living and non-living things on land, in the water, and in the air. Next, Sergio suggests using labels, such as non-living, instead of drawing square blocks. Disagreeing with him, Jane says that she would like to include terrestrial and aquatic components rather than living and nonliving things in each system. Sergio suggests splitting the squares blocks in half and labelling half as terrestrial abiotic and the other half as terrestrial biotic.

Jane begins to think about connections between the three systems through rain, run-off, soil, and organic matter. Sergio says that each arrow represents materials/components that go from one block to another. Elaborating, Jane says that materials for water, carbon, and phosphorous are transferred through precipitation from the atmosphere to the land and sea, whereas decay would only apply to the carbon and phosphorous cycles, but decay would move things from terrestrial biotic to terrestrial abiotic. Sergio says that some of the movements will be within each system, and some of them will be between systems. He then asks if they should split the block for atmosphere up because bacteria are in the air just as much as oxygen. In response, Jane asks if germs are significant factors in any of the three cycles.

Jane says that she tries to find common arrows that show the flow of the materials in the cycles. Pointing out the cycle diagrams, Sergio argues that there are three movements—something going from the land to the sky, something going from the sky to the land, and something going beneath the land. Going further, Sergio argues that arrows in the diagrams would be fairly consistent among the cycles. He adds that there are things going up and down, things going from left to right, and things moving within the cycle diagrams. Jane then realizes that there are things that are shared like between the two of the cycles, but not with the other one, such as burning fossil fuels and evaporation. She adds that both processes put the materials from the land into the atmosphere, but there is not such a process in the phosphorous cycle. Immediately, she corrects herself by saying, "Dust! Okay, so in all of them you have something going back to the atmosphere from the land."

Sergio argues that they are going to lose something when they try to take the three models [cycle diagrams] and make them into one. He adds that because each one is unique, there is going to be something about the water cycle that doesn't occur in the phosphorus cycle. Elaborating, he argues that something is going to have to be tossed aside for the sake of making one model out of three cycles. According to him, they should focus on looking for what the three cycles share and on removing what they do not share. Jane agrees and adds that atmosphere, soil, river, ocean, vegetation—these are all things that the cycles share.

Returning to the Venn diagram idea, Sergio redraws the three blocks that represent land, water, and atmosphere. He adds that they have three systems and that those systems share atmosphere, aquatics, soil, plants, animals, and rocks. Next, the pair decides to call freshwater-saltwater and sediments "aquatics" and "rocks," respectively, for the sake of simplicity.

While the pair tries to label the movements between the blocks, Jane focuses on what the arrow between the atmosphere and the soil means to the water, phosphorus, and carbon cycles, and she makes sure that the arrow applies to all of the cycles. Sergio asks how she wishes to visualize what she says. Jane responds,

> I don't mean to–I'm just thinking about what they are. So, if I'm thinking like, oh, atmosphere to soil, what does that mean for water, just rain falling on the soil? What does that mean for carbon? It means–atmosphere to–I guess photosynthesis would connect it [carbon] to the ground or carbon fixation of some sort. And for nitrogen or phosphorous, dry deposition and precipitation would put those things underground.

Sergio argues that what she says needs to be displayed to create a model. In response, she says,

> I think when we were condensing it we'll lose some stuff, like you said before, and those are the things we lose. And so maybe we're just saying when I–maybe if I introduce this to kids or whatever, I wouldn't say this is the carbon, water, and phosphorus cycle, but I'm just like, guys, there are relationships between living things and geological things and chemical things. And these are the ways that things move between them.

Agreeing with Jane, Sergio says that a unifying model takes three concepts and makes one picture out of them all.

The pair discusses each specific process and pathway between atmosphere, water, soil, plants, rock, and animals—sedimentation, infiltration, breakdown, leaching, evaporation, and decay. The pair then thinks about whether or not they should restrict their arrows simply to what is in the diagrams and not to what they know from common experience. Jane thinks that they should focus on the things given in the cycle diagrams. Jane adds that they should stick to what is in the cycle diagrams. Next, Sergio suggests that if something is not in the cycle diagrams, they should leave it off.

The interviewer interrupts and asks what they call the blocks in the model. Jane says, "Storage!" Sergio argues that each block defines a system [atmospheric system, animal system, soil system, etc.]. Jane says that those blocks are stocks for the elements that they discuss. She then adds that those blocks can be either sources or sinks or both.

Jane suggests not labelling every single arrow in the model. Sergio disagrees and argues that they should label every arrow [process] to make the movements between the blocks [systems] explicit. The pair continues to check if they covered all the important processes such as sedimentation, fertilization, infiltration, and rock formation in their model. Sergio says that they have translated all three of the cycles into their model. In response, Jane says, "Yeah, I just feel like what we did is like model all these things here [cycle diagrams] and put them all together." Going further, Jane says that they include the things [systems and processes] that they synthesize from the cycle diagrams." Sergio adds, "We have gone through–we just went through every – as you said initially, it was just to use these as source materials and not common experience. We've gone through all the processes in all three and have included this in the model."

