

# Measuring Transformative Modeling: A Framework of Formatively Assessing Students' Deep Conceptual Understanding in Physical Sciences

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**Abstract:** Measuring students' conceptual understanding can provide important information for learning and teaching. Many formative assessment approaches elicit students' prior knowledge without identifying the sources of their misconceptions. This proposal presents a framework that guides the development of formative assessment to measure student understanding of physical science topics using three types of connections. Particularly, we assess how students link physical states, processes and mechanism, integrate different scientific models, and connect scientific knowledge to everyday experience. Based on this framework, we construct sample items on sinking and floating and piloted the items with 18 preservice middle grades science teachers. Analyses of student responses to these sample items provide evidence of the effectiveness of the framework in extracting information valuable to improve learning and instruction. Criteria and implications of using this formative assessment framework in science classrooms are then discussed.

## Introduction

Many national and state-level science tests fail to measure deep understanding (Hyde et al. 2008; Liu, Lee, Hoftstetter, & Linn, 2008). As a result, American students continue to languish on international science assessments (OECD, 2006). To reverse this trend and promote science achievement in the U.S., it is critical to design formative assessments that can effectively capture students' prior experience and measure deep understanding (Shen, Gibbons, Wieggers, & McMahon, 2007).

The challenge of capturing students' deep understanding through formative assessment is manifold. The complicated dimensions of science learning create challenges in both assessment design and utility of the information extracted from the assessment. For instance, many science assessments targeting conceptual understanding are designed to measure a single aspect of the correctness of science content. However, science learning is such an integrated and dynamic system that multidimensional abilities should be considered in the assessment (Anderson & Krathwohl, 2001). The assessment should capture student ability in integrating understanding and justifying explanations as well as their mastery of content knowledge. Most importantly, to take advantage of the assessment results, teachers should understand how students apply textbook knowledge in a new learning context.

To address these challenges, many science education researchers have developed frameworks to capture the multiple dimensions of science learning that shifted away from only focusing on content correctness (Linn et al. 2006; Yin et al. 2005). Science educators are also interested in understanding how students develop competences such as inquiry and modeling abilities to conduct science experiments (e.g., Gotwals & Songer, 2006). Acknowledging the multiple dimensions of science learning, we expand the dimension of conceptual understanding to capture students' modeling and inquiry abilities in this study. Particularly, we present a framework that guides the development of formative assessment to measure students' understanding of abstract and complex topics in physical sciences in three types of connections: linking physical processes and states with underlying mechanism, integrating multiple explanatory models, and connecting their science knowledge to natural observations and everyday experiences (National Research Council [NRC], 2000; Shen & Linn, 2010).

We focus on formative assessments that help teachers identify students' weaknesses in order to learn science concepts more effectively. Our framework can be enacted in multiple formats, e.g., paper and pencil quizzes, computerized word problems, oral interviews, or group-discussion questions. In the following section, we first discuss some exemplar assessment approaches in science education on which our framework is built. We then present the rationale and mechanism of our framework. Finally we elaborate on the framework with sample student responses on an item in sinking and floating.

## Measuring Deep Conceptual Understanding

Effective assessment practices in science education are aligned with distinctive learning theories (NRC, 2001; Wilson, 2005). Here we elaborate on three examples that influenced the development of our framework.

### Measuring Integrated Understanding Using Knowledge Integration

Many students gain fragmented knowledge. Linn and colleagues have developed a knowledge integration (KI) framework that emphasizes student abilities in establishing connections among ideas (Linn & Eylon, 2006; Linn et al., 2006; Liu et al. 2008). The KI framework emphasizes the repertoire of ideas that students build as they interact with the world. Students add varied ideas as they experience science in daily life. The KI framework calls for taking advantage of the reasoning that students employ to formulate these views. The framework promotes coherent understanding by encouraging students to add new ideas, distinguish new and existing ideas, develop scientific criteria to reconcile ideas, and build coherent connections. The KI framework is realized through technology-enhanced learning environments that present complex and usually unseen science topics through computer visualization programs. The KI assessment framework features multiple assessment formats (e.g., pre/post tests, annual assessment, embedded assessment) for both formative and summative evaluation purposes. The KI scoring rubric rewards student reasoning and ability to articulate scientific evidence as well as content mastery. The KI assessment framework has been tested with large-scale empirical studies and has demonstrated satisfactory psychometric properties (Lee, Liu, & Linn, in press; Liu et al. 2008).

