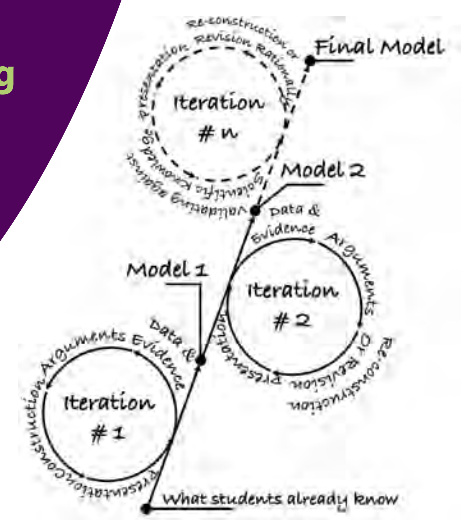
FEATURE ARTICLE

Guiding Students in Constructing and Revising Models Rationally



WENYUAN YANG, SIHANG CHEN, CHENG LIU

Abstract

Modeling is a core practice in science and is a meaningful way to learn the subject. This article introduces a modeling-based approach that highlights the idea that modeling is an iterative process and integrates the fundamental parts of scientists' work and key suggestions for teaching through modeling. The lesson "The Structure and Function of Kidneys" from a middle school biology course serves as an example of how to conduct the suggested modeling-based approach. By the end of the lesson, almost all students demonstrated a scientific understanding of the structure of nephrons and their functions. On the basis of the implementation of this lesson, we also provide further suggestions for modeling-based teaching.

Key Words: *Modeling-based approach, Modeling as what scientists do, Iterative process, Meaningful learning, The structure and function of kidneys*

○ Introduction

Scientific knowledge could be represented in the form of models that are useful for describing, explaining, and predicting phenomena (Gouvea & Passmore, 2017; Halloun, 2006). Scientists work to construct, extend, and refine the models rationally. It is crucial to involve students in the process of modeling, which reflects the fundamental aspects of scientists' work, including using data and evidence as the foundation for developing models, performing argumentation and analysis rationally, and changing models as understanding improves (Guy-Gaytán et al., 2019; National Research Council, 2012, 2013; Schwarz et al., 2022). For K–12 students, it is more important to make decisions and draw conclusions based on available evidence than to collect primary data. Therefore, it is suggested that students construct their own models based on data and evidence that they can explore by themselves or that are provided by teachers. Besides, it is necessary to engage students in having active discursive roles, articulating their own models, critiquing those of others, and determining the best interpretation of the data. To secure a deep and strong understanding, it is helpful for students to revise models that they have constructed to reflect advances in their understanding. Additionally, a meaningful modeling-based approach should provide explicit opportunities for students to experience the modeling process (Gilbert & Justi, 2016). Reasonable expectations for students and the provision of suitable scaffolds by teachers (Berk & Winsler, 1995; Broman et al., 2018) are also necessary in the modeling process.

It is crucial to involve students in the process of modeling, which reflects the fundamental aspects of scientists' work, including using data and evidence as the foundation for developing models, performing argumentation and analysis rationally, and changing models as understanding improves.

○ Suggesting a Modeling-based Approach to Supporting Students' Learning

In light of the above ideas, we proposed a modeling-based approach that absorbs the fundamental aspects of scientists' work and the aforementioned key suggestions for teaching through modeling. Figure 1 illustrates this approach. The dominant idea of this approach is that scientific modeling is an iterative process. In each iteration, students explicitly perform argumentation and analysis that relate evidence and what they already know, construct models rationally, or revise previous models in response to new information and present their models. An important task of teachers is to guide students in reviewing and weighing the different models developed by them, and then reaching a consensus. Occasionally and rationally, there may be two or three reasonable models falling into the next iteration; however, in light of the stepwise data and

The American Biology Teacher, Vol. 86, No. 3, pp. 130–135, ISSN 0002-7685, electronic ISSN 1938-4211. DOI: https://doi.org/10.1525/abt.2024.86.3.130.