The interviewer asks if their model is a representation applicable to all the three of the cycles. Jane responds that the tags [labels on the arrows] are specific, but that the arrows generally show relationships between the blocks [systems]. She then adds that the way the systems share or do not share the processes gives you an idea of what goes on in the world. Interrupting again, the interviewer asks if the pair thinks that it is important to show those processes in their model. Immediately, Jane responds that she has not had enough time to think about what to exclude or what to include. Going further, Sergio says, "I would say, if I may step in on that, I would say, yes, because what we were asked to do was to take these three models [cycle diagrams], we were not told to evaluate which ones were important, the interpretation, therefore, is if they were included in the three models, it should be considered given that they are important because we were asked to take what was on here [cycle diagrams] and make it into a single model. Therefore, it's irrelevant as to what the process actually is; it was on these sheets of paper [cycle diagrams], [so] it's on here." Jane adds, "But I guess we are also meant to come up with a common model instead of like adding everything–like one way to make a common model is to add everything together; another way is to only find what things are in common. But if I only took things that were in common for all three, we'd only have two arrows." Elaborating, Jane says,

> Yeah, I would only have two arrows if I was like it has to be common across all three—then that's pretty much useless. I feel like because then you're not seeing any of these others. So, I guess if it was only one cycle, like only phosphorous has something from soil, so I don't include it. But if more than one of them has something going from one to the other, then I think it's important." Sergio argues that they needed a color code because all the processes are important, but they do not apply to every single cycle.

Appendix C

Henry and Frank's Interview Narrative Summary

Henry and Frank's Narrative:

As the pair begins their task, Henry tries to identify where water, carbon, and phosphorus are coming from in the diagrams. He refers to this as the "key source." He quickly identifies the atmosphere as the source of water in the water cycle saying water is then cycled through land and eventually back to the atmosphere. Frank agrees that the atmosphere is a key source for the water cycle, but points out that rocks are a key source of phosphorus and carbon. He elaborates that these elements come from the build-up of biofuels over many years. Returning to his idea that the atmosphere is the source of water, Henry suggests putting the atmosphere at the top of their model. Frank again questions whether that would be true for all of the cycles or just the water cycle. Elaborating, Henry says that the atmosphere is where water comes from and that it is where carbon and phosphorus end up. Frank then suggests they include land (bio fuels) as the source of C & P at the bottom of the model.

Continuing, they discuss the water cycle diagram identifying where the water comes from and where it goes, using the language of sources and sinks. They agree that the atmosphere is the source, while both the land and ocean are sinks. Frank then points out that the ocean is the largest sink of water, and he wonders aloud whether the ocean also plays a role in the C & P cycles. Answering his own question, he states that the ocean is more important for the C cycle, as P is recycled directly by the land. Henry agrees that the ocean is more important to the C cycle, adding that there are many organisms in the ocean, like coral, that produce CO_2. Frank then explains that in both the C & P cycles material passes through organisms, like plants and animals. They then name the sources and sinks in the C & P cycles, and Henry elaborates on Frank's idea about P going straight to land saying, P "goes back and forth through vegetation" and suggests they add "a circle of phosphorous just being reused" to their model.

The interviewer notes that the group has been talking about the diagrams individually, and reminds them that their task is to create one model that would work for all three cycles. To the prompt Henry responds, "Got it! So if this is the case, then everything is cycled," to which Frank adds, "So we could do a common cycle." Henry begins writing on the whiteboard, speaking as he writes, "Maybe we could do something like this, and I don't know if this will work, but I'm just going to make a circle and then you can input. So, this is going to be atmosphere, it's going to be ocean, and it's going to be land." They begin labeling the diagram and adding arrows, going through each transfer (e.g., atmosphere to land, land to ocean, etc.—this takes a good deal of time). Early in this labeling process Frank wonders if they should include a second label for land that is underground, to which Henry responds, "I think they would understand that everything about land, whether it is underground or above ground, would be land." The interviewer interjects to ask for a description of what they are thinking as it is not abundantly clear from their discussion. Henry responds, "The reason why I was doing that [labeling the arrows] is because not every cycle is the exact same; some cycles, such as the carbon dioxide exchange, which goes from the atmosphere to the ocean, also go from the ocean to the atmosphere. So that's why I was drawing the double arrows." All this time they continue to look for commonalities between the cycles, finding some between the water and carbon cycles, but struggling to find something common to all three, except possibly runoff. They move forward with Henry's proposal of labeling the arrows on their model deciding to use different color markers for the arrows between the spheres and making a key so that, "someone who has never seen this before would not be confused." As a final step Frank suggests adding the self-feeding cycles to make it "more detailed." To do this they look at each diagram for self-feeding cycles that would need to be added to the model. As an example of this they return to Frank's idea that the P cycle is recycled by the land. Frank explains that after a tree dies, its P "doesn't interact with any of the other parts of the cycles." Henry elaborates, "It would go into the sedimentation again and then phosphorus would be reused for soil for another plant." They complete their drawing, which Frank notes resembles, "Mickey Mouse," and they begin discussing more details of the lobe representing the carbon cycle, to which Henry points out is "just getting more detailed." Henry asks whether they should call their model of the three cycles "Geological cycles or life cycles." Answering his own question, he notes that "you couldn't really necessarily call this life cycles because some of these are abiotic factors." They then decide to call those cycles biogeochemical cycles as they complete their initial model.

