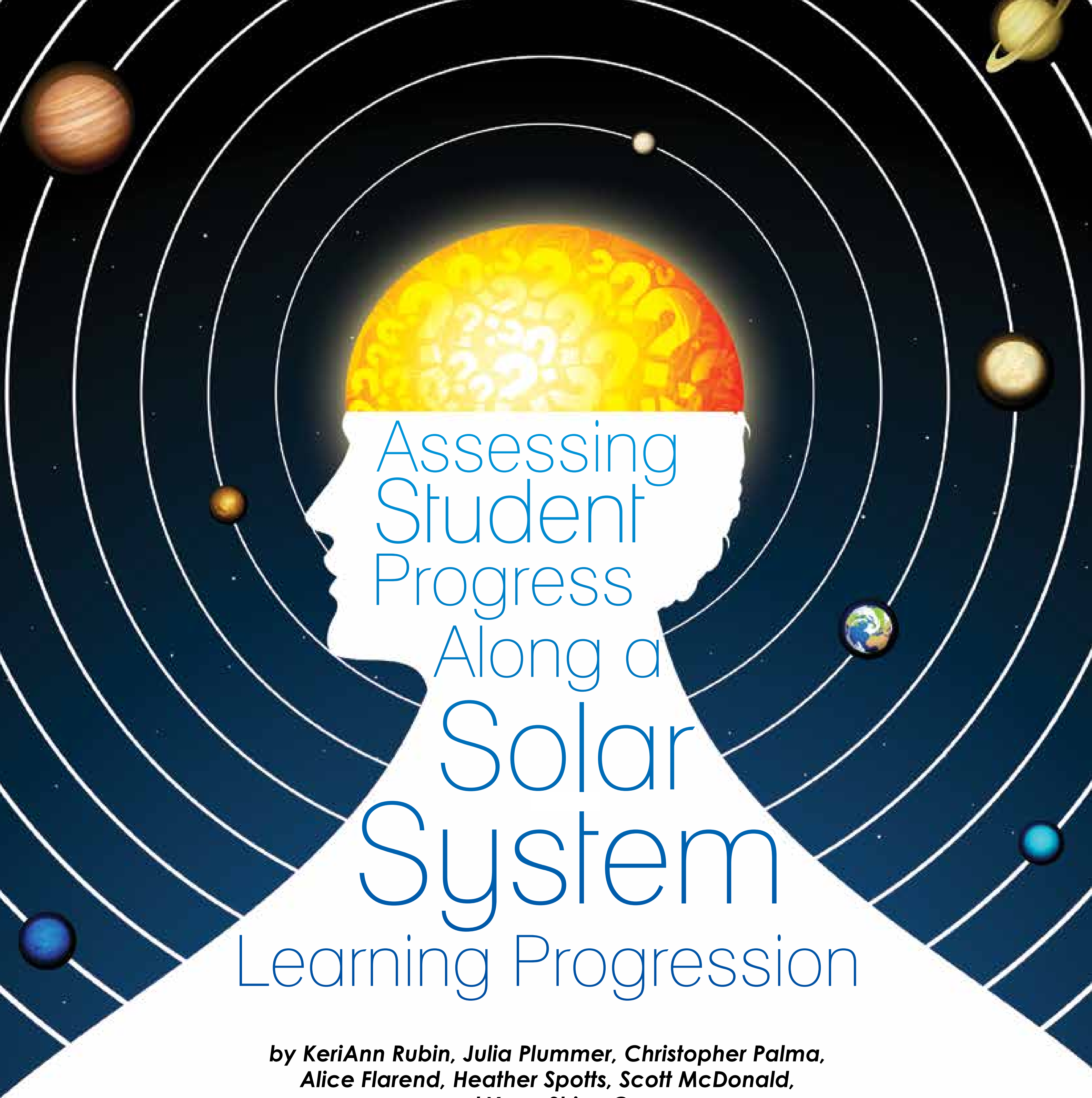

Assessing Student Progress Along a Solar System Learning Progression

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In our experience with middle school classrooms, astronomy is often taught as a set of shallow, disconnected facts. As a way of addressing this, the *Next Generation Science Standards* (NGSS Lead States 2013) place an emphasis on big ideas to unify and organize student learning. One of these big ideas is solar system formation and how it can be used to explain observable patterns within the current solar system. This big idea unifies the disparate astronomical concepts often taught at the middle school level by providing a theory that can be used to explain how these astronomical concepts are connected.