The KI framework states that there are different types of connections (Linn & Eylon, 2006) but does not distinguish these types in scoring (Linn et al. 2006). Building on this framework, we further detail and speculate that three types of connections are extremely important (will be discussed momentarily) in helping students gain deep conceptual understanding across science disciplines. Our assessment framework is aimed at identifying these different types of connections, which in turn can inform instructions.

### Measuring Understanding of Scientific Models

Modeling-based instruction in science classrooms is a constructivist approach that encourages students to develop, use, and evaluate models to describe, explain, and predict scientific phenomena (Chinn & Samarapungavan, 2008; Clement, 2000; Lehrer & Schauble, 2006; Schwarz & White, 2005). For example, through the MoDeLS project, Schwarz et al. (2009) developed a learning progression framework based on modeling for upper elementary and middle grade students. They defined a scientific model as “as a representation that abstracts and simplifies a system by focusing on key features to explain and predict scientific phenomena” (Schwarz et al. 2009, p.633). They considered two dimensions of the practice of modeling. One dimension addressed scientific models as tools for prediction and explanation; the other dimension considered the change of models when understanding improves. They built a construct for assessing students’ progress in each dimension.

The works by Schwarz et al. (2009) and others provide important insights in how to teach and measure modeling in science classrooms. Our work focuses primarily on how deeply students understand scientific models and how well students are able to connect scientific models to natural phenomena. We believe that robust understanding of existing models can help students compare, evaluate, and revise models. We agree with Schwarz et al. (2009, p.635) in that “it is crucial to involve learners in the construction of models.” However, we argue that it is equally important that students firmly grasp provided models because these models provide the solid foundations from which students can construct their own ones (Shen & Confrey, 2007). When students learn more advanced models in higher grades, they need to build on and integrate the simplified ones they have learned earlier on. Therefore, one important component in our framework is to assess how students integrate different scientific models they have learned.

### Measuring Complex Reasoning in Scientific Inquiry

Science education researchers also look at students’ complex reasoning in inquiry. Principled Assessment Designs for Inquiry (PADI) is an assessment framework that focuses on providing design patterns and structures to measure students’ inquiry skills and science knowledge. For example, Gotwals and Songer (2006) created a content-inquiry matrix that laid out different levels of science inquiry and science content required in assessment tasks. They used the matrix to highlight the interplay between inquiry abilities and science knowledge as students performed inquiry tasks or took inquiry assessments. The matrix had three levels of science content knowledge and three steps of science inquiry processes. The simple level of science content knowledge meant that the task or assessment provided sufficient content; the moderate level required students to demonstrate solid understanding of science concepts; the complex level required students to connect among multiple concepts. For the three steps of science inquiry the authors indicated that the steps might differ depending on the aspects of inquiry being targeted, such as generating scientific explanations or constructing representations using data.

While the content-inquiry matrix is used to help assess how students develop science knowledge and inquiry skills at different levels of complexity over time, our framework focuses on laying out important aspects of conceptual understanding that students need to explain complex phenomena specifically in physical sciences. Similar to the PADI framework, our framework assesses complex reasoning closely related to inquiry such as explaining phenomena in light of its underlying mechanism, or connecting between multiple explanatory

models. The difference is that our framework can be used in a variety of teaching and learning contexts that may or may not necessarily measure the full scale of inquiry.

We propose a new assessment framework on conceptual learning to address the limitations that we see in the existing approaches. Built upon the existing literature, our work is an ongoing contribution to advance the formative assessment of students' deep understanding in science classrooms. We envision such a framework as a useful tool for instructors to revamp instruction based on the information extracted from the assessment responses.