The interviewer asks the pair if they are satisfied with their representation. Henry responds, "I was thinking what similarities do they [the cycles] have and they have a few but they have more differences than they have similarities, at least to my eye." So, it's really hard to just make one cycle...I was like, okay, there's no way that you can just make one simplified diagram. So, you would have to include the reversible cycles." Frank agrees with Henry's assessment stating that a "single-cycle solution to all of these might be difficult in terms of correctly portraying each of them."

The interviewer then points out that the group has represented only three cycles and asks, "What if you were asked to make a representation that would work for all biogeochemical cycles?" Frank says, "That might be easier to do than with three because it would become far less detailed." The interviewer challenges the pair to make such a representation. Immediately, Frank says that they can use words like reservoirs and sinks instead of specific names. Henry adds air, water, Earth, energy and fuel to the list. As they develop the list they begin working with the terms in order to decide which are necessary for the representation and work on refining the list. Their criterion is whether the term is "general" enough to work for all cycles. As an example, they debate using the term sediment or land, and decide on land as it would "incorporate everything." In the process of compiling the list of terms, Henry begins thinking about what the diagram will look like noting, "It wouldn't be a circle, it would have to be something similar to this where—because energy goes in both directions, gases would go in both directions, water would as well." Frank works with Henry's idea suggesting, "We could super simplify it and say it's a cycle of energy, water, and gases through land, ocean, and atmosphere." At this point they begin drawing their model. They put atmosphere, land, and ocean in a triangle on the whiteboard. After this Henry instructs Frank to connect the spheres with different color lines representing energy, gases, and water and to put two-sided arrows on all of the lines. As Frank connects the lines between the spheres they talk through each of the connections making sure the arrows should truly be two-sided and that their representation is sufficiently "broad" to incorporate different biogeochemical cycles.

Appendix D

Kate and Mabel's Interview Narrative Summary

Kate and Mabel's Narrative

Starting the task, Kate tries to figure out which steps in the diagrams are linked. She claims that some of the cycles have similar things like the vegetation and decay. Mabel adds, "Anything involved with plants is in the water cycle and the carbon cycle. Anything involved with just like sediments and things like that is mostly going to be in the phosphorous and the carbon cycle. So, you basically need to kind of just mix those two." When Kate asks which process they should start with, Mabel responds, "Weathering!" Kate agrees and explains that weathering involves carbon, phosphorus, and water. Mabel argues that weathering looks like it is mostly phosphorous. Thinking whether there would be a different way to describe weathering for the carbon cycle, the pair defines weathering as any sort of breakdown. Kate suggests writing out things such as vegetation and then figuring out where the things go from there. Continuing, Mabel suggests including extraction as one of the steps for fossil fuels and phosphorus. Immediately, Kate asks if extraction would lead to something, or would something be leading to extraction. Mabel answers her partner's question by saying that for phosphorus, extraction goes into vegetation, because it uses fertilizer. She then says, "I just need to keep all of these [arrows] uncapped." The pair continues to link the pathways and processes in the cycle diagrams with each other.

The interviewer reminds the partners that their goal is to create a general representation that is broadly applicable to each cycle. She asks whether or not the cycles all include a vegetation—the ground cover provided by plants. In response, Mabel states that everything uses respiration, and they need decay, because that releases phosphorus. Elaborating, Kate says, "So, we just need to go through and try to figure out which processes and/or pathways are applicable to each of the three cycles. In response to Kate's argument, Mabel starts circling the things that show up in more than one cycle. First, she adds decay by arguing that decay does not show up in the water cycle, but they could apply it to the water cycle. Next, she adds respiration to the model, because it is in the water and the carbon cycle. Kate says, "Respiration would also uptake phosphorous." Kate argues that if they want to make the process of decaying super general, they can do something similar to like excretion, because that will include like detritus and phosphorus as well.

The interviewer interjects to ask what makes a biogeochemical cycle and what the main idea is behind a biogeochemical cycle to steer them towards the task once again. Mabel promptly responds, "Everything needs to lead back into each other. So, we need more pools, because we have got vegetation and atmosphere." Kate maintains that the three main steps could be ocean, land, and atmosphere. They decide to erase their initial model. Mabel suggests using the word ocean instead of water, because there is fresh water storage and aquatics, as well. Kate asks whether or not those three—ocean, land, and atmosphere—are the basic storage for these chemicals [carbon, phosphorus, and water]. Mabel responds, "Yeah. If we count deep sediment as land." She then says that they have sediment, and they need organisms for one of the steps. Kate thereupon asks whether or not they can use a general term instead of organisms. Mabel asks, "like life?" Then, she claims, "See, organisms bridge all three cycles." The pair begins making connections among land, ocean, and atmosphere by adding two-way arrows, because they argue that they [land, ocean, and atmosphere] feed into each other. While they discuss whether or not the burning process is one-way, they call the process of burning fossil fuels "weather." And, then, Kate starts creating some more links, saying, "The sun helps organisms live, organisms go into sediment when they decay, and sediment also helps organisms. So, this relation can be like a two-way."

