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COMMENT

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Beyond assessing knowledge about models and modeling: Moving toward expansive, meaningful, and equitable modeling practice

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1 | INTRODUCTION

Modeling is a powerful science and engineering practice (National Research Council, 2012). The core work of modeling is embodying, using, and refining ideas through iteratively developing representations to describe, connect, explain, and predict phenomena and systems. That is, any object or representation that is used to think about a process or system can be considered as a model. There are a variety of forms that serve the function of modeling—and those can be remarkably diverse for people in a variety of settings and in different disciplines. From this point of view, testing computer simulations to predict the effects of climate change and using physical embodiments like stream tables to think about how rivers change over time can be considered as acts of modeling. And so, too, can children's pretend play (National Academies of Sciences, Engineering, and Medicine, 2021) and stories developed and told across generations that exemplify critical relationships and systems (Kimmerer, 2013; Marin & Bang, 2018).

Modeling can be powerful for learners in PK-16 settings. It can support learners' sensemaking by enabling them to externalize and revise their ideas, making them public, and experiencing science knowledge development as a social, conjectural, and iterative process (Passmore & Stewart, 2002; Schwarz et al., 2009). Over the past 35 years, science educational researchers have generated critical knowledge about the practice of modeling. Teachers, the classroom learning environment, and curriculum all play an important role in how learners can engage in modeling practice (e.g., Salgado, 2021; Vo et al., 2015; Windschitl et al., 2008;

Zangori et al., 2017) and whether or not the experience is meaningful. For example, modeling is more meaningful for a classroom knowledge building community if the practice is framed as a practice for making sense of phenomena rather than models of information (Gouvea & Passmore, 2017). However, along with promising aspects of modeling come tensions and concerns. In this commentary, we outline concerns related to narrowing the practice of modeling in efforts to support and assess the practice, resulting in experiences of modeling that are less accessible and less responsive to youth's interests and purposes.

As researchers in the field, we (the authors) have studied scientific modeling in education for decades. Collectively, we have backgrounds in science (e.g., astronomy, chemistry) and teaching (elementary, high school, college), and have also worked in PK-16 environments with teachers and students. We value particular aspects of science for its powerful ideas and strategies, and we also understand limitations or boundaries of science as well as the critical role of what learners and communities bring to the classroom community. Our goals are to promote life-long engagement in science that is joyful, creative, powerful, and relevant for humans and their communities. We contend that modeling is a critical epistemic human practice, as human beings need tools and representations to embody complex ideas and feelings, both to make sense of them personally and to predict and engage with the world. It is our desire that modeling practice be useful to humans so that they can thrive and make informed, equity-oriented, and sustainable choices.

The goal of this commentary is to point to some tensions and concerns we have with current scientific modeling efforts and to look toward emerging, promising directions. Our central argument is that models depend on developers' and users' purpose and context, and only work well when they help the person or people using them to make traction on their ideas and goals. As such, when we examine modeling activity, we ask: Who is developing the models? For what purpose? In what contexts? For whom are the models useful (the instructor, classroom community, professional community, personal/public community)? We suggest that these questions can help the field move toward fostering more *expansive, meaningful*, and *equitable* modeling practice.

2 | TENSIONS AND CONCERNS IN THE CURRENT EFFORTS IN SCIENTIFIC MODELING

2.1 | Tensions in narrowing the focus of modeling for assessment

How scientific modeling is represented, defined, and introduced in classrooms is often related to how it is assessed. Yet, assessing how students engage in scientific modeling as a practice is difficult. When it comes to assessing complex practices such as modeling, there is a tendency to develop instruments to measure those components or dimensions that are easily measured. Modeling is such a complex epistemic human practice that assessment of the construct is likely to only address certain facets of the practice, while leaving other equally important, if not more important, components unattended (Alonzo & Ke, 2016). Further, models have different meanings and are constructed in social and historical contexts with particular and relative purposes, making them difficult to interpret for those who may not have shared those contexts (e.g., Nersessian & Patton, 2009).