## Theoretical Framework

Our framework is informed by the instructional theory of transformative modeling (TM) (Shen & Confrey, 2007, 2010). It is a theoretical framework used to describe, analyze, and inform learning processes. TM delineates learning and teaching as a process of modeling the natural world through chains of operations on materials. At the center of the operations are a set of transformations that alter the nature of physical or symbolic objects by adding or suppressing information. The transformed materials, as well as the operations on these materials, render potential for future learning. Examples include transforming detailed observations into numerical records to ground scientific understanding of measurement uncertainty, transforming data and graphs into mathematical formula to enrich abstract conception of motion, transforming between the geocentric model and the heliocentric model to better comprehend the solar system.

In this framework, conceptual learning is defined as the process of gaining ability to transform materials in both physical and abstract forms. Specifically, the consistency among the transformed materials perceived by a cognizing agent defines the depth of the comprehension of the concept. The variety of transformation types and forms determines the broadness of the construed concept. For the depth of comprehension, an example is the common misconception that many students hold about the cause of the seasons (Harvard-Smithsonian Centre for Astrophysics & Schneps, 1988). Many students reason that it is hot in the summer because the sun is closer and it is cold in the winter because the sun is farther away (the distance model). This reasoning draws upon everyday experience (e.g., sitting besides a fireplace) that one feels warmer when sitting closer to a heat source. In the TM theory, we interpret this explanation as being able to transform everyday experience to explaining the seasons to a certain degree, even though it is not compatible with the scientific model. People later learn that the northern hemisphere and the southern hemisphere have opposite seasons, and that in fact in summer the earth is farther away from the sun. The distance explanatory model then becomes conflicting to the new information, which calls for a deeper understanding of the cause of the seasons. For the broadness of conceptual understanding, the TM framework advocates the incorporation of multiple representations in learning science to ensure coherent understanding. For instance, when students learn kinematics, constant transformation among graphic representations can help them summarize many observations and physics principles (Shen, 2009). Students need to acquire a rich set of graphs (e.g., position-time graph, velocity-time graph, free-body diagram) to broaden their understanding of Newtonian mechanics.

Based on the TM instructional theory and previous analyses of students' responses to questions on electrostatics (Shen & Linn, 2010), we identify three most important aspects in knowledge transformations: (a) linking scientific mechanism with both states and processes of the target domain; (b) integrating multiple explanatory models, and (c) connecting scientific models with everyday observations. In the following we elaborate on these three important transformations.

## Linking Physical States, Processes, and Underlying Mechanism

The idea of integrating mechanism with states and processes comes from the fact that much scientific understanding originates from transforming observations of natural changes into data, inscriptions, and digital records. During such an observation, the states and the processes need to be accurately described. The scientific records of the initial, transitional, and final states help students identify the interacting agents and the relevant variables that constitute the key properties of the target system. A physical process of a system consists of changing states over time. Many of these processes lead to a physical equilibrium (e.g., thermal equilibrium) in which the state of the system does not change anymore. A mechanism is defined as an explanation (e.g., mathematical formalism, causal inference) one draws to theorize the patterns of how the key states emerge and change. Oftentimes, the mechanism introduces abstract concepts (e.g., force) or microscopic entities (e.g., electron).

Here are two examples in physical sciences that illustrate how students need to integrate mechanism with states and processes to gain deep understanding. An electrical *state* of an object may be positively charged, negatively charged, or neutral. For example, an object is initially positively charged. Then, it is discharged after touching one's hand, and eventually, the object becomes neutral. Students may only pay attention to the initial state (positively charged) and the final state (neutral) of the object without thinking about the in-between *process* when the change takes place. The understanding of the charging/discharging processes provides a trajectory of the observed changes and trends of the electrical states. Therefore, a better understanding includes