Realizing that the pair is still keen on seeing what is obvious in the cycle diagrams and considering those superficial features that appear to be important at first glance, the interviewer interrupts by asking whether weathering is an underlying feature of all three cycles or not. In response to this question, Mabel suggests, "We need a general term for land to atmosphere interactions. That is not just straight up weathering. Evaporation, maybe?" Kate responds, "But, evaporation does not do anything with phosphate." Mabel explains that they have five different words [weathering, burning, secretion, evaporation, and transpiration] to describe what they want for each process. They do not have any description for all of them [processes], which is kind of what they need.

The interviewer recommends for them to think about living factors since organisms are also depicted in the cycles. After this suggestion, Mabel adds, "So, we could do like–so like abiotic transfer or something like that, because this [the organisms] would be biotic transfer." Then, Kate says, "Organisms are already covered. That is what I thought that general weather and not weathering. I thought that is why you wanted to choose weather." Immediately, she asks, "I understand how weather causes phosphorous, but how does it do carbon?" Mabel answers her partner's question by saying that she is still trying to figure that out, and the closest they have is burning. Kate suggests doing abiotic processes so that they include weathering and burning as examples. Agreeing with her partner, Mabel asks whether or not they could call deep reserves of carbon and phosphorus as lands. When Kate asks what they are missing, Mabel suggests going full out and rewriting every process in a new color. They agree that they should include both abiotic and biotic factors in their second drawing.

The interviewer reminds them that their task is to develop a general representation that will work for all three cycles. She then asks what the function of the sun, which seems to be specific to the carbon and water cycle, in the phosphorus cycle is. Mabel responds, "Atmosphere is not really involved in the phosphorus cycle, unfortunately." In response to her partner's statement, Kate mentions that the atmosphere is involved with dust clouds, and that is how it [the atmosphere] works in the phosphorus cycle. Mabel suggests using "abiotic processes" when they are not sure whether or not the process they want to include in the model is applicable to all the three cycles. Next, the pair discusses if the abiotic processes only occur between the atmosphere and water or not. Kate argues that it [organisms in the middle of the model] links everything. "I think both abiotic and biotic are both really important, yeah, because we have got the abiotic stuff and the biotic in the model. Elaborating, Kate adds, "I think all of these [water, land, and atmosphere] are going to be different on the outside, all these different abiotic processes change, but the one constant between how land and water interact, water and atmosphere, and atmosphere and land, are all through organisms." The pair returns to their initial model draft by labelling the arrows between atmosphere, organisms, land, and water with specific processes such as decay, weathering, respiration, etc.

The interviewer gets involved in the conversation by pointing out that there is no respiration process in the phosphorus cycle even if the pair includes the respiration process in their model. Kate says that that is what she is trying to figure out. Mabel adds, "The only link between the atmosphere and the phosphorous cycle is like dust and all that." Going further, Kate asserts, "Actually, respiration does work, because there are trees. We would have to specifically be talking about autotrophs, but trees can pull phosphorous from the atmosphere, from atmospheric dust. So, we could use respiration for that, but it would be very specific, and at that point, we would have to do – for organisms, we would have to turn it [organisms] to autotrophs." Mabel disagrees with the idea that organisms should only be turned into autotrophs by arguing that they are cutting out a pretty major part of all three cycles, the heterotrophs, for the sake of simplicity. Kate then suggests writing "autotrophs only" underneath the arrow between atmosphere and organisms, showing the respiration process.

Soon after the pair completed their final model, the interviewer asks one more question about how their final model differs from the three cycles. Kate promptly responds, "Well, the main difference is just the fact that we have broken it down so much into just water, land, atmosphere, because for each of these [cycles], they are looking at atmosphere in, I guess, different ways; they are looking at land in different ways and water in different ways." Agreeing with her partner, Mabel explains, "We are basically just splitting it up into these three main reservoirs [water, land, and atmosphere] for all of the cycles. But, over here [pointing out the cycle diagrams], it is like phosphorus is mainly in like sediment and weathering, but carbon can either be like inside life or atmospheric or dissolved. There is lots of different pools." Kate then argues that water and carbon cycles are good at showing the actual cycling whereas the phosphorous cycle is not a good representation. She thinks that their final model is a better example of how phosphorus cycles. Mabel recognizes that they had the hardest time trying to tie phosphorus to atmospheric cycling. Continuing, Mabel explains that they included respiration, because it is just so important for the carbon and water cycle, and they were trying to show how respiration would work with the phosphorus cycle, also.

