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'If you wanted to take this model and throw nitrogen at it, it would fit': synthesis approach to modelling to learn about biogeochemical cycles

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ABSTRACT

The literature on scientific modelling practices in science education has provided a fruitful discussion on how learners tend to view models vs. how and what they should think about them. One approach is to teach students that models are abstractions so that they do not view them as a copy of phenomena they represent. Although teaching students that models are abstractions is a successful strategy in modelling instruction, we still do not know how students engage in and work towards the process of abstraction while they develop a model to understand scientific ideas. This qualitative study examines how a group of undergraduate and graduate students in an upper-level ecosystem ecology course at a research university in the southeastern part of the United States engage in a task that requires constructing an abstract representation of how biogeochemical cycles work by using a specific approach to modelling, namely synthesis modelling. Data corpus entailed paired interviews with ten students and their artefacts. The findings centred upon four episodes regarding how students engage in abstraction through a synthesis approach to modelling as they make sense of the system of biogeochemical cycles: working with surface similarities, abstracting ideas, abstracting structures, and checking on model-source fit.

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Introduction

Central to successful modelling is understanding what models are and how they relate to the phenomena they are meant to represent. Unfortunately, existing ideas about what to teach about what models are not well defined in the modelling literature (Capps & Shemwell, 2020). This lack of definition is evident in how the literature addresses a frequent misunderstanding about models, namely that students think that models are copies of their referents (Grosslight et al., 1991). Prevailing approaches to combating this misunderstanding include explicit instruction that models are not copies (Schwarz et al., 2009; Tasquier et al., 2016) or having students model phenomena that cannot be directly

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observed (Cheng & Lin, 2015; Lehrer & Schauble, 2012). Although such instruction has the potential to address the naive conception of models as a copy of real phenomena, it does little to improve students' understanding of what models are.

Drawing on the widely-acknowledged idea that models are abstractions (Fortus et al., 2016; Gilbert & Justi, 2016; Krell et al., 2015; Schwarz et al., 2009), Capps and Shemwell (2020) proposed a working framework for what to teach about what models are. The framework describes two key structure-preserving transformations between models and their referents that are worth knowing. Briefly, 'models are abstractions of the structure of their referents, and consequently, models have transferability to their referents' (Capps & Shemwell, 2020, p. 3). This abstract and transferability feature of models help us use a single model to understand two different phenomena. For instance, the Copernican model of the heavens can be used to explain Mars' retrograde motion and lunar eclipses (Fortus et al., 2016). In addition to defining a working framework for what students should know about models, they described an approach to modelling, called synthesis modelling. In synthesis modelling, learners are asked to abstract an underlying structure from two or more scenarios that contain it, but differ on the surface level.

Synthesis modelling is guided by the theory of analogical learning (Gentner, 1983; Gick & Holyoak, 1980; Johnson-Laird, 1983). Analogical learning entails 'examples (as few as two) that are not particularly similar in semantic and perceptual features' (Holyoak & Lee, 2017, p. 459). Analogical learning explains how learners can formulate abstractions by seeking the common structure within scenarios that are similar in essence but differ on the surface level (Catrambone & Holyoak, 1989; Gick & Holyoak, 1980). This means that individual components in the multiple scenarios might be semantically quite different, but the structural relations between those components are similar across the scenarios. Analogical thought should help learners abstract and map correspondences between multiple scenarios and apply them to a new domain (target) by using the underlying structure or key ideas. Because analogies involve rich relations (the complexity of the relations), abstraction ranges from low to high depending on the use of superficial similarities or key structural (relational) similarities over multiple examples (Holyoak et al., 2010).

Adopting a synthesis approach to modelling, Capps and Shemwell (2020) conducted a study in which high school students developed a model of how a desert forms by simultaneously observing two different examples of deserts (a rainshadow desert and a mid-latitude desert) and abstracting the common underlying structure that illustrates the air and moisture transport. They used pre-and post-tests to measure student learning as a result of the approach. Importantly, the study did not show the process of student learning, it only showed that students learned.

Therefore, building on this research, we designed a qualitative investigation that focused on documenting the ways students engage in a synthesis modelling task to make sense of how biogeochemical cycles work. Documenting the ways students engage in synthesis modelling to externalise their conceptual models should help educators and researchers understand how students identify similarities and differences across different sources of a complex phenomenon and integrate segmented ideas about the phenomenon (Stratford et al., 1998). It is also expected to help students recognise the aspects of the nature of models, namely abstraction and transferability, as something valuable in modelling in science.