Some in science education focus on assessing features of models, knowledge of models, or dimensions of meta-modeling knowledge such as the idea that models are representations that can be tested and revised (Schwarz & White, 2005). While it is helpful for learners to consider and reflect on the epistemological goals and forms of the practices they are engaged in, narrowly assessing modeling practice based on specific features of models or dimensions of meta-knowledge falsely supports an idea of absolute knowledge of models (e.g., that models are most useful when they predict rather than only explain). Further, narrow aims of modeling assessment come at the expense of holistically studying how to more meaningfully engage learners in the practice in the contexts of particular purposes over time. Schwarz's early work on meta-modeling knowledge (2005) built on psychological notions of the nature of science (e.g., Carey & Smith, 1993; Grosslight et al., 1991). However, in subsequent work (Berland et al., 2016; Schwarz et al., 2009), we have argued that these epistemic goals and purposes are contextualized in the social settings in which they are constructed. Assessing decontextualized modeling or meta-modeling knowledge alone tells us very little about what students are thinking and doing. This approach to modeling continues to project the inaccurate notion that people will use and apply absolute ideas about models productively across context or purpose in their lives, when we know that this is not the case with respect to human cognition (e.g., Nasir et al., 2021).

2.2 | Tensions in engaging learners in meaningful scientific modeling across contexts

A second struggle for the field has been to determine when, what kind, and in what contexts, the practice of modeling is productive for students. This is not a trivial issue. As modeling is taken up in a variety of research and schooling contexts, there are many ways in which modeling practice can be presented, taken up, and used—some of which are rote and procedural. In these cases, modeling may not be meaningful for young people's sensemaking, lived experiences, or communities.

A concern we share is that modeling, particularly a view of modeling that centers the use of invisible or abstracted elements and relations to explain observable phenomena, can become the *object of activity*, or goal, for educators and designers, rather than a *tool* to support sensemaking (see Manz, 2015 and Russ & Berland, 2019 for descriptions of similar concerns in relation to other areas of science education research). We have noticed a movement toward showing that younger children can engage in abstracted forms of modeling—for example, modeling matter using particles or modeling energy transfer with elementary-school children or introducing new forms of mathematical modeling to middle and high school children. We are confident that youth of all ages are immensely capable and can, with support, do this work. And yet, there is a cost– in the form of time, scaffolds and teacher support, and other questions and investigations that do not receive attention. This brings up the question of how we determine whether a form or focus of modeling is worthy of children's and teachers' attention.

2.3 | Tensions in making modeling equitable

When considering modeling as a powerful epistemic human practice, it is necessary to understand for whom, how and why the practice might or might not work, as well as whose knowledge and ways of communicating are being marginalized, and privileged, in the process. In the past 10 years, our field has made substantial progress in understanding what it means to develop equitable learning environments, complimenting and complicating views that focus on providing access and supporting science identities. Science researchers and educators are increasingly grappling with the need to expand what counts as science, examine histories and power structures that shape research, teaching, and learning; and to ask how science can be used toward communities' needs and questions (e.g., Philip & Azevedo, 2017; Tzou et al., 2021).

To date, this work has not been taken up to shift how modeling is conceptualized and implemented in classrooms. The field's work on modeling is largely based on the European-Western scientific canon that values abstracted representational knowledge—and rarely considers how such conceptualization interacts with culturally sustaining pedagogical approaches for children and youth. With some exceptions (see Grapin et al., 2021; Pierson et al., 2021; Salgado, 2021; Suárez, 2020), few studies of scientific modeling focus on equity impacts on children and youth. Alternatively, work on representational practice that could point to more equitable or culturally sustaining practice may not be seen as part of the modeling practice research endeavor (e.g., Scherr et al., 2013; Solomon et al., 2022; Varelas et al., 2022; Washinawatok et al., 2017). For example, the role of narrative, stories, and poetry are important in many different cultures including those of Indigenous, Latinx, and African American communities. These dimensions of knowing are not currently valued in modeling competency frameworks and assessments. As a result, much of the current modeling work does not incorporate ways of knowing that are important in many cultures. This is very problematic, particularly in heterogeneous United States schools and in a heterogeneous future world where this narrow version of practice is privileged. It limits the way young people can use their worldviews, leverage their resources and thrive in a knowledge-building environment.