the process where the negative charges are transferred from the hand to the object to neutralize it. The understanding is further enhanced by learning the *mechanism* of why charges move: like charges repel and opposite charges attract. That is, the forces between charges drive the motion of the charges. Likewise, deep understanding of the state of thermal equilibrium involves explaining the heat transfer processes. A thermal state of an object (hot, warm, or cold) can be measured by its temperature. Consider a hot object in touch with a cold object. The initial thermal states of the two objects are measured in different temperatures. Many students learn that, eventually, the two objects will reach the same temperature. They need to know how this happens by learning the processes and mechanism. When envisioning that heat is transferred from the hot object to the cold object, one is considering the process. A mechanism states that temperature difference drives heat to transfer from an object with higher temperature to another object in touch until they reach the same temperature (thermal equilibrium).

### Integrating Multiple Explanatory Models

One may build different models to explain the same phenomenon since there are different aspects of the phenomenon one chooses to model (Shen & Confrey, 2010). Some of the models are consistent with the accepted scientific models; others conflict with accepted understanding. Students typically start with simple and concrete models, and then advance to more abstract and general ones in learning complex science topics (Lehrer & Schauble, 2006). We argue that when learning more advanced models, students need to integrate the earlier models they have learned. For instance, to explain and predict how the planets move in the solar system (kinematics only), students may start with a geocentric model since that is what one sees from the earth. Then students may move to learn the heliocentric model used to explain the geocentric model. A higher-level understanding indeed incorporates the two models and helps students go back and forth between the two models depending on the context.

For the discharging example, one may employ a charge-based model as discussed in the previous section. One may also use a particle-based model: initially, the object has less electrons (which carry negative charges) than a neutral state (the final state). During the discharging process, electrons from human hand move to the object. The movement of electrons is driven by the interactions (forces) among the particles. The connection between the two models lies in the fact that types of charges are properties of certain particles (e.g., electrons are negatively charged). For thermal equilibrium, the heat transfer process may be attributed to a substance carrying heat that flows from one object to another, which may be considered as a misconception. Alternatively, one may consider a particle model. In this model, temperature of an object is a measure of the average kinetic energy of the particles, which corresponds to the average speed of the particles. That is, an object with a higher temperature has particles vibrating faster on average than an object with a lower temperature. In the heat transfer process, collisions between particles drive the transfer of the kinetic energy from one object to the other.

### Connecting Science Knowledge to Physical Observations and Everyday Experience

Physical sciences study the patterns of the physical world and students experience the physical world every day. It is expected that students learn science more effectively and meaningfully if their learning is built upon and tied back to their everyday experience (Linn, 2006). Unfortunately, many teachers do not use students' experience as resources for teaching. As a result, students often build models in the learning context but rarely connect to their learning experiences in other contexts or to everyday experiences (Kozma, 2003). Being able to connect scientific models to other learning contexts or everyday experiences is an indicator of the degree to which students develop integrated understanding of the represented concept.

Many examples of everyday experience are related to discharging: e.g., grabbing a metal doorknob and getting shocked, touching the metal part of a car before refueling, spraying water to prevent fluffy hair. Deep understanding of electrostatics requires students to make sense of these phenomena outside of classrooms. Similarly, when learning heat and temperature, students should reflect on everyday experiences such as determining a better material to keep things warm.

### **Constructing Assessment Items on Sinking and Floating**

Sinking and floating are interesting phenomena for students to investigate. It involves different explanatory models and everyday experience. Abundant previous research was devoted to identify students' understanding of sinking and floating (e.g., Dentici et. al. 1984; Halford, Brown, & Thompson, 1986; Mullet & Montcouuiol, 1988; Rowell & Dawson, 1977; Yin, Tomita, & Shavelson, 2008). In the following section, we first introduce the physics behind the phenomena of sinking and floating. We then present three sample items to illustrate how we apply the TM framework to build assessments that help students identify the connections among key states and processes, link multiple explanatory models, and apply to the physical world. Finally we present sample student responses and demonstrate how the responses can be analyzed using our framework.