Generations of Models	Sources of Data and Evidence	Students' Activities	Teachers' Activities
Model 1	• Provided by teachers or investigated by students • If possible, connecting with what students already know	• Analyzing the data • Arguing from evidence • Constructing models • Presenting models	• Organizing students' activities • Providing guidance • Focusing on the essence, but not the terminology or other facts
Model 2	• New information that can evoke students' rethinking of their previous models • Provided by teachers or investigated by students • If possible, connecting with what students already know	• Analyzing the new information • Arguing from evidence • Revising previous models • Presenting current models	• Organizing students' activities • Providing guidance • Focusing on the essence, but not the terminology or other facts
Final Model	• New information that can evoke students' rethinking of their previous models • Provided by teachers or investigated by students • If possible, connecting with what students already know	• Analyzing the new information • Arguing from evidence • Revising previous models • Presenting current models	• Organizing students' activities • Providing guidance • Focusing on the essence • Validating students' models against scientific knowledge

Figure 1. The suggested modeling-based approach.

evidence, the students would reach the consensus model at the end of the final iteration. Meanwhile, it is necessary for teachers to realize that the principle of evaluating students' models is whether they capture the essence of the target phenomenon rather than whether they are exact replicas of the target phenomenon in every detail, whether specific terminologies are used, or whether their appearances are beautiful. Additionally, a suitable difficulty level for each iteration is one where activities can fairly challenge students while still being achievable with teachers' guidance.

○ Applying the Suggested Modeling-based Approach to Middle School Class

Here, we take a lesson from a middle school biology course, namely "the structure and function of kidneys," as an example to detail how to go about the suggested modeling-based approach. Before beginning this lesson, the students learned the circulatory system, the respiratory system, and the digestive system. The core questions that students are expected to explore in this lesson are (1) what happens in the kidneys, resulting in blood processed into urine; and (2) what structures there are in the kidneys that perform that function?

We ran four iterations, respectively, aiming to help students: (1) understand the filtering process and the corresponding structure, (2) understand the reabsorption process and the corresponding structure, (3) be aware of about one million tiny factories in each kidney, and (4) name the accurate structures of a nephron and describe its function. In each iteration, students analyzed data or information provided by the teacher and drew their own models independently. To help the students concentrate on drawing the expected essential structure instead of drawing on other facts, we prepared a worksheet with the shape of the kidney (see Supplementary Material 1 provided with the online version of this article). While students drew their models, the teacher walked around the classroom, made sense of student ideas, and talked with individual students if necessary. After that, students shared their models by using a visual presenter and engaged in argument with teacher's guidance. The teacher encouraged students to share ideas, especially those with different ideas. By the end, students came to a consensus rationally. It took two class periods (about 80 minutes in total) to complete all activities. Each iteration took about 20 minutes.

○ First Iteration

This iteration aims to help students understand that a filtering process occurs in the kidneys before blood is processed into urine and that there is a corresponding structure executing that process. The essence of filtering is that some types of substances could pass through while others could not. Accordingly, strong evidence of filtering should be a reduction of substance types. Therefore, we displayed a table (Table 1), which showed the main compositions of blood and urine, and guided students in reading the table, analyzing the data, inferring what happens in the kidneys, and drawing a possible structure corresponding to the inference.

Almost all the students inferred that blood was filtered after entering the kidneys. Most of them could not explain how the blood was filtered but stated that there were some magic cells performing the function of the filter. There are four examples of this type of student model (Models 1, 2, 3, and 4 in Figure 2). A few students stated that the one-cell-thick capillary wall performed the function of a filter, two example models of which are presented in Figure 2 (Models 5 and 6). Additionally, some students thought that kidneys had valves to filter the blood (e.g., Model 7 in Figure 2), while others forgot that the blood should loop back to the heart (e.g., Model 8 in Figure 2).