3 | PROMISING DIRECTIONS FOR MODELING

We know that modeling will always be important in science, engineering, and social science because humans need ways of making sense of complex information in the world to function and thrive. At the same time, the field has gained insights for making the practice of modeling more relevant and powerful for teaching and learning. Those insights suggest that our field needs to expand current notions of what modeling is and how to engage in the practice. We present some promising directions for how to expand modeling research in ways that could address the aforementioned tensions and concerns.

3.1 | Make modeling multidimensional

Like any scientific practice, modeling is multifaceted in nature and encompasses conceptual, epistemic, social, and material dimensions. Engaging in modeling involves developing, using, evaluating, and revising representations, individually or collaboratively. It is also connected to other scientific practices such as argumentation and carrying out investigations. Despite the complexity of the practice, modeling work has primarily focused on the individual level and on the cognitive dimension of developing or using models. As described earlier, modeling research and assessment efforts have often valued and measured specific types of knowledge people hold about models (e.g., meta-modeling knowledge, science content knowledge) that are insensitive to purpose, context and resources. Less well-studied are areas including students' epistemologies in practice, the social, cultural or political dimensions of modeling, and how modeling modalities interact with those dimensions.

We suggest that the community expand the focus of modeling to consider dimensions of the practice that are essential for student engagement under various contexts. For example, it is critical to understand how people orient toward different modeling goals and how goals might vary within and across activities in classroom contexts (e.g., do we focus on mechanisms or on making our model more persuasive for our audience?). Further, it will require developing new means of and tools for assessment. If one is interested in assessing students' epistemic ideas about models, then studying students' reflective language (meta-knowledge) in situ during classroom talk as part of the practice or in reflecting on the practice retrospectively can more effectively capture how learners are making meaning in modeling practice (see Krist, 2020). Another strategy is to focus on using student interviews and formative and embedded assessments in which students can point to their knowledge, goals, purposes and moves within the modeling practice in that classroom context (Ke & Schwarz, 2019). It is a step in the direction of understanding better how students think with models in their worlds.

Similarly, the social and relational dimension is critical to learners' engagement in modeling practice and would benefit from further study. How does learners' social interaction around models contribute to collective sense-making? In a kindergarten case study example (Salgado, 2021), relational aspects of engagement in scientific practices were critical for sense-making. In this study, children were first grouped with self-identified friends to engage in classroom talk which then supported intellectual risk taking in small groups. Later, children continued these sense-making conversations during non-instructional times and engaged in spontaneous co-modeling sessions with their friends. These same conversations and modeling revisions often came up during whole groups discussions as children continued to make sense of new information about the phenomenon. Other research indicates that the power dynamics among participants plays a role in students' navigation of the practice (e.g., Shim & Kim, 2018). Social, relational and power interactions are essential to investigate if we are serious about making modeling work for the classroom knowledge building community.

Other important aspects to critically consider include the epistemic goals of modeling practice and how modeling interacts with other practices (Ke & Schwarz, 2021). For example, modeling might be particularly powerful for figuring out how and why phenomena happen or the mechanisms underlying phenomena (e.g., Krist et al., 2019; Schwarz et al., 2020). Doing so may provide a useful repertoire of core mechanisms for people to function in the world such as how changes in DNA can cause resulting proteins to have different functions which can cause significant effects on biological processes. Other work has considered how investigation and argumentation emerge from and are supported by modeling (Manz et al., 2020; Passmore & Svoboda, 2012). This work focuses on sensemaking as the primary enterprise, asking when and how young people take up modeling in service of sensemaking. Ultimately, modeling practice and assessments should focus on what really matters for how and why people are developing and using models in the world.