This investigation was conducted in a cross-listed course (one that is offered by more than one discipline, department, or faculty, but has the same content and in which students should expect to have the same or similar experience) for upper-level undergraduate and graduate in ecology-related fields. The data came from five paired interviews in which pairs of students engaged in the modelling task by working together and interacting with each other. The interview task was to develop a model that would be broadly applicable to three biogeochemical cycles. The student pairs were asked to talk aloud and interact with each other while working on the task so that cognitive outputs of the student pairs can be examined. By drawing from the paired interviews, we developed five narratives to elucidate the range of ways that emerged as learners attempted to develop abstract models to externalise their ideas about biogeochemical cycles. The main goal of the study focused on generating insights into the ways students approach synthesis modelling tasks as they made sense of the complex natural phenomenon, biogeochemical cycles. Specifically, we asked the following question: How do students engage with a synthesis approach to modelling to learn about science ideas?

Theoretical framework

Synthesis approach to modelling is informed by the literature on analogical learning. This literature 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; Loewenstein et al., 1999). The theory of analogical learning 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 science, students need to learn the deep structure of scientific phenomena (Schwartz et al., 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). The process of identifying similarities and differences between two or more cases helps capture abstract structures and uncover deep relational similarities between cases (Gentner, 1983; Gick & Holyoak, 1983; Loewenstein et al., 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 key ideas from multiple scenarios were more apt to transfer them to novel situations than participants who learned the scenarios without support for abstracting. Following Gentner (2010) and Nersessian (2008), Capps and Shemwell (2020) called these key ideas the deep or underlying structure of the phenomenon within synthesis. The researchers defined models as constructs that are abstractions of the underlying structure of the phenomenon they represent and called the process of developing abstract structures synthesis modelling (Capps & Shemwell, 2020).

Synthesis modelling 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). Leveraging the theory of analogical learning, our focus was on students' understanding of the shared deep similarity between superficially dissimilar, but abstractly related examples of a phenomenon, in this case, three biogeochemical cycles. Because abstraction through synthesis modelling in this study requires comparing the three scenarios and coming up with a structural alignment, students needed to extract a principle common to the three examples and then transfer that principle to an emergent model.

Methods

Study design

This instrumental case study examined how students engage in a modelling task by using a synthesis approach modelling. An instrumental case study allows researchers to gain insights into individuals' experience on a phenomenon (Stake, 2005). The case was bounded (a modelling task) and instrumental (insight into a specific way of modelling, namely synthesis modelling) (Merriam, 2009).

Participants

Using a convenience sampling approach, we recruited five pairs of students for the study who had recently taken an upper-level ecosystem ecology course at a research university in the southeastern part of the United States. We chose this group because the interview task related to a course they had just taken, and they would therefore be familiar with the topics as a major emphasis of the course was on how biogeochemical cycles work.

Table 1 shows the participants' pseudonyms, intended degree, and degree programme. We assumed that the students were familiar with basic ecological concepts such as biogeochemical cycling and scientific practices, like modelling, given their advanced standing in their majors and the fact that they had just taken an ecosystems ecology course that focused on both biogeochemical cycles and modelling. However, we did not assume 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

Table 1. Participant information.

Pseudonym	Intended degree	Degree program
Calina	Ph.D.	Forestry & Natural Resources
Frank	B.S.	Biology
Henry	B.S.	Biology
Jade	Ph.D.	Ecology
Jane	Ph.D.	Forestry & Natural Resources
Kate	B.S.	Ecology
Kacy	Ph.D.	Ecology
Mabel	B.S.	Ecology
Sabrina	Ph.D.	Forestry & Natural Resources
Sergio	Ph.D.	Forestry & Natural Resources

another; instead, it was to describe what it means to develop an abstract model through the process of synthesis modelling for these students.

Data collection

The primary data sets were the audio- and video-recorded paired interviews that used a structured interview protocol. Paired interviews help interviewees establish an atmosphere of confidence, interact with each other in producing knowledge, and fill in gaps for each other (Wilson et al., 2016). The purpose of the interviews in this study was to explore what it means for the participants to develop an abstract model using a synthesis approach to modelling and to uncover possible patterns incorporating their experiences. Each interview took place on campus and lasted approximately 60 min. Participants received a $10 gift certificate to a local coffee shop for their willingness to participate in the study.