After the students presented their models, we guided them to rethink the typical models. Overall, all the developing understandings mentioned above could be changed by evoking students' memories of what they have already learned. With regard to the

Table 1. Comparing the main compositions of blood and urine.

	Water	Blood cells	Glucose	Proteins	Urea	Salts
Blood	+	+	+	+	+	+
Urine	+	–	–	–	+	+

"+" represents inclusion of this substance, while "–" represents exclusion of this substance.

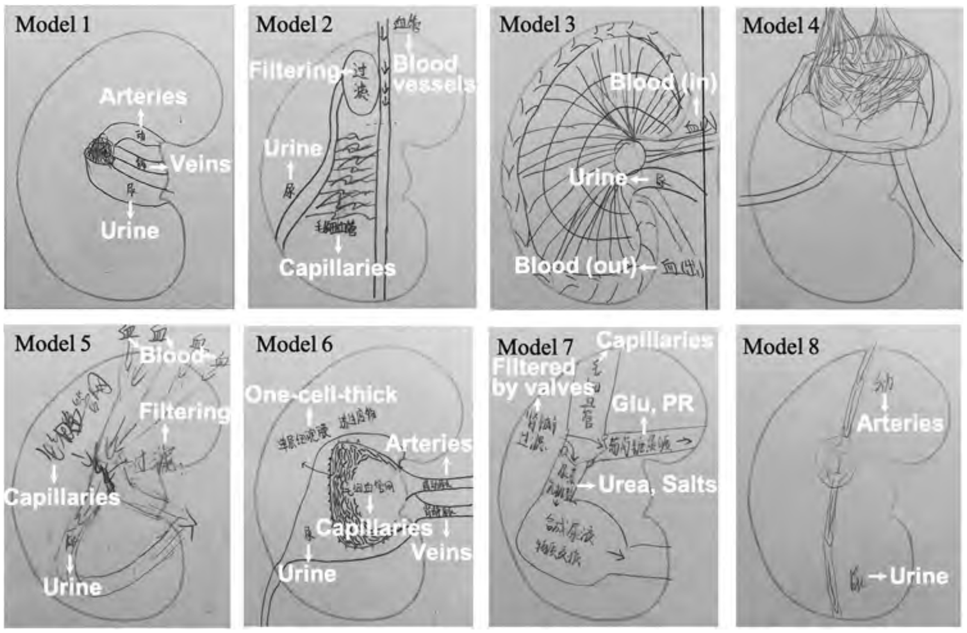


Figure 2. Eight examples of student models in the first iteration. The original characters have been translated into English (i.e., the text in white).

models that lacked blood vessels leaving the kidney, we asked students to recall that blood vessels are closed loops in which blood flows through capillaries in different parts of the human body and then back to the heart. Regarding the models showing that blood is filtered by renal valves, we asked students to consider what they have learned in the chapter on the circulatory system: valves can prevent blood from flowing backward instead of changing the composition of the blood; however, Table 1 shows that there are differences between the compositions of blood and urine. For students who thought there may be magic cells performing the function of a filter, we reminded them that maybe it requires no additional magic cells, as capillary walls are only one cell thick through which materials could be exchanged between the blood and the surroundings out of the capillaries. In the end, all students achieved the goal of this iteration and reached a consensus that the blood is filtered in the kidneys, while the capillaries performed the function of the filter. We explicitly drew a consensus on the blackboard (see Supplementary Material 2 provided with the online version of this article) to determine the achievement of the first iteration.

○ Second Iteration

This iteration aims to help students understand that there is a reabsorption process after the filtering process before the blood is processed into urine, and that there are corresponding structures that execute this process. The essence of reabsorption is that some types of substances coming out of the original place are absorbed back. Accordingly, evidence of reabsorption could be a second reduction of substance types. Therefore, we introduced that a liquid named primary urine was discovered in the tubes of the kidneys, and we displayed a second table (Table 2) showing the main compositions of blood, primary urine, and urine. Then, we guided the students in reading the table, analyzing the data, revising the previous inference of what happens in the kidneys, and accordingly revising their previous models.