When they are asked if they think that their model is broadly applicable for each cycle, Kate responds, "Yeah, because you could show this [their final model], and this is how it works for phosphorous. This is how it [the final model] works for water. This is how it [the final model] works for carbon. I mean, yeah, things that are pretty necessary in each cycle are left out, but that is simply because those things do not make any sense for any of the other cycles."

Appendix E

Kacy and Jade's Interview Narrative Summary

Kacy and Jade's Narrative

As the pair begins the task, Jade says, "If we are going to make something that is representative of all of these cycles and even like nitrogen, that is a different cycle, like I just look for things in common." Elaborating, on her idea she says that cycles all have a pretty similar setup with a few different details, sources, and sinks. She argues that she would like to see what the cycles have in common and then how they could make the model general so that they can adapt it [the model] to whatever they are interested in. Kacy reminds Jade that they should try to incorporate the three cycles in one image and suggests starting with coupled processes that happen at the same time. What she means is that some materials are coupled as flow through systems together (e.g., organics and water). Jade asks whether or not by coupled her partner means that there are different kinds of runoff (e.g., surface runoff or river runoff) in the different cycles and if they could put those processes together. Jade also points out that there are similar flow directions across the cycles, but Phosphorus has a lot of internal cycling. In response, Kacy says that there is overlap between the arrows (flow directions), but different things (materials) move in the cycles.

After their initial discussion, they decide to put their ideas on a whiteboard. Jade says they should begin with the major pieces from each cycle. She adds that vegetation, soil, water, and atmosphere are what the cycles boil down to. Kacy starts by drawing land and water, making it look like the cycle diagrams. Jade recommends simplifying the model saying, "If we were showing this to someone, they would understand it more easily if we had like a super simplified, like minimalist thing." She directs Kacy to draw a box instead of making that part of the model look like land. They then start discussing whether or not the size of the arrows in the cycle mean anything. Kacy suggests using one size arrow and one size pool in their model as they are focusing on movement of materials and not the amount of material that is moved. After drawing four boxes to represent pools, Kacy suggests calling one of the boxes Earth's crust. Jade prefers to call that box lithosphere or sediment instead. They end up deciding to call the boxes lithosphere, atmosphere, biosphere, and hydrosphere assuming that those labels would work in each of the cycles.

Continuing, Jade asks what the most important part of flow to portray is. Kacy suggests that they should begin with the water cycle as other elements are coupled with the movement of water. They focus on internal cycling in each cycle diagram pointing out that internal cycling is very important in the phosphorus cycle. They begin looking for materials that move between the spheres. Jade claims that the water cycle has inputs to the atmosphere through evaporation and transpiration. She then adds that she cannot see anything coming from the lithosphere. Kacy says that phosphorus would go from biosphere to atmosphere. Meanwhile, they draw arrows between spheres to show how they are linked to each other through pathways such as transpiration, evaporation, and sublimation. With this aim, Jade suggests including the water cycle in the model and adding things that are needed to represent the other cycles using color. Kacy suggests including a smaller cycle within the boxes. Elaborating, she says that evaporation is an internal cycle within the water and phosphorus cycles. Disagreeing with Kacy, Jade argues that those smaller cycles such as interception loss—water reabsorbed by the soil before it evaporates—are not important to consider.

At one point, the pair begins to include some specific processes in their model, like sublimation, that are only present in one of the cycles. The interviewer interrupts, reminding them that their task is to develop a general representation applicable to all of the cycles, something the pair themselves had already stated. Jade returns to her ideas of boxes saying, "Basically, you have these same boxes [spheres] and we need to represent a flow between them that could be—it could be the nitrogen cycle, it could be the carbon cycle, it could be the water cycle. It just is like a general representation of flow between different spheres it sounds like to me." Continuing, Jade adds that they need to represent the flows of materials between the boxes. Kacy then asks whether the model with boxes should explain the cycles or provide a frame that words can be added to. Jade explains what her idea of boxes is by saying, "You do not have any specifics from any cycle, but you have commonalities or general things you take from all of the cycles that would be applicable and that you could, if you wanted to, take this model and then throw nitrogen at it, it would fit." She adds that the model should be cyclical with losses and gains, with internal cycling within each box (sphere). Going further, she explains what every box in the model means by saying, "The concept is, it's not a biosphere in a box, but we're representing it as a box in this case (of biosphere). Agreeing that boxes are a good idea, Kacy thinks about how to link four boxes showing different spheres to make it more self-explanatory without going into specific cycles. Jade suggests connecting the spheres with arrows. She then says that each box [sphere] could link to some of the boxes, but probably not to all the boxes [spheres]. After realizing that there is no direct link (flow) to the atmosphere from the lithosphere in any of the three cycles, they argue over what the simplest way to explain cycling between spheres would be. Jade suggests that they need to show an internal cycle that cycles within one of the boxes. Kacy gives an example of the internal cycle by saying, "For example, here in the phosphorous cycle, there is some of the phosphorous that gets reabsorbed from the decaying plant matter and it does not leave the biosphere." Jade then talks about how they can link the different spheres to each other. She argues that they would not connect lithosphere and atmosphere, but they would link hydrosphere and biosphere, atmosphere and biosphere, and atmosphere and hydrosphere, and the lithosphere connects biosphere and hydrosphere.