Ten students agreed to participate in an interview in which we asked them to develop a general representation applicable to three biogeochemical cycles (the phosphorus – P, carbon – C, and water cycles – W). We provided students with diagrams of the phosphorus, carbon, and water cycles. Each diagram showed the major reservoirs and processes that the materials take through the ecosystem and had a caption briefly explaining the phenomenon. The participants were asked to look through the cycle diagrams, work together, and talk aloud while working on their models. The interviewer only interrupted the interview to ask or answer some questions and remind the students of the task when needed. After giving the students scratch/scrap paper, pens, a large whiteboard, and dry-erase markers to develop their models, the first author conducted all five paired interviews in person by using the same interview protocol to explain the task and materials for each interview to ensure consistency in the data collection. Additional data sources were copies of participants' work including both photographs of the models that they produced on the whiteboards and physical copies of the models that they drew on scratch/scrap paper.

Data analysis

To answer the research question, we 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 we could extensively and quickly access data related to the second research question from a larger segment of data in the interviews. In coding the interviews, we 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. We reduced turns of talk into short phrases beginning with the gerund form of the verb used by the participants, *process coding* (Saldaña, 2013). We wrote all

Table 2. 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.

the phrases alongside the transcripts (see Table 2 for an example of gerund-based phrases).

After reducing the responses into short phrases, we read through each phrase to look for similarities and differences within each transcript. We then used this process to pick out notable phrases and began 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 3 displays some examples of the codes.

Next, we developed a coherent and readable narrative – a descriptive retelling – for each pair. Here, our goal was to obtain a sense of how the participants' experiences developing abstract models originated and evolved during the synthesis modelling task. Narratives described how some participants were able to get nearer to developing abstract models while others did not make as much progress with their models in terms of abstraction. In developing the narratives, we first grouped the phrases using the emergent codes as the main idea connecting them. Next, we developed paragraphs connecting the phrases into a coherent story related to the code. We took care to keep the phrases in chronological order based on the original interview transcripts. We kept these narratives as close to the data as possible.

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

Table 3. 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 the 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.	Generalising 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.	Generalising ideas

We developed the episodes from the narratives 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.' In this case, the episode 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, we presented each of the episodes that arose from the narratives and described the variation in the ways these episodes were expressed across the groups by using illustrative examples.

Results

In response to our research question, we described the ways the participants engaged in synthesis modelling through a comparative analysis of the five narrative summaries developed from the interviews. Through the analysis of the data, we developed four episodes. The episodes were: *Working with Surface Similarities, Abstracting Ideas, Abstracting Structures,* and *Checking on Model-Source Fit*. The episodes are listed and defined in Table 4. In addition, we describe variations within the episodes that were elaborated on through the quotes and images in the text.

Each of these episodes is described and justified in separate subsections below. As representative examples of what the specific processes explained under each episode looked like, we provide quotes from the interview transcripts. The quotes are meant to be representative of the essential idea of the positions taken and the ideas advanced in the interviews.

Table 4. The ways the students approach synthesis modelling task.

Episodes	Definitions	Variations within episodes
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 overgeneralise the features and/or structures • Checking whether or not the final models map to cycles beyond source materials.

Working with surface similarities

The groups attempted to develop their model by looking for shared features, surface level similarities, common to all three cycles. As there were no features that met this criterion, the students ended up combining features they saw in two of the sources into their representation. This process was ultimately unproductive as it did not satisfy the proposed task which was to develop a model that applied to all of the cycles. This is because these surface level commonalities were not deep structures that applied to each of the 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, we present these variations.

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. 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 respiration – so, respiration and then decay. Because decay can also release phosphorus.
Kate: Because respiration would also involve the transpiration.
Kate: So, respiration, transpiration. Okay, wait.
Mabel: I guess, going back to – we could have extraction be one of the steps for – okay – for fossil fuels and phosphorus? For phosphorus, extraction goes into vegetation, because it uses fertiliser.

The features that we 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, try to put them together into one representation instead of creating a structure common to all three cycles.

Even though some participants could determine the essential features that are common in each of the cycles, 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. Another 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 of the way the carbon and phosphorus cycle, but it does not apply to the water cycle.

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. In other words, some students decided 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 about 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 indicate 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.

Abstracting ideas

In this section, we explain how the performance of the groups in the abstracting of ideas differed from each other during synthesis modelling. To do so, we 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 processes in analogical learning. These processes were uncovered in this episode.

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 realised 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 min. For example, at the beginning of the interview, Kacy and Jade began by looking at the big ideas across the different cycles. The quote below marked their successes in abstracting, or drawing key features away from the cycles.