In this iteration, all students still believed that blood was filtered after entering the kidneys, whereas two inferences emerged about what happened to the materials filtered out of the blood. Most students inferred that the needed materials are absorbed back into the body, while other students thought that a second filtering process may occur. Based on these two inferences, several kinds of explanatory models for the corresponding structures were proposed. Some students claimed that capillaries are in close contact with the renal tube so that the needed materials are absorbed back into the blood (e.g., Models 1, 2, and 3 in Figure 3), while a few students believed there may be magic cells for absorption (e.g., Model 4 in Figure 3). Additionally, some students stated that there may be villi, such as the structure in the small intestine, that absorb the needed materials from the primary urine (e.g., Model 5 in Figure 3). One student stated that there may be tubes leading to the small intestine (Model 6 in Figure 3). Several students thought

Table 2. Comparing the main compositions of blood, primary urine, and urine.

	Water	Blood cells	Glucose	Proteins	Urea	Salts
Blood	+	+	+	+	+	+
Primary urine	+	–	+	–	+	+
Urine	+	–	–	–	+	+

"+" represents inclusion of this substance, while "–" represents exclusion of this substance.

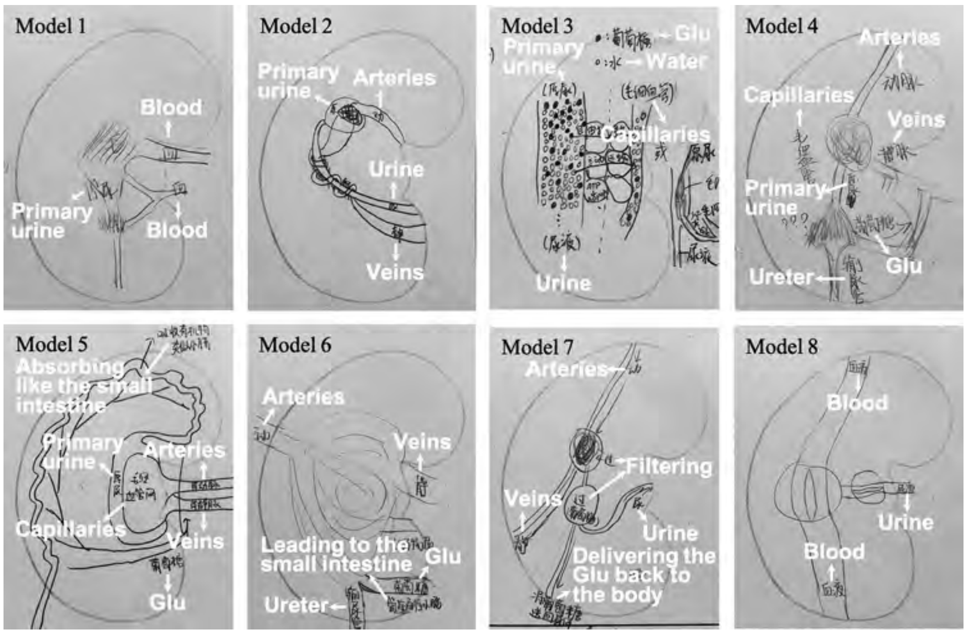


Figure 3. Examples of student models in the second iteration. The original characters have been translated into English (i.e., the text in white).

that the needed materials should be delivered back to the body after the second filtering process (e.g., Model 7 in Figure 3), while a couple of students let these materials stay in the renal tubes (e.g., Model 8 in Figure 3).