3.2 | Make modeling meaningful

Models and modeling are powerful when they help the person or people using them to make traction on their ideas (e.g., Schwarz et al., 2019), which often involves practices and thinking beyond the realm of science disciplines. Therefore, in addition to being meaningful in relation to disciplinary values and norms, classroom modeling also needs to be meaningful to the person or people participating in the practice.

Focusing on meaningfulness can involve first, examining forms of modeling across representational means and modalities to understand how modeling is serving the goals of the modeler and understanding what the modeler brings to the experience. A young child who is imagining an interaction in free play is arguably engaged in an early form of modeling by re-presenting aspects of the world they are interested in using the materials they have at hand, creating contexts in which they can explore and extend ideas. An elementary student using different types of fabric to model how animal fur might carry and disperse seeds is using physical phenomena to leverage possible mechanisms for how seeds might disperse in the world. A middle or high school student might be developing drawings or computer models that capture their ideas of how a phenomenon happens and may use those ideas in computational models to understand how elements/factors/components interact or are related in systems. College students might think through details of biological processes of transportation in and out of cells. Each of these humans are doing important modeling work, but they each have different purposes and tasks, histories and contexts and their engagement in the practice, and what they take away from that engagement is different.

Prior history and knowledge of the modeling context matters for how people make the modeling practice meaningful. The more a person or group "knows" about the phenomena including having history and experiences with the phenomena, the more they can do within that modeling context. For example, our prior work indicated that an important move that 5th grade children made as they began considering generalizable mechanisms in their models, was determining conditions under which phenomena (evaporation/condensation) occurred such as temperature differences, presence/absence of factors. In other words, they were "getting to know" the phenomena in important ways. This is a necessary step for truly understanding a system and being able to predict one in the future. They were doing this as a step toward understanding the mechanisms of the processes. Other research shows that even for college students who are learning about more complicated phenomena, there is a great deal of "getting to know" what is going on in the system as they work on developing models for predicting or explaining (e.g., Bierema et al., 2017). Therefore, if researchers and educators only value particular kinds of models (e.g., those with specific types of mechanisms or only those that predict rather than describe), they may miss critical processes and dimensions that learners need for modeling to be meaningful.

We can see how the modeling context matters when considering modeling at the elementary level (e.g., Schwarz et al., 2019). While powerful abstracted conceptual modeling ideas may work well for people who have had history and many experiences with phenomena and the conceptual structures underlying those phenomena, Manz and others (e.g, Manz, 2012; Marcum, 2018) have found that using physical materials in modeling can help younger learners leverage material properties that they have familiarity with (the texture and pattern of cloth; the speed of a fan, the height at which they let objects fall) to work with models as contestable, revisable, and conceptually powerful. This work and other work we have conducted (Salgado, 2021; Schwarz et al., 2019) indicates that for modeling to do work *for* sense-making, children need to have agency in their representational choices, be encouraged to represent their diverse ideas, and have models that are accessible based on their own experiences and resources.

There have been some current efforts that foreground making modeling meaningful that do not take for granted that it is. For example, research on integrating modeling and socio-scientific issues suggests that students bring their everyday experience about complex societal issues to their modeling work that may not necessarily be science related. In these contexts, students develop models not only to make sense of scientific phenomena, but more importantly, as a sensemaking tool to better understand the interrelationships between science and other social dimensions relevant for their community or everyday life (Ke et al., 2021). As such, the purposes of modeling are expanded from just focusing on scientific endeavors toward students' lives and well-being: to develop positions and responsible actions toward critical issues that matter to them. Other work has explored what conditions and contexts are important for productive modeling regarding learners with different foci and life experiences, such as younger or older learners (e.g., Lehrer & Schauble, 2015; Schwarz et al., 2019).