### Physics of Sinking and Floating

To determine if an object is either a sinker or a floaters without putting it in a fluid, one can compare its average density with the density of the fluid - the density model. If the average density of the object is greater than the fluid, then the object will sink when put in the fluid. If it is smaller, the object will float. If the average density of the object is equal to the fluid, then the object will suspend in the fluid. Alternatively, one may also compare the weight of the object with its buoyancy - the force model. Buoyancy on an object is defined as the net force exerted by the surrounding fluid.<sup>(1)</sup> One may simply predict that an object will sink when put in the fluid if the buoyant force on the object is smaller than its weight. But the opposite is only partially true: the object will *start to* float if its buoyancy is greater than its weight. This only applies for an object completely submerged under water. It may lead to the misconception that the buoyancy is greater than weight when an object floats on water. Having learned the density model, one may think that the force model is redundant. In fact, the force model is able to explain the processes of sinking and floating in much more details.<sup>(2)</sup>

A deep understanding needs students to be able to integrate the density model and the force model. To compare the buoyancy and the weight of an object completely submerged under a fluid, one may compare its weight with the weight of the fluid displaced since the buoyancy of an object is equal to the weight of the fluid displaced (Archimedean principle). Also since the object is immersed in the fluid, the volume of the object is the same as the volume of the fluid displaced. Hence, it is equivalent to compare the density (mass/volume) of the object with the density of the fluid.

### Instruments Used to Assess Understanding of Sinking and Floating

Figure 1 shows a sample item in an instrument used to identify students' misconceptions developed by Yin, Tomita, and Shavelson (2008). This item does a nice job in revealing students' misconception, i.e., "Big/heavy things sink, small/light things float." Some students may predict the two blocks will "sink" when stacked together (or subsurface float) because the bundle of blocks A and B is heavier than each individual block.

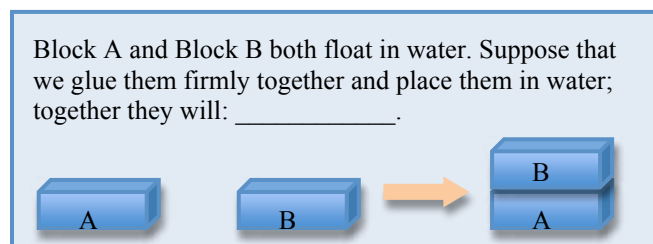


Figure 1. A sample item on sinking and floating from Yin et al. (2008).

However, this kind of items does not inform the teacher of the possible origins of these misconceptions. Using our TM framework, a possible explanation for the misconception is that the students may not distinguish density (mass over volume) from weight (a force). This explanation is also consistent with our experiences of teaching the topics on sinking and floating. In everyday language, the term heaviness often refers to the two terms interchangeably.<sup>(3)</sup> One can explain the phenomenon of sinking and floating using the density model or the force model (detailed explanation is provided in the next section). But these explanatory models may be taught in a fragmented fashion, and students are not able to connect these models. Moreover, this kind of items does not inform the teacher if students are able to connect the knowledge of sinking and floating to observations. We may infer that the incorrect answer entails that the student cannot connect to everyday experience, e.g., if one bundles two pieces of wood together, the bundle still floats.

### A Sample Item on Sinking and Floating Using the TM Framework

**Participants.** We created an instrument on sinking and floating using the TM framework and piloted with 18 undergraduate students working towards middle grades science teaching certificates (17 female, 1 male). These students had weak science background based on the results of a survey measuring general physics knowledge (25% correct). The items on sinking and floating were administered in a quiz after they had two lessons on sinking and floating (4 hours in a total) including a lab confirming Archimedean Principle. The quiz has six constructed-response items. It took the students half to one hour to finish. Here we provide an example.

#### *Item Two Balls [due to space limit, here we only present one sample item and students' responses]*

The item Two Balls (see Figure 2) asks students to predict and explain what will happen to two balls (one floater and one sinker) in water when salt is added. A physical demonstration can also be set up. Students can use either the density model or the force model to explain the observations as in the previous item. The key points are summarized in Table 1.