As in the previous iteration, we guided the students to rethink typical models after they presented their models. All developing understanding can be changed through logical reasoning under the guidance of the teacher. For students who inferred that there was a second filtering process that allowed the filtered materials to stay in the renal tubes, we asked the questions, "Can these materials be left there forever? If so, what would happen? Since these materials are needed nutrients, how does the body normally deal with them?" After that, all the students who inferred that there was a second filtering process agreed that the needed materials should be delivered back to the body. We continued to ask questions, "Which parts of the body are these materials delivered to? What structures perform this delivery function? Why does it not absorb the needed materials from primary urine directly instead of additional filtering and delivery? What would the additional process of filtering and delivery bring to the body?" After all the students recognized that it is a better choice to absorb the needed materials from the primary urine directly, we called their attention to the models referring to the small intestine, asked students to recall the structure of the villi and its function, guided them in transferring that understanding to the absorption process in the kidneys, and then affirmed that the renal tubes were long, twisting, and surrounded by capillaries. Finally, we explicitly drew on the blackboard, that is, we revised the previous drawing (see Supplementary Material 2 provided with the online version of this article) according to the consensus achieved in this iteration (see Supplementary Material 3 provided with the online version of this article).

○ Third Iteration

When entering this iteration, the goal is to help students become aware that each kidney contains approximately one million tiny units that work to form urine. The volume of each kidney is less than 150 mL, whereas the renal blood flow is approximately 1500 L/day, which means that each kidney is perfused with about 5000 times its total volume every day. Simultaneously, these fluids are processed into approximately 150 L of primary urine and then 1~2 L of urine daily (Eaton & Pooler, 2013). With this in mind, we described the task as follows, "The consensus structure achieved through the previous two tasks is actually the structural and functional unit working to form urine in the kidneys. If we consider this structure as a tiny factory, how can we construct a kidney with high productivity? Please recall the structure of the alveoli, transfer their characteristics to the kidney, and draw the possible structure of a kidney."

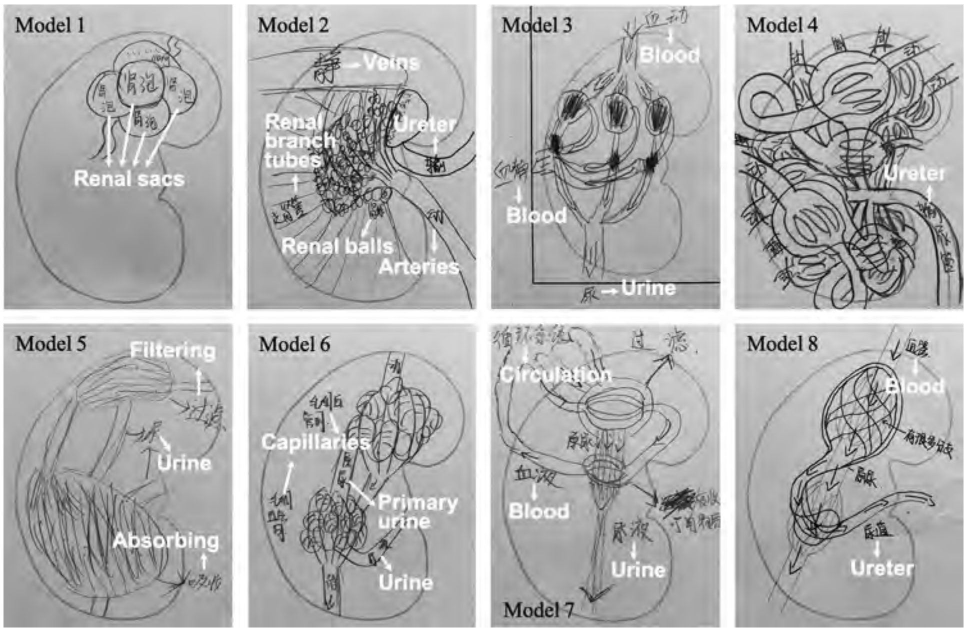


Figure 4. Examples of student models in response to the need of high productivity. The original characters have been translated into English (i.e., the text in white).