An implication of these bodies of work is that we should hold phenomena and forms of modeling accountable to being meaningful to young people. Researchers can attend to signs of modeling emerging from activity and being taken up by students. For example, by considering students' sustained engagement, social interactions around the model (e.g., spontaneous agreeing and disagreeing), and students bringing target concepts to bear on their modeling and social work (Manz, 2012, 2015). In these cases, the energy and drive for modeling comes from students pushing ideas along, rather than teachers "doing all of the work." Other work has begun to ask young people whether they understand why they are doing what they are doing in class and what their experience of classroom activity is (Raza et al., 2021; Zivic et al., 2018) and attending to the role of emotion in students' activity (e.g., Lanouette, 2022). Such indicators need to be at the center of efforts in promoting and evaluating modeling—rather than at the periphery.

3.3 | Make modeling equitable

The field and educators working with science and engineering practices like modeling need to think explicitly about equity and resources from a "what is meaningful to the learner and community perspective" (e.g., Bang et al., 2017). The notion that there is an absolute correct (or incorrect) way to develop and use models does not well-serve heterogeneous goals, people, and contexts. Modeling practice, instruction and assessments should move beyond singular authoritative views about who develops models, for a particular purpose and a particular context to replicate European-Western canonical practice and toward versions of modeling that may look less familiar. Furthermore, social positioning and power dynamics also play important roles in how modeling plays out in classrooms (e.g., Shim & Kim, 2018) and need to be explicitly attended to.

What might equitable modeling look like? There have been some powerful examples moving productively in this direction. For example, Grapin et al. (2021), Salgado (2021), and Shim and Kim (2018) have shown that students, communities, and cultures have enormous resources that can be built on and benefit from modeling. Providing students with multiple and diverse opportunities to engage in modeling by noticing and building on their own lived experiences and resources, supporting that work, and highlighting and expanding diverse ways of knowing is critical for making modeling equitable. For example, science educators have productively used prompts such as: What do you notice about this phenomenon? What do you wonder about? Draw ideas about how/why you think this happens. What does this remind you of (e.g., Reiser et al., 2021)? Finally, it is important to include community histories, values and practices that have played an important role for individuals and communities. Examples include conducting family and community walks as part of understanding and collaborating on ethical decision making in complex ecosystems (e.g., Learning in Places Collaborative, 2021), and enabling youth to include histories and experiences in making representations such as maps of their environments (e.g., Headrick Taylor, 2017; Sobel, 1998).

Furthermore, using other representational systems and means of expression may be important for making sense and making meaning of phenomena—including other modes of expression such as art, dance, play, stories, etc. Some work has begun to explore what we could learn about modeling and its possibilities if we expand what counts as modeling. For example, embodied dance work shows how youth can express themselves and model in culturally rich ways that allow for freedom and envisioning the possible (e.g., Georgen, 2019; Pollitt et al., 2021; Solomon et al., 2022). Children's play with forest dioramas expresses their thinking about biological entities, their behaviors, and relations. Washinawatok et al.'s (2017) study of four-year olds' play found that children across Native American and Non-Native cultures drew on the diorama rather than just the animals as a context for play and took up the diorama to model ecological relations, with Native children enacting more play and engaging in more perspective-taking as part of play.

Social and social science phenomena as well as interactions between the natural or engineered world and humans are other equity dimensions that are critical to people and science but often left out. Tzou et al. (2021) show how history, connection and culture are essential parts of science and highlight the importance of "making choices about what questions to ask, which data to collect, and when and how to intervene in natural processes" when working toward socially just science teaching. Models and modeling could be used when making these choices, thus working toward socially just teaching. Finally, working with teachers to understand and promote equity and epistemic justice (e.g., Penuel & Watkins, 2019) using modeling will also contribute to the field. Such efforts will be critical for working toward implementing expansive, meaningful, and equitable modeling.

