Hybrid Modeling in 6th Grade STEM: Seeds of Convergence Research

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Abstract: The NSF has identified a need for convergence research that blends practices and perspectives from different scientific disciplines (NSF, 2019b). Studies of professional science describe convergence research at the frontiers of emerging disciplines (e.g., Chandrasekharan & Nersessian, 2017; Fox Keller, 2003). These fields address problems that demand hybrid representations, which materially integrate multiple models to compose model systems, offering perspectives on large complex systems. We argue that habits-of-mind that support hybridization exist not only in professional labs but also in classrooms; we demonstrate that 6th grade students recognize the need for hybrid model systems to explain complex phenomena. Like researchers, students justify the need for hybrid models in relation to sometimes-conflicting commitments and constraints. In this context, we find that students hybridize models narratively and rhetorically, a resource for convergence thinking and a precursor to material hybridization.

Objectives and significance

The National Science Foundation's 10 Big Ideas identify a need to blend scientific disciplines through convergence research (NSF, 2019b). Convergence research is highlighted in emerging fields, like computational physics and biomedical engineering (Chandrasekharan & Nersessian, 2017; Fox Keller, 2003). Labs and research teams in these fields bring together individuals from different specialties or disciplines and individuals trained in multiple disciplines. In these hybrid labs, researchers work simultaneously toward contributing to "basic science" and achieving design goals, drawing on practices and perspectives from multiple disciplines to address complex challenges (NSF, 2019b). Dual conceptual and design goals motivate the creation of hybrid devices and model systems, which integrate multiple models of different aspects of a phenomenon to address sometimes-conflicting commitments, such as ethics, control, and accuracy (Nersessian, 2017). While hybrid devices do not resolve tensions in a simple way, they create new ground for addressing problems (Chandrasekharan & Nersessian, 2017).

Model systems can help K-16 students build complex understandings and appropriate disciplinary practices and epistemologies. Several successful designs leverage multiple model types to help students build knowledge, understand relationships between models, and navigate uncertainty (e.g., Blikstein, Fuhrmann, & Salehi, 2016; Gouvea & Wagh, 2018; Sengupta, Dickes, & Farris, 2018). These designs typically leverage tightly-coupled model systems, which bring together multiple representations to render a phenomenon. Differences among the representational features of tightly-coupled models can be used to create a deeper understanding of the models and of the phenomenon captured in the *intersection* of their representational "footprint." In contrast, our design emphasizes linking models that represent different yet related aspects of a phenomenon to extend the reach of a model system, strengthening students' understanding of the complex systems covered by the *union* of the models' footprints. In this paper, we aim to understand: (1) how students recognize and respond to tensions that preclude attempts to create a tightly-coupled model system and instead motivate the creation of multiple models representing different aspects of a phenomenon, and (2) how students coherently "hybridize" these models.

We show that, like professional scientists, middle school students recognize a need for hybrid model systems for explaining complex phenomena. We also show they justify the need for multiple models in relation to similar commitments and constraints, including: *accuracy, ethics, control, design, completeness,* and *transparency*. We find that these commitments are *not* mapped directly to model types; for example, students use *accuracy* to justify the use of physical models in some cases and computational models in others. Our analysis also surfaces students' resources and practices for hybridizing models as they reason about the complex systems they are using these models to understand. We describe how students *narratively* and *rhetorically* hybridize models to create trustworthy conceptually *"*runnable*"* model systems that allow them to explain phenomena with increasing depth and breadth. We find that not all models are weighted equally in students' model systems and that these systems are not stable; instead, model systems are assembled in response to specific problems. We argue that students' imagined hybrid model systems are resources for the kinds of professional scientific thinking and inquiry that occur in convergence research and precursors to the construction of material hybrid devices.

This study contributes to our understanding of learning as disciplinary participation. Our data show 6th grade students have resources for engaging in habits-of-mind essential to convergence research, like hybridization, and that they recognize a need for convergence in their inquiry. Therefore, convergence is not only an important strategy at disciplinary frontiers, but it can also be a productive tool for classroom learning. In response, we call for increased attention to students' resources for engaging in multimodal modeling as a precursor to convergence thinking. These habits-of-mind are valuable and possible to promote in classrooms; therefore, rather than implicitly resolving, avoiding, or addressing tensions that arise in modeling, designs for learning should offer students opportunities for recognizing and responding to these tensions, affording students a pathway to practices that are becoming increasingly important for disciplinary engagement in STEM.