Returning to her idea that everything leads to everything, Jade draws a crossing arrow in the middle and double-sided arrows on the outside linking all of the boxes to one another. She then asks if their model would look better if it was a circle instead of a square. Kacy argues that a cloud-like shape that can make the boxes look like more dynamic (likely to interact each other) might be better to show the right placement of the four spheres. Jade responds that the clouds rounded edges add unnecessary details to their model. Feeling confused about their representation, Jade says that their representation would not be the easiest way to teach the subject to someone. She adds that when they have a box and arrow representation, they would not have enough resolution of the cycles. In response to this concern, Jade says, "This is like the big, like the abstract concept, it is not like if you had a test, you would not know specifics from this, it would just be like generally, we have different spheres and they have materials that cycle between them and there is internal recycling." Returning to discussing whether or not it would be useful to teach the concept with their model. Kacy says that it wouldn't. Jade, reversing course from earlier, argues that it might be a good way to introduce the concepts, starting with the general model before going to the specifics. She also notes that she might use the general model on a test and ask how it could be adapted for a new biogeochemical cycle such as the nitrogen cycle.

Returning to the model the two begin to make improvements. Jade notes that the middle section of their model that show the interactions between four boxes with two-sided arrow is confusing and suggests removing it. She deletes the middle section of the model and draws a circle connecting the boxes. Kacy points out that the circle implies a certain directionality from one box to another, which is not right, because that circle does not represent multiple interactions between the boxes. Jade suggests removing the outside arrows, keeping the circle, and crossing arrows in the center. Kacy then adds arrows to show the circles are reversible.

While editing and evaluating their model, they decide to erase it and start over, to make sure their fundamental idea makes sense. Jade suggests making circles instead of squares, while Kacy considers how to arrange spheres. Jade tries making a Venn diagram-like model, but realizes that it shows a sharing of materials, not flow of materials. Kacy says that she does not prefer the diamond arrangement over the square. After a short time, they realize that they do not need to redraw the model, but instead just flip the board.

Summing up their model, Jade says, "You have four things and you have internal stuff happening in those things [spheres] that do not go outside. And you have stuff transferring around and you have stuff going into everything. Does that make any sense for a biogeochemical cycle?" The interviewer interrupts, asking if their model is only of abiotic factors. Kacy explains why they do not include abiotic factors in the model by saying, "At this point we were thinking more of the transfer of an element, energy source, nutrient, and not thinking about that distinction specifically because it depends on the cycle." Going further, she says that when narrowing down you need to make decisions of what is included in the model. When they are asked to label boxes, Kacy begins thinking again about the orientation of the boxes (square vs. diamond). In response, Jade says that she does not understand why orientation of the boxes should matter. Elaborating, Jade argues that their existing arrangement gives the general concept when she wants to explain that materials move between spheres. Returning to the discussion of whether abiotic and biotic factors should be included in the model, Jade says, "I don't think I would look at this and say, I could tell you like, oh, what is a biotic flow versus an abiotic flow, I would just say material, like I don't think I have that specificity here. I mean, you could be like this is the only like living thing if you wanted to make a special symbol that was like – if you didn't know that biosphere meant biotic and this is all abiotic, you could do something."

The interviewer asks what the different colors in the model mean. Jane responds that the colors distinguish different groups, biotic versus abiotic. Jade then suggests defining boundaries between "abiotic and biotic" components. She then adds a dashed line around the biosphere box to represent the biotic component and frames all the three boxes—atmosphere, lithosphere, and hydrosphere—to show where abiotic components are located in the model by putting another dash line.

The interviewer asks whether or not they are satisfied with their model. They both say that that model looked better than the ones they had before. After adding a footnote to the model to show what the arrows mean in their model, they complete the model development process.

Appendix F

Sabrina and Calina's Interview Narrative Summary

Sabrina and Calina's Narrative

When the group begins the task, Sabrina suggests drawing a symbolic ecosystem and using different colored markers to represent the pathways for each biogeochemical cycle to show how the pathways overlap. Calina points out that most simply, the carbon and water cycles are between the atmosphere and Earth's surface, elaborating, "If you extremely simplified it, you would have one arrow going up and one arrow going down and like maybe a few undergrounds." Immediately, she corrects herself, saying, The arrows going up and down do not, "fit into phosphorus as well because that is something that seems to be happening in a different way." Going further, Calina notes that the three biogeochemical cycles cannot be simplified in terms of the ways of cycling of the materials. Returning to Sabrina's idea of showing overlapped pathways, she suggests separating all three cycles. Sabrina responds that they can combine their ideas and have a more simplistic carbon and water cycle by building the phosphorus cycle into the simplified cycle. She then explains that in order to represent all of the cycles, it is important to draw out the primary differences by emphasizing the fact that atmosphere does not play a role in the phosphorus cycle. Calina agrees and notes that phosphorus does not become part of the atmosphere other than the particulate matter in the dust. Next, Calina notices that the phosphorus cycle has short arrows, whereas the water cycle has long arrows. Elaborating, Calina says that phosphorus differs from the other two cycles while trying to build the phosphorus cycle in the model. Sabrina responds that the phosphorous cycle is not as effective as the other two cycles on ecosystems so phosphorus stands out from the other two cycles.