4 | CONCLUSION

How can modeling be meaningful and equitable? Who is benefiting from modeling in schools and in life and how? Such questions are critical as the field moves forward. Rather than focusing on assessing modeling knowledge or decontextualized modeling competencies, we need to move toward meaningful and equitable practice. To do so, we need to design experiences in which modeling does work that people care about. Modeling should also be a shared experience that is cultivated through engagement and sustained by the community. Research and educators can work together to ask questions about when modeling is powerful for people across a range of ages and contexts and learn what representational, conceptual, and social resources people bring to bear on their modeling. Working toward these goals will enable people to enjoy, develop and use this powerful scientific and human practice toward their immediate sensemaking goals and, we hope, in service of a more just, equitable, and sustainable world.

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REFERENCES

Alonzo, A., & Ke, L. (2016). Taking stock: Existing resources for assessing a new vision of science learning. *Measurement: Interdisciplinary Research and Perspectives*, *14*(4), 119–152.

Bang, M., Brown, B., Calabrese Barton, A., Rosebery, A. S., & Warren, B. (2017). Toward more equitable learning in science. In C. Schwarz, C. Passmore, & B. Reiser (Eds.), *Helping students make sense of the world using next generation science and engineering practices* (pp. 33–58). NSTA Press.

Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., Lo, A. S., & Reiser, B. J. (2016). Epistemologies in practice: Making scientific practices meaningful for students. *Journal of Research in Science Teaching*, *53*(7), 1082–1112.

Bierema, A., Schwarz, C., & Stoltzfus, J. (2017). Engaging undergraduate biology students in scientific modeling: Analysis of group interactions, sense-making, and justification. *CBE–Life Sciences Education*, *16*(4), ar68.

Carey, S., & Smith, C. (1993). On understanding the nature of scientific knowledge. *Educational Psychologist*, *28*(3), 235–251.

Georgen, C. (2019). "Can't nobody floss like this!": Exploring embodied science learning in the third space. In Lund, K., Niccolai, G. P., Lavoué, E., Hmelo-Silver, C., Gweon, G., & Baker, M. (Eds.), *A wide lens: Combining embodied, enactive, extended, and embedded learning in collaborative settings, 13th International Conference on Computer Supported Collaborative Learning (CSCL) 2019*, Volume 1 (pp. 280–287). International Society of the Learning Sciences.

Gouvea, J., & Passmore, C. (2017). Models of versus 'models for'. *Science & Education*, *26*(1), 49–63.

Grapin, S. E., Llosa, L., Haas, A., & Lee, O. (2021). Affordances of computational models for English learners in science instruction: Conceptual foundation and initial inquiry. *Journal of Science Education and Technology*, *31*, 1–16. https://doi.org/10.1007/s10956-021-09930-3

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching*, *28*(9), 799–822.

Headrick Taylor, K. (2017). Learning along lines: Locative literacies for reading and writing the city. *Journal of the Learning Sciences*, *26*(4), 533–574.

Ke, L., Sadler, T. D., Zangori, L., & Friedrichsen, P. (2021). Developing and using multiple models to promote scientific literacy in the context of socio-scientific issues. *Science & Education*, *30*(3), 589–607.

Ke, L., & Schwarz, C. V. (2019). Using epistemic considerations in teaching: Fostering students' meaningful engagement in scientific modeling. In A. Upmeier Zu Belzen, D. Krüger, & J. Van Driel (Eds.), *Towards a competence-based view on models and modeling in science education* (pp. 181–199). Springer International Publishing.

Ke, L., & Schwarz, C. V. (2021). Supporting students' meaningful engagement in scientific modeling through epistemological messages: A case study of contrasting teaching approaches. *Journal of Research in Science Teaching*, *58*(3), 335–365.

Kimmerer, R. W. (2013). *Braiding sweetgrass: Indigenous wisdom, scientific knowledge and the teachings of plants*. Milkweed Editions.

Krist, C. (2020). Examining how classroom communities developed practice-based epistemologies for science through analysis of longitudinal video data. *Journal of Educational Psychology*, *112*(3), 420–443.

Krist, C., Schwarz, C., & Reiser, B. (2019). Identifying essential crosscutting epistemic heuristics for guiding mechanistic reasoning in science learning. *The Journal of the Learning Sciences*, *28*(2), 160–205.