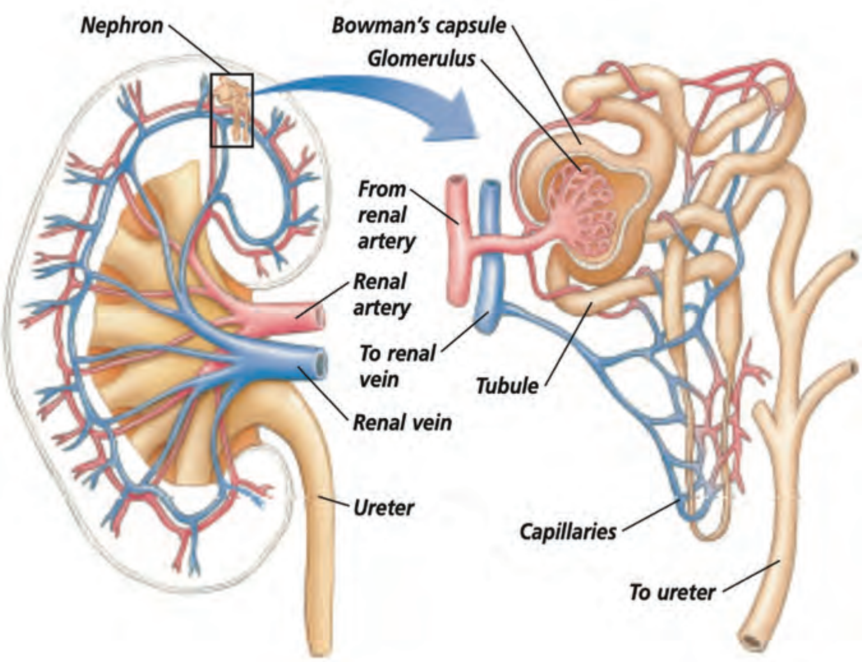


Figure 5. A scientific picture of the structures of the kidneys (Biggs et al., 2004; used with permission of the publisher).

Once again, the students demonstrated different ideas. Most stated that they needed as many tiny factories as possible (e.g., Models 1, 2, 3, and 4 in Figure 4), whereas the other students preferred one factory as much as possible (e.g., Models 5, 6, 7, and 8 in Figure 4). As the "huge factory" has relatively smaller surface area and higher risk of malfunction, those students with the preference of one huge factory before were persuaded eventually. At the end of this iteration, all students perceived numerous tiny units working to form urine in each kidney.

○ Fourth Iteration

By the end of this iteration, the students were expected to name the main structures of a nephron and describe the process of urine formation. A desirable way to learning the exact structure of something is observing directly or with tools. However, microscopic images of nephrons are far beyond the ken of middle school students. Moreover, as students have gained the essence of the structure and function of kidneys through the previous activities, the objective of this

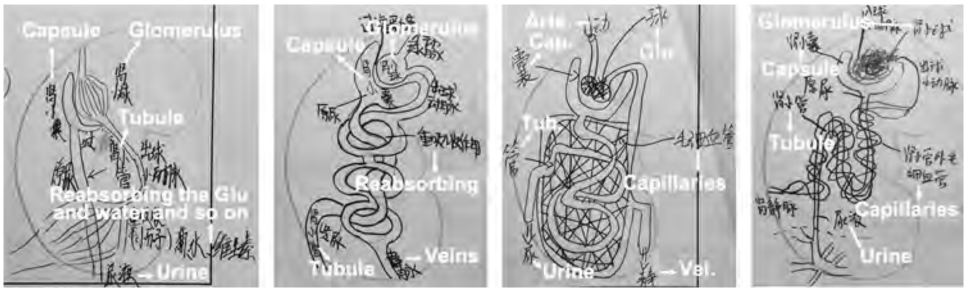


Figure 6. Examples of student models in the final iteration. Though the styles vary as always, almost all of the students could capture the specific structures of a nephron and explain how they work. The original characters have been translated into English (i.e., the text in white).

step is just to help them draw more accurate models. Therefore, we displayed a scientific picture of the structures of the kidneys (Figure 5) and provided clear explanations of these structures and how urine was formed. We then asked students to draw their fourth model—the structure of a nephron—and explain how it worked. Almost all students completed this task independently. Four examples of the students' final models are presented in Figure 6.