As they begin to draw their model they discuss which color will represent carbon, water, and phosphorus. The first thing Sabrina draws is a coastline which Calina agrees is "common" to all of the cycles. She also adds waves, atmosphere and some vegetation and, "a little farm plot that seems to be a common element to the carbon and the phosphorus cycle." Sabrina suggests making a key to show which color represents what. Starting with the water cycle, Sabrina says that the atmosphere is linked both to photosynthesis and the ocean. Immediately correcting herself (with her partner's help), she notes that the atmosphere and ocean are connected by precipitation, and that the reverse connection is made by evaporation and evapotranspiration. At this point the interviewer asks, "is evapotranspiration also part of the phosphorus cycle?" Calina responds, "No – I do not think it [phosphorus] goes into the atmosphere, but it does come from living matter, it cycles through the living matter, so that is a common link, but I do not know if we can express the same concept with one single symbol." Turning their attention to the Carbon cycle, Sabrina suggests adding a lot of parallel arrows calling one of them "respiration." She then asks how they are going to connect the arrows. Calina points out that the carbon cycle is not only biological carbon, but also includes, "coal and gas stuff." Arguing that they have a quick biotic cycle under wraps, Calina suggests drawing an ocean. In response to her partner's suggestion, Sabrina draws a rocky layer on land that is next to the ocean. Calina then adds the seafloor to the ocean to show the interaction with an arrow from the seafloor to the sediment on land and calls the arrow "rock formation." Right before completing their initial model, Calina suggests drawing a carbon to represent fossil fuels.

The interviewer notes that the pair has been talking about ideas specific to one or two of the cycles and reminds them that their task is to make a general representation that is applicable to all the three cycles. Calina responds, "I misunderstood then. I thought we were making like one picture that included all the cycles, not making one model." Calina begins asking if they can focus on slow and fast/quick cycling. Sabrina suggests calling the quick cycling "biotic cycling."

Calina agrees with her partner and starts drawing a representation of what she means by fast cycling on a scratch paper. Calina adds, "We have the more like internal cycling that works for– that is more of the biotic–like I think like maybe this [drawing on scratch paper] without labels would be our best representation, like quick cycling instead of slow cycling? Trying to find common ground between the cycles, Sabrina says, "We had a lot of arrows that aligned, and I was going to simplify those arrows down to the ones that overlapped, and you do lose some of your specifics in there, but that is fine if they do not apply across all models [cycle diagrams]." Calina suggests labeling the model slow and fast cycling, which is what connects all cycle diagrams. Elaborating, Calina says, "We have the fast cycling carbon that is going through the biotic cycle with water, and then there is the slower cycle where it is seeping through the ground water, and then it goes into the ocean, and then maybe part of that enters the fast cycle."

Thinking of how the pathways overlap, the pair simultaneously focuses on the fast and slow cycles in the model. Sabrina looks at the carbon cycle and the water cycle to see if the precipitation is common for both cycles. Calina suggests calling precipitation "inputs" to include some pathways that have the same function across the three cycles in their model. This conversation continues… Simultaneously, they work on their idea of fast and slow cycles in the models. Calina points out that below the surface is where a slow cycle happens, and their model can branch off into the biotic cycle on Earth's surface. Sabrina then asks how to describe below the surface. Answering her own question, she says, "I am thinking of like for water it is slow migration because it is moving through the aquifers and things like that." Calina suggests calling that part of Earth "the holding area." Sabrina corrects her partner, saying, "Reservoirs. We could just say that." Continuing, they discuss whether or not the things that become atmospheric through the processes such as evaporation, respiration, and dust can be called "outputs." They then focus on movements from underground reservoirs to Earth's surface, adding some arrows to show how fast cycles go into slow cycles. After that, Calina adds "in cycle" to "out cycle" arrows, saying, "So we have got phosphorous. We have got like things grow and then they decompose and then the plants take up those things that grow and like for water there is also the tight cycling of like water that is taken up by plants and then perhaps reused by the plant or dropped to the ground, right, like that kind of stuff, and then the same for carbon, too." Once they have several arrows in their model, Sabrina makes sure that wherever they put arrows, those arrows should have functions related to each cycle. That means they check whether or not the arrows in the model have a meaning for each cycle. Sabrina thinks of the possibility of having two nondescript arrows that link the fast cycle to the slow cycle. They complete their model by calling the fast cycle and the slow cycle "biotic" and "abiotic," respectively.