Theoretical framework

The NSF (2019a) describes convergence research as: (1) "driven by a specific and compelling problem," which can arise from deep scientific questions or pressing societal needs, and (2) involving "deep integration across disciplines," including knowledge, theories, and methods. From deep disciplinary integration, new frameworks and even new disciplines emerge, offering new ground for addressing complex problems. Studies of emerging fields, such as computational physics (Fox Keller, 2003) and biomedical engineering (Nersessian, 2017), offer illustrative examples of convergence research. These fields leverage different disciplines to address novel, complex problems. Computational physics bridges traditional theoretical physics with empirical methods of experimentation and observation using hybridized tools, like models and simulations, which leverage high-speed computation to run experiments-in-theory (Fox Keller, 2003). Biomedical engineering labs blend engineering with science practices such as cell culturing; researchers develop hybrid identities as they simultaneously aim to contribute to "basic science" while designing new medical technologies (Nersessian, 2017).

To address dual conceptual and design goals, researchers materially blend transdisciplinary perspectives and practices in hybrid devices, like computational models and model systems that combine "in vitro" and "in vivo" elements (Fox Keller, 2003; Nersessian, 2017). These representations parallel aspects of real-world phenomena, but they do not map directly to the phenomena. Researchers build these parallel worlds in response to constraints and commitments. For example, biomedical engineers balance commitments to *control* and *ethics* with *accuracy* and *completeness*. Initially, they build simple models to develop selective understandings of the constituent concepts, methods, and materials relevant to their research questions, prioritizing experimental control over representing phenomena as complex. This commitment is balanced by systems thinking, which acknowledges that isolated experiments do not capture the complexity of real-world phenomena. Researchers build increasingly complex model systems that link together their initial component models to create a connected system. Model systems are also constrained by *ethics*. For instance, biomedical engineers begin by designing non-living devices, then incorporate cells and tissues; they do not immediately test their designs with animals or humans, even when these contexts would produce knowledge more relevant to their questions and design goals.

Computational physics also involves balancing commitments. Initially, the use of models balanced *control* and *accuracy*, allowing researchers to rapidly approximate solutions (Fox Keller, 2003). Later, models were valued for their *transparency* – their capacity to approximate or reveal underlying principles of phenomena for which no equations exist or for which existing equations fall short, like in biological development (Fox Keller, 2003) or pathways of molecular interactions (MacLeod & Nersessian, 2013). Across emerging fields, researchers express commitments to *design* as a way of producing knowledge that ultimately maps to real-world phenomena; a functioning system provides evidence for arguments and explanations that link models rhetorically by demonstrating that components also work together materially (Nersessian, 2017).

Above, we offer examples of convergence research at disciplinary frontiers. Yet, we propose that habits-of-mind central to convergence research, like hybridization, are also accessible and valuable in classrooms. Science standards, including the NGSS (NGSS Lead States, 2013), address complex phenomena like ecosystems. These phenomena cannot be reproduced in a classroom due to issues of ethics and scale; therefore, understanding them requires engaging with representations. K-12 classrooms are unlikely to address complex phenomena in the same way as professional labs, because scientists draw on established disciplinary identities and expertise. Even so, students can engage in forms of convergence thinking, like hybridization, because they can engage with multiple model types (e.g., diagrammatic, physical, computational, and embodied models), each of which entails the development of different practices and perspectives that could be hybridized to explain complex phenomena.

Several designs for learning demonstrate that K-16 students are able to leverage multiple model types to build conceptual knowledge, understand the relationship between models, and navigate uncertainty in inquiry. Specifically, *bifocal modeling* (Blikstein et al., 2016) and *hybrid labs* (Gouvea & Wagh, 2018) leverage experimental and computational methods to support science learning. In these designs, tightly-coupled model systems support students' progress on descriptive tasks, such as identifying phases of bacteria growth (Blikstein et al., 2016) and considering conditions in which it is advantageous for bacteria to have high or low mutation rates

(Gouvea & Wagh, 2018). Differences between tightly-coupled models can be used to create a deeper understanding of these models and the phenomenon in the *intersection* of the models. However, less is known about how students recognize and respond to tensions that require the use of multiple models to represent different aspects of a phenomenon and, in turn, about how students hybridize these models to understand and explain complex systems covered by the *union* of these models. In response, in the context of a 6th grade STEM class, we ask: (1) What commitments do students express in relation to conceptual and design goals, and how do these commitments shape the way that students justify the creation and use of different models? (2) How do students hybridize models to make sense of them as a collective system and to make sense of real-world phenomena?