> Jade: Right, so I guess when I first go through this 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. I just look for things in common. So, they all have a pretty similar setup with a few different details … they all have atmosphere, and they have 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.

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 some processes that could happen at the same time, you know …

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 which 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 an abstraction, the structure that was taken out from the sources. They explicitly stated that the general model should apply to any kind of biogeochemical cycle. 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. Supposedly, it also shows that students implicitly came to understand that abstraction is one aspect of the nature of models.

The essential features that cut across the cycles were not apparent on 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 at the beginning of the interview, they were not able to consolidate the underlying structure of all of the cycles for a while. After approximately 23 min, 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. 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 generalising ideas from the three cycles presented in the quote below.

Frank: So, instead of I guess giving names to everything, we could just say, these general terms like resources – reservoirs – reservoirs – sinks – right. And – what else? Fuels. And then, I guess, < Inaudible > … 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. They dived into the cycles separately and took out a couple of features that seemed to be important in their perspectives (i.e. the 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. The operational definitions for the essential features in the cycles did not contain any considerable variations in the narratives. All the groups tended to define their 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: … let's look at the carbon cycle, so we have precipitation for the water cycle.
Calina: We can just call it inputs.
Sabrina: Okay. So, what describes this [below Earth's surface]? Is this like slow migration? Transformation? I'm thinking of 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.

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 realise that models should apply 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 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). Sabrina and Calina tried to develop a structure that would apply to all three cycles. The structure sufficiently depicted how inputs and outputs between underground and above ground move through slow (abiotic) and fast (biotic) cycling. This structure can be adapted to show how a substance flows through the compartments of Earth – how a biogeochemical cycle works globally.

Abstracting structures

Only two of the groups arranged the abstract ideas and incorporated them into a model that is capable of explaining all the sources. 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 setup 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 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 realised 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 was not a copy of any of the cycles; instead, it represented the key features (structure) of all the cycles.

Both groups that developed an abstract model had a similar way of organising 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 1). 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. For instance, Calina and Sabrina 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.

They were 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. Their attempt to represent the underlying structure of all the cycles was evident in the following dialogue:

Calina:	… if you extremely simplified it, you would have one arrow going up and one arrow going down and maybe a few underground.
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:	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:	I think we would label it slow cycling and fast cycling because to me that's what I see is the connector between them [cycle diagrams] all, right?
Calina:	… we should maybe make it not so much like land and water so much as like Earth's surface.
Sabrina:	let's look at the carbon cycle, so we have precipitation for the water cycle.
Calina:	We can just call it inputs.

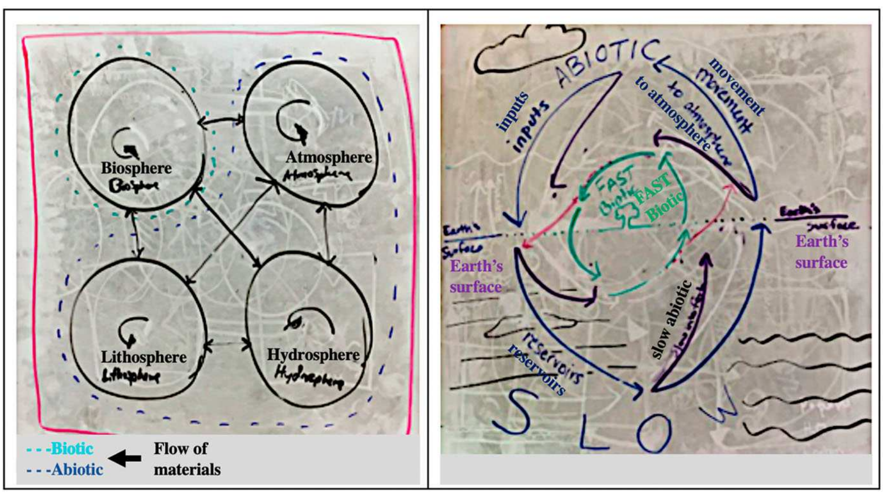

Figure 1. Kacy and Jade's model (on the left) and Sabrina and Calina's model (on the right).

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 modelling 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 modelling.

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 applied to all three cycles. 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, and (2) checking whether final models are mapped onto 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: 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 … to build a model, I guess it would be best to start with each cycle's main source.
Henry: So, the atmosphere would definitely be at the top.
Frank: Would that be for all of them or just for the 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.

Furthermore, there was evidence of groups checking whether their (abstracted) model 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 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 general things you take from all of them that would be applicable and that you could, if you wanted to take this model and then throw nitrogen at it, it would fit.