In order to help students achieve the performance expectations of the *Next Generation Science Standards* (NGSS Lead States 2013), teachers need tools to assess students as they progress toward the big idea during instruction. The goal of this article is to describe a framework for guiding the development of assessments teachers can use to identify student ideas that are in need of further development. While the *Next Generation Science Standards* (NGSS Lead States 2013) and *A Framework for K–12 Science Education* (NRC 2012) describe an astronomy learning progression in broad strokes, our work provides more detail to help teachers design assessments (and, by extension, instructional units) for their classroom to work productively with students' ideas.

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Learning progressions

Learning progressions are research-based descriptions of how students' understanding of big ideas is likely to become more sophisticated over time with appropriate instruction (NRC 2007). A learning progression is anchored at the top by a big idea, which helps to organize a scientific domain and has broad explanatory power. At the bottom of a learning progression is a description of the naive understanding(s) of science that students bring to the classroom. Finally, between these two points are levels of increasing sophistication of scientific understanding. To create a learning progression, all levels are developed empirically by determining students' understanding through a variety of assessment formats, such as conceptual interviews. Although learning progressions describe student movement toward more sophisticated levels of understanding, they are not dependent on age; they are dependent on the instruction students receive. Therefore, a sixth-grade student who experiences targeted instruction could achieve a higher level of understanding than an eighth-grade student who does not.

According to *A Framework for K–12 Science Education,* students need "sustained opportunities to work with and develop the underlying ideas and to appreciate those ideas' interconnections over a period of years rather than weeks or months" in order to develop a comprehensive understanding of science (NRC 2012, p. 26). Because learning progressions describe how ideas develop over time with appropriate instruction, they were used as the key organizing principles for the design of *A Framework for K–12 Science Education* (NRC 2012), which led to the *Next Generation Science Standards* (NGSS Lead States 2013). Despite the fact that the idea of learning progressions was used to organize the *Framework* (NRC 2012), few were fully developed at the time that the *Framework* was written. Therefore, our work is focused on developing an empirically based learning progression for solar system astronomy that can help teachers create supports for students, including designing and implementing formative assessments, during astronomy instruction.

Solar system learning progression

Over four years, we have developed and refined our learning progression using evidence drawn from increasingly more focused conceptual interviews, conducted by the authors, with a total of 80 middle and high school students. At the most sophisticated level of our learning progression, students can explain how the solar system formation process led to patterns in the locations, motions, and physical properties of the current solar system. In order to reach this level, students need to develop an understanding of the connections among four key components: (1) the physical properties of the objects in the solar system, (2) the dynamical properties of the objects in the solar system, (3) the role of gravity, (4) and the solar system formation model. For example, students

need to have an understanding of how the solar system formation model explains dynamical properties of the objects in the solar system, such as why all of the planets orbit the Sun in the same direction. As we developed our learning progression, we targeted student thinking about these four key components of the big idea, which led to the development of four individual construct maps.

Construct maps are components of learning progressions. Like learning progressions, construct maps include multiple levels that describe increasingly sophisticated ways students may understand a concept, building toward the scientific level of understanding (Wilson 2009). However, construct maps focus on the progress of student understanding of a particular conceptual piece of the learning progression's big idea. For example, our dynamical properties construct map (Figure 1) describes levels of student understanding in one component of the big idea: how and why objects move in the solar system. In addition, the highest level