Research context and methods

This design study (Cobb et al., 2003) is part of the [blinded] project (NSF DRL#[blinded]). The study was conducted in a public school in the southeastern US. According to the state report card, 18% of the school's students qualify for free or reduced lunch. Students are culturally and linguistically diverse: 55% identify as White, 34% as Hispanic/Latino, 7% as Black/African American, and 4% as Asian. 8% are classified as English Learners. The study was conducted with a STEM teacher, Ms. S, who had been teaching for 26 years. Five of Ms. S's 9-week 6th grade STEM classes participated (13-23 students per quarter, 80 total). Ms. S and the first author, Ashlyn, codesigned and cotaught all lessons, which were aligned to NGSS ecology standards. Lessons took place three times a week during the students' 56-minute STEM class (23 classes). This paper analyzes data from five cycles of the design (August 2018 to October 2019). All iterations of the design foregrounded modeling (Table 1), a practice that affords students opportunities to express ideas across multimodal tangible and testable representations, facilitating argumentation and explanation (Lehrer & Schauble, 2015).

Table 1: Sequence and summary of modeling activities

Name, type	Days	Description
Plant investigation, physical	1-3, 7	Design and implement an investigation to determine the materials plants need to grow bigger
Computational model, computational	4-6, 8-12, 17-21	Create a sustainable system with sun, plants, guppies, killifish (guppies' competitors) and cichlids (guppies' predators)
Biosphere plan, diagrammatic	8-11	Design a closed-system sealed jar that supports guppies
Biosphere/jar, physical	12-23	Build and monitor a closed-system sealed jar that supports guppies
Food web, diagrammatic	13-14	Represent the flow of energy in guppies' environments
Embodied model, embodied	15-16	Represent behavior and energy for algae, guppies, killifish (competitors), cichlids (predators); represent population dynamics

We collected whole class data and data from 5-6 focal students per quarter (28 students total). Focal students were selected with input from 6th grade teachers to represent a range of backgrounds, academic performance, and engagement. We collected student work, and we captured classroom discourse with two cameras and with software on focal students' computers that collected video, audio, and screen-capture recordings. We interviewed focal students to triangulate data about their enactments of modeling with their experiences. This paper focuses on these interviews; the full paper also includes analysis of classroom discourse. We used methods of inductive coding and constant-comparative analysis (Charmaz, 2006; Strauss & Corbin, 1990), beginning by identifying students' commitments in relation to conceptual and design objectives. We looked for instances in which students justified creating or using a specific model type. We also identified instances in which students "hybridized" models. Students explicitly hybridized models by reflecting on multiple models as components of a larger system used to explain a phenomenon. They implicitly hybridized models by drawing on unique aspects of multiple models to reason about a phenomenon. With qualitative data analysis software, we created coding categories to describe students' commitments and hybridization practices (Strauss & Corbin, 1990). We compared categories with descriptions of professional hybrid labs. We conducted negative case analysis, looking for statements in which students described models as: isolated, exactly the same, or literal replications of phenomena.

RQ1 findings: Commitments

In this context, students expressed commitments analogous to those of professional scientists, including accuracy, ethics, control, design, completeness, and transparency. Rather than justifying the creation of a new model by describing a previous model as inaccurate or exhausted, students justified the creation of a new model in response to their commitments, expanding and extending their existing model system by using the new model as a lens for interpreting other models and real-world phenomena. In this section, we first identify students' commitments, then describe how their commitments motivated and justified the creation and integration of multiple models.

In their interviews, a majority of the focal students (23 out of 28) expressed a commitment to *accuracy* – creating knowledge with their models that incorporates real-world data or maps to real-world contexts. For example, when asked about her plant model, Karla explained that it was useful because it generated real-world data that could inform the biosphere and computational models. She said, "okay so I thought it was a good idea, because like I don't know, I just loved how we could like see what the plants needed and for like what we did next, like our bottle. We can like, see what we like needed for it I guess, for like the energy and everything." She also argued that adding data from the plant model would make the computational model more accurate:

> Karla: We only just put like the energy levels stuff [into the computational model], but if we if we were to put like how much like air and stuff and get further into it we could.
>
> Ashlyn: Why would- why would that make your computational model better?
>
> Karla: Because we would know like, just in case like, they wouldn't be over something. There wouldn't be less plants because we did something wrong with like the soil and air or something, or way too much plants to the point where like it took over everything.