○ Summary

The modeling-based approach introduced above is challenging for teachers in many respects, but very meaningful for students. The following suggestions may help teachers overcome these challenges. It is necessary for teachers to perceive that, like scientists may develop different explanations of a phenomenon, students may construct various models for the same target. There is no uniquely correct style for demonstrating a consensus on a target phenomenon. For example, Models 5 and 6 in Figure 2 are different in appearance, but they share a broad consensus; the same applies to Models 1, 2, and 3 in Figure 3; Models 1, 2, 3, and 4 in Figure 4; and the four models in Figure 6. Moreover, it is extremely important for teachers to focus on the essence of the target phenomenon—that is, the scientific consensus understanding existing independent of the forms of representation—and set it as the goal for student modeling. Teachers should determine how to provide guidance according to the differences between the students' models and the essence of the target. Taking the above lesson as an example, we provide different guidance for students to reconsider different types of developing understanding in each iteration. Additionally, because modeling is not a one-step activity, we should not expect students to complete every task without additional guidance. Teachers must be prepared to deal with various student responses. When we were designing the above lesson, we made a prediction about what student responses may appear in each activity and carefully considered how to deal with each response. For example, we predicted that some students may propose "magic cells" because they created this phrase in previous lessons. We also predicted that some students may propose "a second filtering process" in the second iteration because it was a reasonable inference based on Table 2 if they did not consider how to deal with the filtered materials. In most cases, students' developing ideas could be changed by evoking their funds of knowledge and providing rational guidance. Besides, the predictive function of models, which was not embodied in the example lesson, should be taken into account whenever planning a modeling-based lesson.

References

Berk, L. E., & Winsler, A. (1995). *Scaffolding children's learning: Vygotsky and early childhood education*. National Association for the Education of Young Children.

Biggs, A., Hagins, W. C., Kapicka, C., Lundgren, L., Rillero, P., Tallman, K. G., Zike, D., National Geographic Society. (2004). *Biology: The dynamics of life*. McGraw-Hill.

Broman, K., Bernholt, S., & Parchmann, I. (2018). Using model-based scaffolds to support students solving context-based chemistry problems. *International Journal of Science Education*, *40*(10), 1176–1197.

Eaton, D. C., & Pooler, J. P. (2013). *Vander's renal physiology* (8th ed.). The McGraw-Hill Companies.

Gilbert, J. K., & Justi, R. (2016). *Modelling-based teaching in science education*. Springer International.

Gouvea, J., & Passmore, C. (2017). "Models of" versus "Models for": Toward an agent-based conception of modeling in the science classroom. *Science & Education*, *26*(1–2), 49–63.

Guy-Gaytán, C., Gouvea, J.S., Griesemer, C., & Passmore, C. (2019). Tensions between learning models and engaging in modeling. *Science & Education*, *28*(8), 843–864.

Halloun, I. A. (2006). *Modeling theory in science education*. Springer.

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

National Research Council. (2013). *Next generation science standards: For states, by states*. The National Academies Press.

Schwarz, C. V., Ke, L., Salgado, M., & Manz, E. (2022). Beyond assessing knowledge about models and modeling: Moving toward expansive, meaningful, and equitable modeling practice. *Journal of Research in Science Teaching*, *59*(6), 1086–1096.

WENYUAN YANG (yangwystudio@foxmail.com) is an independent scholar working in the field of K-12 science/biology education, formerly worked at Capital Normal University. SIHANG CHEN (chensihang@bnu.edu.cn) is a biology teacher at Beijing Sanfan Middle School. CHENG LIU (liucheng@bnu.edu.cn), the corresponding author, is an associate professor at College of Life Sciences, Beijing Normal University, Beijing 100875, People's Republic of China.