FIGURE 1 Dynamical properties construct map

Level	Level description
5A	Orbits in the solar system are the result of a balance between the object's tangential velocity and the gravitational force between the object and body it is orbiting. Students understand that the solar system is relatively flat and that the planets orbit in the same direction.
5B	Orbits in the solar system are the result of a balance between the object's tangential velocity and the gravitational force between the object and body it is orbiting. Ideas about the shape of the solar system and/or the direction of planetary orbits are inaccurate.
4A	Orbits in the solar system are the result of a balance of the gravitational force between the object and the body it is orbiting and some inaccurate force. The role of velocity and/or gravity is not clarified. Students understand that the solar system is relatively flat and that the planets orbit in the same direction.
4B	Orbits in the solar system are the result of a balance of the gravitational force among the object, the body it is orbiting, and some inaccurate force. The role of velocity and/or gravity is not clarified. Ideas about the shape of the solar system and/or the direction of planetary orbits are inaccurate.
3A	Orbits in the solar system are the result of the gravitational force between objects, holding one in orbit about another. Students' reasoning for why objects do not crash into the object they are orbiting is unclear or inaccurate. Students understand that the solar system is relatively flat and that the planets orbit in the same direction.
3B	Orbits in the solar system are the result of the gravitational force between objects, holding one in orbit about another. Students' reasoning for why objects do not crash into the object they are orbiting is unclear or inaccurate. Students' ideas about the shape of the solar system and/or the direction of planetary orbits are inaccurate.
2A	The planets orbit the Sun and the Moon orbits the Earth, but students provide inaccurate reasoning for why objects maintain their orbits. Students understand that the solar system is relatively flat and that the planets orbit in the same direction.
2B	The planets orbit the Sun and the Moon orbits the Earth, but students provide inaccurate reasoning for why objects maintain their orbits. Ideas about the shape of the solar system and/or the direction of planetary orbits are inaccurate.
1	The Moon does not orbit the Earth and/or the planets do not move or do not move along distinct orbits about the Sun.

of the construct map describes an appropriate level of scientific understanding of the dynamical properties of the objects in the solar system for middle school learners, rather than the complete big idea. As students' understanding develops within each construct map, the teacher supports them in putting the pieces together as they move toward understanding the big idea of the solar system and its formation. Students are likely to progress up each of the construct maps at different rates; progress along the construct maps is not necessarily sequential. Instead, students' progress is determined by the instruction they experience. The goal is for all students to eventually reach the upper level of all four construct maps, which will lead them to an understanding of the learning progression's big idea.

The big idea that we developed is appropriate for middle school astronomy curricula. What students learn prior to middle school will determine where they start on the progression. Students do not need to be at a certain place when they enter middle school to start studying this topic. Instead, our goal is for teachers to use the levels of the construct maps to identify where

FIGURE 2 Formation construct map

Level descriptions			
6	The solar system formed from the accretion of microscopic materials such as gas, rock, and/or dust that built up until they were massive enough for gravity to continue at the macroscopic level. The Sun and the planets formed from the same initial cloud of dust and gas. Gravity caused the collapse of this material into the Sun and planets. Students' description of the force of gravity may include inaccurate aspects.		
5A	The solar system formed from microscopic materials such as gas, rock, and/or dust. Planets were formed by the accretion of this microscopic material. The formation may have occurred after an explosion. The Sun and the planets formed from the same initial cloud of dust and gas. Gravity caused the collapse of this material but not the formation of the planets. Students' description of the force of gravity may include inaccurate aspects.	**5B**	The solar system formed from macroscopic materials such as gas, dust, rocks, meteors, etc. Planets were formed by the accretion of this macroscopic material using gravity as part of this process. The formation may have occurred after an explosion. The Sun and the planets formed from the same initial cloud of dust and gas. Gravity caused the collapse of this material but not the formation of the planets. Students' description of the force of gravity may include inaccurate aspects.
4	The solar system formed from materials such as gas, rock, and/or dust (either microscopic and/or macroscopic, or unclear size). The formation includes accretion-like processes. The formation may have occurred after an explosion. Gravity played a role in the formation or maintenance of the whole system but not in forming the planets.		
3A	Students describe some type of accretion-like mechanism for how planets formed from preexisting material. The formation may have occurred after an explosion. Gravity played no role in this process.	**3B**	Students describe no mechanism for how the planets formed from preexisting materials. The formation may have occurred after an explosion. Gravity plays a role in the formation or maintenance of the whole system but not in forming the planets.
2	The solar system began as an explosion. Students describe no mechanism for how the planets formed from preexisting material. Gravity played no role in this process.		
1	The solar system has always existed, so no formation process occurred.		

to start with particular students. From there, teachers can continue to use the construct maps to assess students' progress and modify their instruction.