Above, Karla explained that adding plant data would improve her computational model by more accurately representing features of the environment that might cause plants to decrease or overpopulate. When asked to elaborate on why these data would be important, she argued that it would help scientists better understand real-world contexts. She explained, "if scientists use this, like so they won't harm anything in the environment, so if they were probably doing that [computational modeling] before they do it, like kind of to test it before, they would know what to do and what not to do so like- so they don't mess up the environment or anything like that."

In addition to accuracy, Karla's response implied a commitment to *ethics*. Over half of the focal students (16 out of 28) expressed a commitment to ethics by caring for components of their models, like guppies in their biospheres, or caring for real-world contexts, like the ecosystems their models represented. In some cases, attending to ethics prompted students to interrogate their representations. For example, Vanessa said the biosphere was most helpful, because, "it was really fun like taking care of the fish and like coming and checking on it and looking at our oxygen level, and that we did a good thing on not actually putting in our fish when the oxygen level was really low." Vanessa attended to oxygen because she cared for her guppies; not putting the fish in the jar when oxygen was low was "good," because, from her perspective, it would be wrong to endanger guppies.

This type of *control* – being able to manipulate a model – was valued by students (14 out of 28). Porter explained that computational modeling is an important step when designing solutions for real-world contexts, because: "You've pretty much only got one chance with the real river. Like there's no re-dos. But like in the computational model, you can make it 200 cichlids, but then if that doesn't work you can make it go down, and you can get that exact number." Just as Vanessa valued being able to isolate oxygen levels before adding guppies to the jar, Porter valued being able to isolate and test different population sizes in his computational model. In these examples, students valued being able to manipulate the number of organisms in their models and "re-do" their investigations with limited consequences before increasing the stakes in terms of ethics or complexity.

Students' commitment to control is related to another commitment: *design* as a way of building knowledge (17 out of 28 students). Hunter explained that the biosphere was an important tool for learning because, "a lot of times like- teachers like- with science like- they only do the stuff that works and they won't really let you try something that doesn't work, because they think it's kind of wasted time, and like you guys said mistakes like can be the biggest discoveries and stuff. I think it was just really cool that you like let us make mistakes so that we could like, see what was the best." Hunter valued design as an epistemic tool because it allowed him to test sub-optimal configurations of his model ("something that doesn't work"). This allowed him not only to understand the parameter and design space of stable ecosystems, but also unstable ecosystems, so that he could "see what's best." In this way, design allowed students to explore a system's broad functioning in a number of contexts.

Hunter's statements above resonate with another commitment – *completeness* (18 out of 28 students). When asked which models were most helpful, many students chose models that represented a larger ecosystem, because these models showed more interactions. This commitment suggests that students saw ecosystems as more complex than a collection of their components. For example, Jasmin valued the embodied model for showing, "how like animals interact, and I thought it was cool to like really slow it down and see like how things work in an actual ecosystem." Jasmin's response suggests the embodied model was helpful because it was more complete than prior models – it allowed her to see animals interacting – and because it could be controlled ("slow it down").

In addition to completeness, students emphasized *transparency*, preferring models that allowed them to clearly observe complex interactions (20 out of 28 students). Sofia said that the biosphere model was most helpful because "it's visual. You can actually like see what's going on," whereas Alexis said the computational model was most helpful because, “with the jars that we did I think that was more difficult to see everything because of the sunlight, and we didn’t have soil in some of our bags, so it was difficult to see in those, but in this one [computational model] you can add as many sunny spots as you want and see how the multiple sun spots affect the plants.” Sofia and Alexis therefore valued models that clearly showed aspects of ecological phenomena.