Lanouette, K. (2022). Emotion, place, and practice: Exploring the interplay in children's engagement in ecologists' sampling practices. *Science Education*, 1–35. https://doi.org/10.1002/sce.21702

Learning in Places Collaborative. (2021). Educator frameworks and storylines.

Lehrer, R., & Schauble, L. (2015). The development of scientific thinking. In L. S. Liben, U. Müller, & R. M. Lerner (Eds.), *Handbook of child psychology and developmental science: Cognitive processes* (pp. 671–714). John Wiley & Sons, Inc.

Manz, E. (2012). Understanding the co-development of modeling practice and ecological knowledge. *Science Education*, *96*(6), 1071–1105.

Manz, E. (2015). Resistance and the development of scientific practice: Designing the mangle into science instruction. *Cognition and Instruction*, *33*(2), 89–124.

Manz, E., Lehrer, R., & Schauble, L. (2020). Rethinking the classroom science investigation. *Journal of Research in Science Teaching*, *57*(7), 1148–1174.

Marcum, M. (2018). *A year-long study of fourth graders' sense-making with modeling across phenomena* (Doctoral dissertation). University of Michigan.

Marin, A., & Bang, M. (2018). "Look it, this is how you know:" Family forest walks as a context for knowledge-building about the natural world. *Cognition and Instruction*, *36*(2), 89–118.

Nasir, N. S., Lee, C. D., Pea, R., & McKinney de Royston, M. (2021). Rethinking learning: What the interdisciplinary science tells us. *Educational Researcher*, *50*(8), 557–565.

National Academies of Sciences, Engineering, and Medicine. (2021). *Science and engineering in preschool through elementary grades: The brilliance of children and the strengths of educators*. The National Academies Press.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academies Press.

Nersessian, N. J., & Patton, C. (2009). Model-based reasoning in interdisciplinary engineering. In A. Meijers (Ed.), *Philosophy of technology and engineering sciences* (pp. 727–757). Elsevier.

Passmore, C., & Stewart, J. (2002). A modeling approach to teaching evolutionary biology in high schools. *Journal of Research in Science Teaching*, *39*(3), 185–204.

Passmore, C. M., & Svoboda, J. (2012). Exploring opportunities for argumentation in modelling classrooms. *International Journal of Science Education*, *34*(10), 1535–1554.

Penuel, W. R., & Watkins, D. A. (2019). Assessment to promote equity and epistemic justice: A use-case of a research-practice partnership in science education. *The Annals of the American Academy of Political and Social Science*, *683*(1), 201–216.

Philip, T. M., & Azevedo, F. S. (2017). Everyday science learning and equity: Mapping the contested terrain. *Science Education*, *101*(4), 526–532.

Pierson, A. E., Clark, D. B., & Brady, C. E. (2021). Scientific modeling and translanguaging: A multilingual and multimodal approach to support science learning and engagement. *Science Education*, *105*(4), 776–813.

Pollitt, J., Blaise, M., & Rooney, T. (2021). Weather bodies: Experimenting with dance improvisation in environmental education in the early years. *Environmental Education Research*, *27*(8), 1141–1151.

Raza, A., Penuel, W. R., Allen, A. R., Sumner, T., & Jacobs, J. K. (2021). "Making it culturally relevant": A visual learning analytics system supporting teachers to reflect on classroom equity. In *Proceedings of the 15th International Conference of the Learning Sciences-ICLS 2021*. International Society of the Learning Science.

Reiser, B. J., Novak, M., McGill, T. A., & Penuel, W. R. (2021). Storyline units: An instructional model to support coherence from the students' perspective. *Journal of Science Teacher Education*, *32*(7), 805–829.

Russ, R. S., & Berland, L. K. (2019). Invented science: A framework for discussing a persistent problem of practice. *Journal of the Learning Sciences*, *28*(3), 279–301.