If students reach the upper levels of the construct maps in middle school, they will be ready to learn the more quantitative and predictive aspects of this model, both in explaining our current solar system and other systems beyond our own, at the high school level.

Use of construct maps in the classroom

In our work, we use construct maps to guide both instructional goals and assessment choices, as these are intertwined. Construct maps can be more helpful than big ideas or standards because they focus on specific pieces of the larger phenomena and uncover intermediate levels of understanding to help the teacher decide where to target instruction for particular students. This focus on student thinking can also be used to inform the creation, revision, and interpretation of formative and summative assessments. To illustrate our process of using construct maps to guide assessment, we chose two construct maps recently tested in a sixth-grade classroom: dynamical properties (Figure 1) and the formation process (Figure 2). These construct maps were selected because they engage students in explaining astronomical phenomena with important physics concepts. We used interviews, classroom talk, and student artifacts drawn from this sixth-grade astronomy unit, designed around the big idea of solar system formation, to assess where students were along the construct maps.

Dynamical properties construct map

At the most sophisticated level of the dynamical properties construct map (level 5A, at the top of the map; see Figure 1), students understand orbits in the solar system are the result of a balance between an object's tangential velocity and the gravitational force between the object and the body it is orbiting. Students at this level also understand the solar system is relatively flat and the planets orbit in the same direction. This level of the construct map addresses the Forces and Motion disciplinary core idea (MS-PS2.A) of standard MS-PS2 (Motion and Stabiltiy: Forces and Interactions) because it requires students to understand "the motion of an object is determined by the sum of the forces acting on it" (NGSS Lead States 2013); in this case, the only force influencing a planet's motion is gravity. Additionally, level 5A addresses one part of the Space Systems performance expectation (MS-ESS1-2) of MS-ESS1 (Earth's Place in the Universe) because it requires students to understand the "role of gravity in the motions within galaxies and the solar system" (NGSS Lead States 2013).

Prior to instruction, a teacher could use this construct map to identify the information that should be assessed to determine students' initial understanding of how and why objects move within the solar system. For example, if a teacher wanted to identify students' understanding of the cause of planetary orbits, the following two questions could be included on formative assessments:

(1) Why don't the planets just shoot off into space?

(2) Why don't the planets crash into the Sun?

The responses to these questions could then be used to determine students' level of understanding on the dynamical properties construct map (Figure 1).

Using these questions during our pre-instruction interviews, we found that several sixth-grade students stated the Sun's gravity is the right amount to keep the planets from shooting off into space or from crashing into the Sun. This response suggests these students were at a level 3A or 3B on the construct map, because they were able to explain orbits are the result of the gravitational force between objects but were not able to provide scientific reasoning for why a tangential velocity is necessary for preventing objects from crashing into the object they are orbiting.

To improve students' understanding of this topic, instruction would need to focus on the relationships among gravity, velocity, and inertia in orbital motion. Examples of instructional activities that can move students along the dynamical properties construct map (Figure 1) can be found for free on the Pennsylvania Earth Science Teachers Association website (see Resources). Throughout instruction, the construct map can be used to develop additional formative assessments to determine students' progress toward the most sophisticated level.

After instruction, we asked the same preinterview questions to our group of sixth-grade students. These students were able to recognize that something was needed in addition to gravity to maintain the planets' orbits but had difficulty explaining the role of tangential velocity, even after instruction. For example, many students stated that another force counteracted the pull of gravity, rather than the planets' tangential velocity. Therefore they progressed to levels 4A and 4B on the construct map (Figure 1) because they explained that orbits are the result of a balance between gravity and some inaccurate force. These students did not reach the upper level because they were not able to explain how the tangential velocity combined with the acceleration due to gravity results in stable orbits.