As is evident above, students’ commitments do not map directly to specific model types; Karla and Porter valued different model types for control, and Sofia and Alexis valued different model types for transparency. We also found that, from the students’ perspectives, none of the models addressed all commitments. Some students (14 out of 28) described using multiple models to manage sometimes-conflicting commitments and constraints. For example, Hunter described how he balanced commitments to completeness and ethics by using several model types. When asked what he was trying to show with the food web model, Hunter responded, “We’re just trying to show like that kind of environment in it, really. It [biosphere model] didn’t really involve the bird but we needed something up top… because we’re not really gonna let a bird fly around in the room trying to eat these guppies.” Using multiple models, Hunter managed tensions between completeness and ethics; the food web model was *complete*, because it included a bird, but the biosphere model was *ethical*, because guppies were protected from birds. Later, Hunter described how the computational model also contributed completeness to the model system by operating beyond its referent (the biosphere). When asked whether all of the models were related, he said, “Well, they’re all related to our model, like what our final project was putting the guppy in the tank and doing it. And then like, some of them are going past, like the code. We’re still doing the code and we’re like excelling past the guppies.” Ashlyn clarified, “Like predicting out past the jar?” Hunter said, “Yeah, like if we added killifish,” referencing the guppies’ competitors. These examples show how Hunter used the food web and computational model to address his commitment to completeness without violating his commitment to ethics in the biosphere.

Not all students resolved tensions between commitments in the same way. For example, while Hunter demonstrated a commitment to ethics by doing what he though was best for the guppies, Porter managed tensions between ethics and accuracy differently. When asked what he would have changed about the unit, Porter said:

> Porter: Maybe test it for oxygen in the tank for the guppies, see how much oxygen the guppy really needs before it gets really sick, like- um just kind of testing how much space it needs in the water…If it doesn’t need more space in them- then we could test that and see how much- it’s just also we didn’t have time so- but if we did have the time, we could just test a lot of stuff, and it’d be a lot more testing than just doing the plants. What temperature the water needs to be- does it need to be room temperature? Does it need to be cold water, hot water?
>
> Ashlyn: Okay, but then wouldn’t we- but then you said you wanted to see how much like- how little oxygen you can give it before it would get sick?
>
> Porter: Or die.
>
> Ashlyn: But what if we had a lot of guppies die in that situation? Because like, with our plant bags we had a lot of plants not make it. Would that be ok?
>
> Porter: I mean they’re not- they’re living things so not really, but like it would be okay for science, because then we know not to do that test again.

Above, Porter was attending to ethics; because guppies are “living things,” it would “not really” be okay to harm them. However, he managed his commitment to ethics in a different way from Hunter, arguing that it could be acceptable to harm some guppies to build knowledge that could prevent harm to guppies in the future.

The examples from Hunter and Porter show how students used multiple models to manage tensions that arise from commitments. Beyond this justification for model systems, students indicated that multiple models were needed because none of the models on their own adequately mapped to real-world ecosystems (21 out of 28 students). Instead, students described models as representing different yet overlapping components of systems. For example, when asked if all the models were related, Kaya explained that the models showed different aspects of ecosystems: “they all like show like what it gets energy from but it’s in different ways… like computation model you can see like how they reproduce, and you can see of how the fish grow and the algae growing. And in this paper [food web model] you can- it’s different because you can’t see them reproduce, but like you can see what they give energy to.” Vanessa also argued that each model makes different aspects of ecosystems visible:

> Taking the picture [computational model], it looked kind of similar to that one [biosphere model], except like algae wasn’t on the rocks. Just like, in the computer one we didn’t really, like, see the algae like it was supposed to be. And like the car- like the carbon dioxide was like this blue color on the computer, but we don't see it in the fish tank because like it’s like invisible.

Vanessa explained that the computational model did not show the algae “like it was supposed to be,” whereas the biosphere plan accurately represented algae growing on rocks. The computational model was able to show carbon dioxide, which was invisible in the biosphere. Each model made visible and salient different aspects of the ecosystem, so each model was needed for two purposes – to contribute to the emergent system-level understanding of ecological phenomena and to explain systems features that were backgrounded by other models.

In summary, we find that students expressed commitments similar to those of professional scientists, and they justified the need for multiple models in relation to these commitments. In some cases, commitments acted as constraints that prevented students from relying solely on a single model. For example, Hunter’s commitment to ethics, as well as constraints related to classroom-scale inquiry, prevented him from observing interactions between guppies and birds or killifish in his biosphere, justifying the creation of the food web and computational model. In other cases, rather than constraining inquiry, students’ commitments prompted them to closely attend to relevant variables in their models. For example, because of her commitment to ethics, Vanessa checked the oxygen level in her biosphere daily. Taken together, our data demonstrate that students’ commitments shape their inquiry, motivating multiple model types and guiding the construction and use of each model as part of a model system. Each model offers opportunities for students to engage with different practices and perspectives, and as a system, they offer students opportunities to engage in forms of convergence thinking, including hybridization.