The interviewer asks the group if they are satisfied with their representation. Sabrina responds that they did not have to label the three different cycles; they [the cycles] are all covered. Agreeing with her partner, Calina says, "Yeah, and I like that [the final model] while it [the final model] does not necessarily have the specific fluxes and pools, it [the final model] gives a more general idea for how the cycles work globally, which I like. And I think the connections between the fast and the slow cycle are some of the things that people lose sight of when they are thinking about biogeochemical cycles, so I like that we highlighted that." She also adds, "I like its [the final model's] abstractness. I think it [the final model] provides a lot of opportunities for conversation if we were using this as some kind of teaching tool." After this, Sabrina compares their model and the cycle diagrams, saying, "I feel like if I were learning these cycles it would be more helpful to understand this general format and then go and learn all the different specific ways that they are transformed because these are very busy, so there is a lot of terms going on and learning all of those individually could probably be overwhelming when all you really need to know is that it [material] cycles and what is really important is how quickly it [material] cycles, especially when learning about climate change and moving into some of the higher level understandings of why these cycles are important, it is really the rate."

Appendix G

IRB Consent Form

UNIVERSITY OF GEORGIA
CONSENT FORM
Synthesis Modeling as a Way of Thinking about the Nature of Models in Biology

Researcher's Statement

We are asking you to take part in a research study. Before you decide to participate in this study, it is important that you understand why the research is being done and what it will involve. This form is designed to give you the information about the study so you can decide whether to be in the study or not. Please take the time to read the following information carefully. Please ask the researcher if there is anything that is not clear or if you need more information. When all your questions have been answered, you can decide if you want to be in the study or not. This process is called "informed consent." A copy of this form will be given to you.

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College of Education
105K Aderhold Hall

Co-Investigator: Ayca Karasahinoglu

Purpose of the Study

The purpose of this study is to investigate the processes through which synthesis modeling supports learners in constructing general models. It will also shed light on what can be learned about the nature of models through participating in synthesis modeling.

Study Procedures

The study will consist of a 30-minute think aloud interview where you and a partner will be asked to talk out loud as you complete a task related to scientific modeling. For example, you might be asked to construct a general model for a scientific concept, such as desert formation, working from multiple specific desert types.

If you agree to participate, you will be asked to:

Participate in a short, think-aloud interview where you and a partner will be video and audio recorded as you talk out loud about a science topic.

Allow your video and audio recordings and materials you create during your interview (e.g., drawings) to be used for research purposes.

Risks and discomforts

We do not anticipate any risks from participating in this research.

Benefits

- Providing us a deeper understanding of how we can support students to think abstractly about phenomena in biology
- Encouraging teachers to view models as an abstract and transferable construct rather than a copy/image of reality so that they can recraft their instructional approaches
- Leading curriculum developers to review the way of using models in both curriculum design and contents of science textbooks development

Incentives for participation

A $10 gift card from a coffee shop will be offered for participation as an incentive in this study.

Audio and Video Recording

The think aloud interviews will be employed by this study has been chosen as a way of understanding the learners' thinking of the nature of models. Think-aloud is a process where participants say everything that is on their mind as they are working through a problem. For example, you might be asked to construct a general model for a scientific concept, such as desert formation, working from multiple specific desert types. A video and audio recording will be taken as they work. The think aloud interview will be conducted on UGA campus. The procedure should only take about half an hour. The original data from this study will be kept in a secure locked location in Aderhold Hall for a period of one year from the completion of the study, or one year from the date of any publication of the results whichever is longer.

_______I do not want researchers to use my drawings in publications.
_______I am willing to have my drawings used in publications.

Privacy/Confidentiality

The confidentiality of each research study participant will be maintained by assigning a code number based on the total number of students who choose to participate. Participant names and code numbers will be correlated using a code key (i.e. participant name= code number, for example Ayca Karasahinoglu= Participant # 001). The drawings and video and audio recordings will be identifiable by code number only and no reference to the identify of the study participant will be possible. The original data from this study will be kept in a secure locked location in Aderhold Hall for a period of one year from the completion of the study, or one year from the date of any publication of the results whichever is longer. All original documents will be shredded and disposed of as confidential document waste.

Taking part is voluntary

Your involvement in the study is voluntary, and you may choose not participate or to stop at any time without penalty or loss of benefits to which you are otherwise entitled. If you decide to stop or withdraw from the study, the information/data collected from you up to the point of your withdrawal will be immediately shredded ad disposed of as confidential waste. Your decision to participate or not will have no bearing on your grades or class standing.

If you have questions

The co-investigator conducting this study is Ayca Karasahinoglu, a graduate student in Mathematics and Science Education at the University of Georgia. Please ask any questions you have now. If you have questions later, you may contact Ayca Karasahinoglu at ayca45@uga.edu or at 706-765-5744. If you have any questions or concerns regarding your rights as a research participant in this study, you may contact the Institutional Review Board (IRB) Chairperson at 706-542-3199 or irb@uga.edu.

Research Subject's Consent to Participate in Research:

To voluntarily agree to take part in this study, you must sign on the line below. Your signature below indicates that you have read or had read to you this entire consent form, and have had all of your questions answered.

_______________________	_____________________	________
Name of Researcher	Signature	Date
_______________________	_____________________	_________
Name of Participant	Signature	Date

Please sign both copies, keep one and return one to the researcher.