Salgado, M. (2021). *"I like sharing ideas because that means people learn": Cultivating a Kindergarten Science Knowledge Building Community* (Doctoral dissertation).

Scherr, R. E., Close, H. G., Close, E. W., Flood, V. J., McKagan, S. B., Robertson, A. D., Seeley, L., Wittmann, M. C., & Vokos, S. (2013). Negotiating energy dynamics through embodied action in a materially structured environment. *Physical Review Special Topics - Physics Education Research*, *9*(2), 020105.

Schwarz, C., Manz, E., & Baker Marcum, M. (2019). Modeling for sense-making in the elementary classroom: Research, exemplars, and initial principles for modeling that works. Paper presented at the Annual Meeting of the American Educational Research Association, Toronto, CA.

Schwarz, C. V., Cooper, M. M., Long, T. M., Trujillo, C. M., de Lima, J., Kesh, J., Noyes, K., & Stoltzfus, J. R. (2020, Volume 1). Mechanistic explanations across undergraduate chemistry and biology courses. In M. Gresalfi & I. Horne (Eds.), *The Proceedings from the Fourteenth International Conference of the Learning Sciences (ICLS) 2020* (pp. 625–628). International Society of the Learning Sciences. https://repository.isls.org/handle/1/6286

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching*, *46*(6), 632–654.

Schwarz, C. V., & White, B. Y. (2005). Metamodeling knowledge: Developing students' understanding of scientific modeling. *Cognition and Instruction*, *23*(2), 165–205.

Shim, S. Y., & Kim, H. B. (2018). Framing negotiation: Dynamics of epistemological and positional framing in small groups during scientific modeling. *Science Education*, *102*(1), 128–152.

Sobel, D. (1998). *Mapmaking with children: Sense of place education for the elementary years*. Heinemann.

Solomon, F., Champion, D., Steele, M., & Wright, T. (2022). Embodied physics: Utilizing dance resources for learning and engagement in STEM. *Journal of the Learning Sciences*, *31*, 1–34. https://doi.org/10.1080/10508406.2021.2023543

Suárez, E. (2020). "Estoy Explorando Science": Emergent bilingual students problematizing electrical phenomena through translanguaging. *Science Education*, *104*(5), 791–826.

Tzou, C., Bang, M., & Bricker, L. (2021). Commentary: Designing science instructional materials that contribute to more just, equitable, and culturally thriving learning and teaching in science education. *Journal of Science Teacher Education*, *32*(7), 858–864.

Varelas, M., Kotler, R., Natividad, H., Phillips, N., Tsachor, R., Woodard, R., Gutierrez, M., Melchor, M., & Rosario, M. (2022). "Science theater makes you good at science": Affordances of embodied performances in urban elementary science classrooms. *Journal of Research in Science Teaching*, *59*(4), 493–528.

Vo, T., Forbes, C. T., Zangori, L., & Schwarz, C. V. (2015). Fostering third-grade students' use of scientific models with the water cycle: Elementary teachers' conceptions and practices. *International Journal of Science Education*, *37*(15), 2411–2432.

Washinawatok, K., Rasmussen, C., Bang, M., Medin, D., Woodring, J., Waxman, S., Marin, A., Gurneau, J., & Faber, L. (2017). Children's play with a forest diorama as a window into ecological cognition. *Journal of Cognition and Development*, *18*(5), 617–632.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, *92*(5), 941–967.

Zangori, L., Vo, T., Forbes, C. T., & Schwarz, C. V. (2017). Supporting 3rd-grade students model-based explanations about groundwater: A quasi-experimental study of a curricular intervention. *International Journal of Science Education*, *39*(11), 1421–1442.

Zivic, A., Smith, J. F., Reiser, B. J., Edwards, K. D., Novak, M. J., & McGill, T. A. W. (2018). Negotiating epistemic agency and target learning goals: Supporting coherence from the students' perspective. In *Proceedings of International Conference of the Learning Sciences, ICLS* (Vol. 1, No. 2018-June, pp. 25–32). International Society of the Learning Sciences.

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