RQ2 findings: Hybridizing models

Below, we describe how students use models and model systems to add to their understanding of ecosystems. Students used models as a lens on other models and the world, hybridizing models to explain phenomena. While professional labs *materially* hybridize models, students hybridize models *narratively* and *rhetorically*. We propose this practice is a resource for convergence thinking and precursor to material hybridization.

In the interviews, most students (25 out of 28) used at least one model as a lens for interpreting other models. For example, Owen drew graphs to represent how he imagined resources in his biosphere would change. When asked how he knew what to draw, he said, “when we were drawing, I just looked at the biosphere and this [computational model], and that’s how I got- how I got all the answers for the graph.” Owen used the biosphere and the computational model as resources, leveraging them as lenses for a new representation. In addition, nearly all students used at least one model as a lens on the world (25 out of 28). For example, Sofia said the biosphere showed “how the environment works,” the embodied model showed “how life is, or how to be a guppy,” and the computational model showed “basically the ocean life,” mapping each model to a real-world context. Students also hybridized multiple models as a lens for understanding real-world systems (21 out of 28 students). When asked if the models were related, Karla explained that each model was needed to understand ecosystems:

> Like for the plants one it gives you like what you need in order to like make a plant survive… And then like the one where we did like the- where the energy would come from, we needed to see that there would be enough energy to go around, so there wouldn’t be like any animals dying. It would be enough plants for everything to eat s- and like enough of like everything so- because everything like- everything plays a part, I guess, in the ecosystem, because like if you didn't have one thing, then the whole thing- like my like [computational model]- if one thing it goes out- goes wrong- then like the a- like another small thing, and like those small things can add up to a big thing, so then it like just all messes up and the ecosystem is very bad.

Above, Karla explained that each model provides critical information for understanding a fragile and complex real-world ecosystem. When Karla and other students were asked how they would approach new problems, like algal blooms or invasive species, they also responded with hybrid solutions. For example, when asked how scientists might prevent or address algal blooms, Hunter suggested pairing physical experiments, recorded in a journal like the students’ biosphere journal, with a computational model. He said he would use “both of them, where you did this [computational model] and the best – where you pick the best predications and then you added it like- and did it each- a different one each day, and then adding that to the journal, whichever ones were like the best effective. You just keep doing those until it’s all gone.” With this solution, Hunter imagined alternating between physical and computational models as a lens for addressing a real-world problem.

We found that students hybridized models *narratively* and *rhetorically* to create model systems. Nearly half of the students (12 out of 28) hybridized models by describing the creation of a model system as a narrative pathway, explaining sequentially why each new model was needed as part of the system. For example, when asked whether there were differences between the models, Nora responded: “Well some of them just showed one thing. Like the plant just showed how plants survived. And if we went to the- kind of when we were doing our biosphere, it was without predation, and then the embodied model we included predation and reproduction. And in this [computational model] it's reproduction and how much Sun – it's like everything together." Here, Nora characterized the models as nested systems and her progression throughout the unit as expanding through increasingly complex layers. From her perspective, the final computational model is trustworthy and complete because it incorporates each prior model, representing each level of the ecosystem from the Sun to predation.

Students also hybridized models *rhetorically* (21 out of 28 students), explicitly or implicitly. Most students (21 out of 28 students) hybridized *explicitly*, arguing for why multiple models would be necessary to understand complex phenomena. For example, Caleb explicitly hybridized the biosphere and the computational model. When asked what he would change about the unit for the next 6th graders, Caleb argued for more tightly linking the biosphere and computational models for two reasons: to better understand guppies' survival needs and to address commitments to accuracy and ethics. He suggested spending more time on computational models before putting guppies in biospheres, and he suggested having only water and plants in the jar for "probably the first four weeks." When asked why, he said, "to keep it stable and like check the oxygen and make sure at first, before y'all put them in the water, that it's clean and that it doesn't have any bad stuff in it." He said this would be important because, "if you just put them right in, and you haven't done your computational model, and they just went straight in, just like how we said with a river, then you wouldn't know what would happen, and then like you're just putting them in and like I said, one mistake could probably damage the whole ecosystem." When asked why the computational model specifically would be helpful, Caleb said it could offer important information about "sort of like how much oxygen it [the guppy] would need." He said this would be helpful, "to see like- at a certain amount of oxygen they might die, and we probably don't know what amount of oxygen that might be." Caleb was not sure how to calibrate these models – when asked, "can the computational model tell us how much oxygen a real guppy needs?" he responded, "probably not, because like- it wouldn't know the exact way. Because we're at 5.4 [mg/L oxygen in biosphere]… that's how much oxygen they have, and then how much actually what they need would be a certain amount." Still, Caleb imagined integrating these models in a "runnable" system that could be used to reliably construct a safe environment for guppies. This imagined hybridization – recognizing a need to integrate models – is an important precursor to materially hybridizing models into coherent systems.