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 how you would adapt this for the nitrogen cycle.

This dialogue shows that while students checked their final model against the different cycles to make sure that the underlying structures from the source materials applied to all three cycles, they implicitly focused on another aspect of the nature of models, transferability, besides abstraction. By doing so, they seemed to move away from the idea that models are literal interpretations of real phenomena.

Discussion

In this study, we aimed to document how students engage in a modelling task using a synthesis approach to modelling to understand and explain how biogeochemical cycles work. The results of this study suggested that the synthesis modelling was approached in four episodes, illustrated in Figure 2: *Working with Surface Similarities, Abstracting Ideas, Abstracting Structures,* and *Checking on Model-Source Fit*. Taking the results together, it seems that students abstracted a stable structure by simultaneously observing multiple sources of the phenomenon (i.e. three biogeochemical cycles) rather than selecting a structure that would fit a phenomenon at hand (i.e. an individual cycle), as we know from the prevailing approaches to modelling in science education. As Capps and Shemwell (2020) discussed, we found that a synthesis approach to modelling provided students with an abstract structure that can be transferred to novel situations in science learning. This experience seemed to show students how models can be abstract and transferable. Learning about these two aspects of the nature of models, namely abstraction and transferability, has the potential to help students shift their naive understanding of what models are (i.e. models are copies of their referents).

In light of the observations presented in the previous paragraph, we argue that the presence of multiple instances during a process of model development might support learners in recognising that their final models do not have to resemble the instances on the surface level. Lin and Chen (2002) also reported that when students realised that all of the models differed from one another, they could 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 we identified in this study, *abstraction of ideas* and *abstraction of structures*. Abstraction of ideas generally preceded the abstraction of structures. In other words, extracted key features from the sources (i.e. three biogeochemical cycles) were transformed into structures. This helped students understand that models were more than copies of their referents. Rather models include key features and structures that cut across multiple sources and are not direct translations of any phenomena (Loewenstein, 2017; Schwarz et al., 2009).