Ball A and ball B have the same volume. A is floating on water, B is sitting at the bottom of the water tank.

(1) Which ball has the greater buoyancy? Explain.

(2) Which ball has the greater density? Explain.

(3) Sam adds some amount of salt in water and let them dissolve. What happens to the buoyancy of the two balls? Explain.

(4) What changes would you expect after Sam has added salt in the water?

[A physical demonstration can be shown when students respond to this problem].

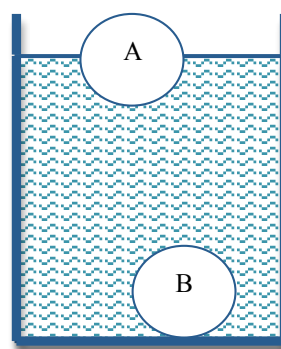


Figure 2. Item “Two Balls” on sinking and floating.

Table 1: The density and force models used to explain the item Two Balls.

	Density Model	Force Model
State	<ul style="list-style-type: none"> <li>Ball A is floating initially. Part of ball A is submerged under water.</li> <li>Ball B is sitting at the bottom initially. All of ball B is submerged under water.</li> <li>After adding salt, ball A still floats. Ball B may sink or float depending on the amount of salt added in.</li> <li>After adding salt, the density of the water increases.</li> </ul>	<ul style="list-style-type: none"> <li>Ball A is floating initially. Part of all A is submerged under water.</li> <li>Ball B is sitting at the bottom initially. All of ball B is submerged under water.</li> <li>After adding salt, ball A still floats. Ball B may sink or float depending on the amount of salt added in.</li> <li>After adding salt, the weight of the water of the same volume increases.</li> </ul>
Process	<ul style="list-style-type: none"> <li>When the salt is added, more part of ball A comes out of water.</li> <li>When salt is added, ball B may still sit at the bottom. It may also move up and becomes a floater.</li> </ul>	<ul style="list-style-type: none"> <li>When the salt is added, more part of the ball A comes out of water.</li> <li>When salt is added, ball B may still sit at the bottom. It may also move up and becomes a floater.</li> </ul>
Mechanism	<ul style="list-style-type: none"> <li>An object less dense than water tends to float. An object denser than water tends to sink. An object having the same density as water suspends in water.</li> <li>For a floater, the proportion of the volume of the object that is submerged under water over its whole volume equals the proportion of the density of the object over the density of the fluid (relative density).</li> </ul>	<ul style="list-style-type: none"> <li>An object accelerates if the net force acting on it is non-zero (Newton’s second law). An object is at rest or moves at a constant velocity if the net force acting on it is zero (Newton’s first law).</li> <li>There are two forces acting on an object floating on water: weight and buoyancy.</li> <li>There are three forces acting on an object sitting at the bottom of a water tank: weight, buoyancy, and normal force by the tank.</li> <li>Buoyancy is equal to the weight of fluid displaced (Archimedean Principle).</li> </ul>

The detailed explanation follows. Since ball A displaces less volume of water than ball B, it has a smaller buoyancy than B. For a floater, its density is less than the density of water; for a sinker, its density is greater than the density of water. So the density of ball A is smaller than that of ball B. When salt is added, the density of the salt water is increased. Therefore, ball A keeps floating. For any floater, the buoyancy equals its weight, so the weight of ball A does not change. This means that the buoyancy of ball A does not change. To maintain constant buoyancy, ball A has to rise up a bit to displace less volume of salt water. For ball B, it may still rest at the bottom, but exerting less force on the bottom of the water tank. It may also move up if the amount of salt dissolved leads to a greater density of the salt water than ball B. If that is the case, Ball B will go all the way to the top until a part of it comes out of the salt water.

#### *Students’ Responses and Implications for Instruction*

All students stated that ball B has a greater density in sub-question #2. This indicates that all the students are able to use the density model to explain the final states of sinking and floating at this stage. However, students’ responses to sub-questions #1, #3 and #4 revealed that most of them did not integrate the buoyancy model to explain and predict the phenomenon of sinking and floating.