Students also hybridized models *implicitly* (14 out of 28 students), drawing on multiple models to explain phenomena. For example, Billy combined the computational model and the food web. When asked what the computational model helped him think about, Billy said, "how it all connects into one circle." To clarify, Ashlyn asked, "Can you talk more about what you mean by, 'how it all connects into one circle?'" Billy's response incorporated organisms only represented in the food web (dead plants, water bugs, grasshoppers) and dynamics only represented in the embodied and computational models (die off, too much populated, have too much food):

> It all gets energy from the like the Sun is the main thing… it gives its energy to like the algae and the dead plants, and then the grasshopper or the water bugs eat that, and the guppies eat that or the algae. Then something else eats the guppy and then it just keeps on going until like everything is gone- there's nothing- no more guppies left to eat, or then one of them would die off, or one of them will get too much populated and then it won't- it won't – it will have too much food and probably eat too much and die from that.

Above, Billy implicitly blended multiple models to describe population dynamics in a large-scale ecosystem. In his mind, he assembled a runnable model system to make predictions extending beyond the models in isolation.

Across the interviews, almost all students hybridized models either narratively or rhetorically (24 out of 28 students). These data suggest that most students, in some contexts, feel a need to draw on multiple models to make sense of complex ecological phenomena. Even so, our data demonstrate that this lens is not stable. Some of the same students made seemingly contradictory claims in their interviews. For instance, some students (4 out of 28) said that the models were not related to each other, implying that the models were isolated tools rather than components of a hybrid system. In addition, some students (15 out of 28) said that all of the models showed the same thing, suggesting that the models were interchangeable rather than unique and complementary. These data suggest that rather than assimilating each model into a stable theory-of-system that could be deployed to understand ecosystems broadly, students hybridized models in response to specific problems or contexts. We also found that students did not attribute equal value or weight to each model. Some students referenced one model more frequently than others, and some students seemed to map each model through the lens of a primary model that they believed was most similar to a real-world phenomenon. For example, above, Hunter organized all the other models around the "final project" of "putting the guppy in the tank" (the biosphere). In contrast, Nora described each model in relation to the computational model, which put "everything together." These data suggest that students can engage with the same model types, yet value them in different ways, just as data from the first research question suggest that students can share commitments, yet manage them in different ways.

In summary, we find that students *narratively* and *rhetorically* hybridized models to explain complex phenomena. Students brought together models created in response to different commitments, enabling them to explain ecosystems in ways they saw as more robust and trustworthy than with isolated models. Recognizing or acting on a need for hybridization is a precursor to convergence research as it is enacted in professional labs. Our data show that students are able to engage in forms of convergence thinking, because they are able to imagine runnable model systems that can explain ecological phenomena with increasing depth and breadth.

Conclusions and implications

This study contributes to our understanding of science learning in terms of conceptual knowledge and science practices. Our data demonstrate that like professional scientists, 6th graders recognize a need for hybrid model systems to understand and explain complex systems, and they justify the need for multiple models in relation to commitments and constraints. We show how students narratively and rhetorically hybridized model types to create trustworthy runnable model systems to explain ecosystems. These practices are resources for convergence thinking and precursors for the material hybridization observed in professional labs. Designs for learning should therefore create opportunities for students to develop habits-of-mind related to hybridization rather than minimizing or resolving tensions for students. Further research is needed to understand (1) students' commitments and resources for engaging in multimodal modeling as a form of convergence thinking, (2) the diversity of ways that students recognize and respond to constraints and tensions between commitments, and (3) designs that productively support convergence thinking. To realize the NSF's goal of growing convergence research, it is essential that designs for K-12 STEM learning attend to and develop students' resources for convergence thinking.

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