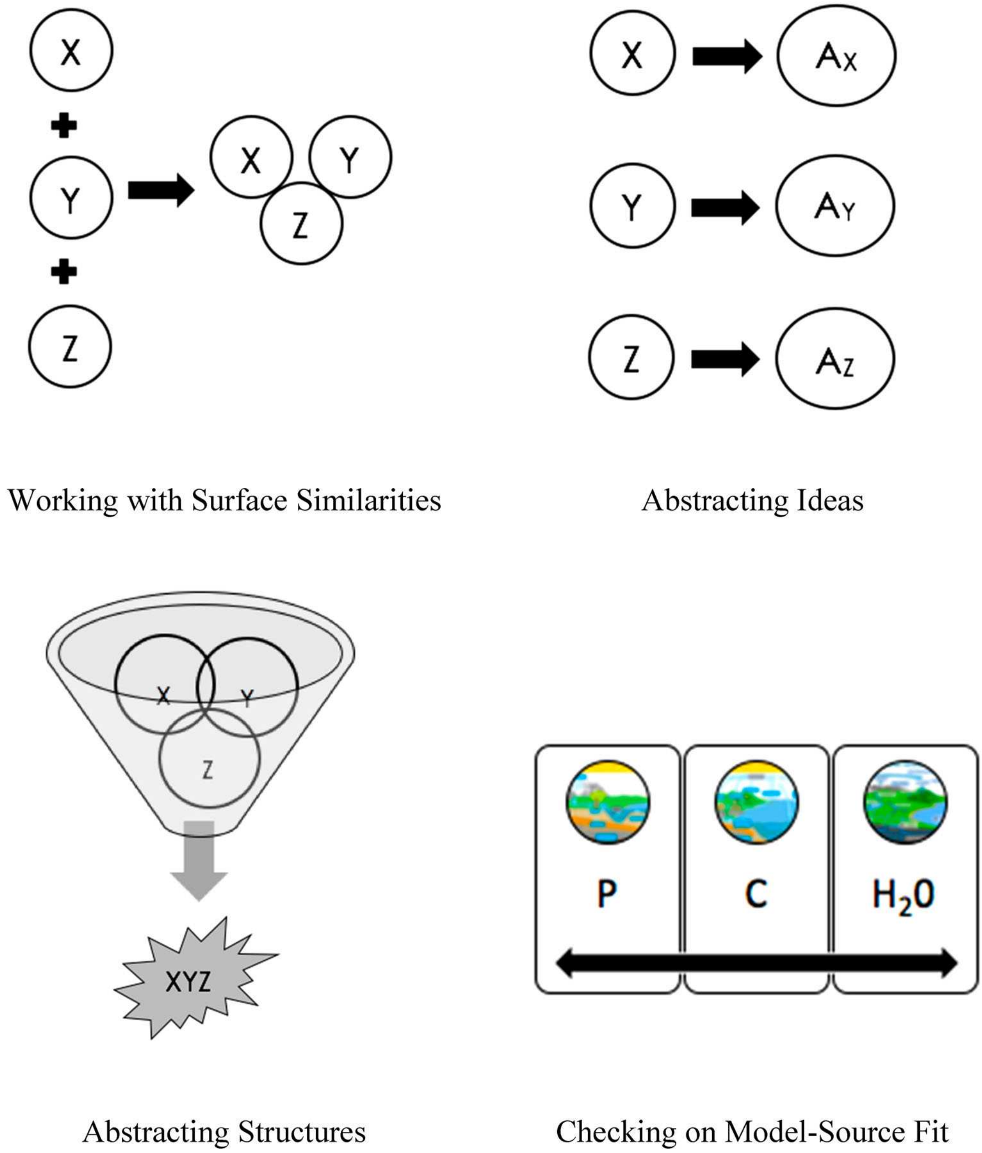

Figure 2. Schematic of four episodes the students approach synthesis modelling task.

The findings suggested that students who worked on key features common to all sources could use information that was provided in the sources effectively and logically to the mapping of abstract key 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 emphasising that the ability to perceive the underlying structure across multiple contexts requires drawing further inferences, rather than reproducing a representation that is provided as a source (Gentner & Smith, 2013; Hofstadter, 2001).

One may ask 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 modelling 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. In 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.

Limitations

As with all studies this study has limitations. Since this study was an instrumental qualitative case study with a relatively small sample size, the generalisability of the results is limited in the traditional sense. Even though 'generalizability of qualitative research findings is usually not an expected attribute,' we suggest that the generalisability in this study has the potential to compare the findings to other findings from similar situations (Leung, 2015, p. 326). The reason is that the focus of this study was directed towards providing in-depth explanations and meanings as to how students engage in synthesis modelling rather than focusing on the collection of representative data. Therefore, in this study, we interpret generalisation as generalisation towards a theory, a process, or an approach rather than towards a population (Polit & Beck, 2010). For instance, the cognitive aspect of the student engagement with the modelling task (the way of working towards synthesis modelling) seems applicable to high school students, and it is briefly presented in an earlier study (see Capps & Shemwell, 2020).

We also acknowledge that this specific approach to modelling could be taken up and reproduced differently by other populations (e.g. K-12 students) due to differences in their developmental level, content knowledge, and other background information. For instance, we expect that the level of abstraction would be different when elementary-level students engage in synthesis modelling. We even observed slight variations in the process of abstracting ideas (i.e. pulling relevant and applicable features away from the source materials) with the participants in this study (see Results section for details).

An additional limitation is the potential for interviewer bias that could affect how reproducible this approach to modelling would be. To avoid this, we prepared an interview protocol to follow when conducting each interview. We intentionally did not mention concepts such as 'abstraction' and 'transferability' during the interviews to eliminate the potential to cloud our judgment of the process being examined.

Conclusion

The central question we engaged with in this study can be summed up as follows: what does it look like for students to engage in a modelling task through a synthesis approach while making sense of a complex scientific phenomenon? Although this study is situated in the context of scientific practices in the United States, the problem addressed and the solutions suggested here are a matter of disciplinary, rather than national, practices in science learning and teaching and therefore are relevant to other inquiries about the practice of modelling beyond the U.S. context.

Reform movements in science education have placed a strong emphasis on modelling as a key scientific practice at the primary and secondary levels (e.g. NGSS Lead States, 2013). As promising as modelling 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 long-standing 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 how and what students should think about models that make them something other than copies.

As a step towards answering the central question, we built on Capps and Shemwell's (2020) suggestion that abstraction could be one such idea about models worth learning and described how students approached synthesis modelling that leads to an abstract construct to externalise students' thinking about scientific concepts. We think that understanding these ways could help science educators support the key purpose of using and developing models in science classrooms. Needed is research on other pedagogical approaches concerning how to design a modelling task along with informative and innovative ways of supporting both teachers and students in better understanding of the nature of models (e.g. Charara et al., 2021). We hope that this work will provide new insight for educators to organise model-based instructions that facilitate learning the deep structure of scientific phenomena in science classrooms.

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