Students may confuse the sinking and floating states with the underlying mechanism of competing forces. Buoyancy is a variable (force) that influences the sinking or floating of an object. However, students often think that buoyancy refers to the state of floating (i.e., floating higher indicates a greater buoyancy), and may think that buoyancy is a property of an object. In the pilot test, 10 out of 18 students thought that ball A had a greater buoyancy in sub-question #1. A typical response stated that “Ball A has the greater buoyancy because it is floating on the water.” Another student wrote, “Ball A has a greater buoyancy because it has a density that is less than water and is floating, (therefore) buoyant forces acting on it are greater.” It was very likely that this student had a concept of “relative buoyancy” in mind. This student might equate buoyancy to the relative magnitude of buoyancy and its weight, corresponding to the relative density of the object compared with the density of the water. Students often ignore associated changes when one change is introduced to a physical system (Shen et al. 2007). For sub-question #3, all students responded that both balls changed in the same manner: the two balls either had a greater buoyancy, smaller buoyancy, or the same buoyancy. Similarly, for sub-question #4, 12 out of 18 students responded that both balls floated “better” or “higher.” All of them recognized the change that when salt was added, the density of the fluid was increased. However, most of them didn’t distinguish the two balls as two different cases, as one student reasoned, “the two balls will float better in the salt water, since the difference between the densities of the balls and salt water is greater, both balls will float higher than they did in plain water.”

Analyses of these responses provide many insights on how to help students gain deep understanding of sinking and floating in future instruction. These items create the need and the instructional means for students to integrate different models they have learned, as they may realize through class discussion or instructors’ feedback that their explanatory models conflict with each other. Follow-up questions that target detailed changing processes of sinking and floating may help students to connect these models. Sample questions may include “how does ball A ‘know’ how much to rise up when salt is added? How does ball B ‘know’ when to go up? What happens to its buoyancy when ball B moves up? When ball B comes out of water, does it stop right away?” These questions also call for more careful observations that help the students link the states and processes of sinking and floating. Students’ alternative conceptions and prior experience can serve as knowledge resources for bridging different explanatory models. For instance, conceivably, students’ understanding of “relative buoyancy” as the ratio of buoyancy over its weight may lead to the scientific understanding: for an object less dense than water, it has a greater ratio of buoyancy over weight.

## Conclusion and Implication

In this study we present an assessment framework that focuses on three aspects of conceptual understanding: linking physical states and processes with underlying scientific mechanism, integrating multiple explanatory models, and connecting scientific models with everyday experience or natural observations. We illustrate with students’ responses to items on sinking and floating. Careful analyses show that these aspects are imperative for students to learn science. Specifically, the proposed framework has potential to help instructors identify the important links that students often miss among multiple explanatory models. With information provided by the framework instructors can effectively observe the detailed processes that students need to explain certain science phenomena, and help students integrate prior knowledge or experience to new science concepts.

## Endnotes

- (1) From a microscopic view, the net effect of buoyancy is due to the collisions of numerous fluid particles -- the particle model, which is not discussed in this paper.
- (2) Considering an object completely submerged under a fluid. If its buoyancy is greater than its weight, then the object starts to move up in acceleration until it floats above the fluid. When the object moves out of water, it displaces less water, hence experiences less buoyancy. When the object displaces the right amount of water so that its buoyancy equals its weight, the object does not stop immediately. It has acquired momentum, so it keeps moving out of water. Then the weight takes over and the object is pulled back towards the water. After some oscillations at the surface of the water, it stops eventually and its buoyancy and weight are balanced. This force model connects to Newtonian mechanics (force corresponding to acceleration) and links process (moving up and down) and with initial and final states (floating or sinking). The density model also connects to the mathematical construct of ratio, which has many implications.
- (3) Most of them are also not able to distinguish mass and weight, which is relevant, but probably not critical here.

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