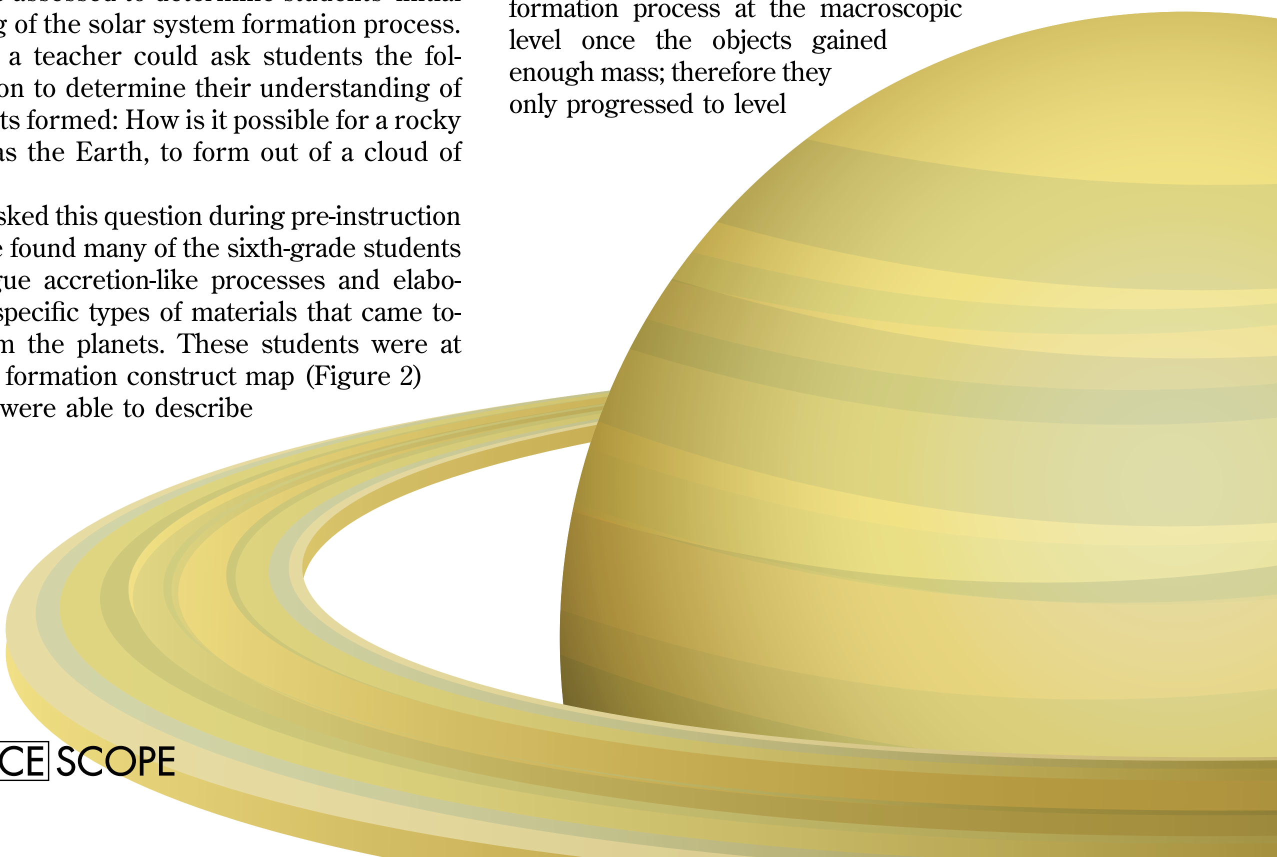
Formation construct map

Students at the most sophisticated level of the formation construct map (level 6, at the top of the map; see Figure 2) understand the solar system formed from the accretion of microscopic materials, such as gas, rock, and dust particles, that built up until they were massive enough for gravity to dominate the formation process at the macroscopic level. Students at this level also understand the Sun and the planets formed from the same initial cloud of dust and gas. Finally, these students understand that gravity caused the collapse of this material into the Sun and planets. This level of the construct map addresses one component of the disciplinary core idea (MS-ESS1.B) of MS-ESS1 (Earth's Place in the Universe) because it requires students to understand that the solar system "formed from a disk of dust and gas, drawn together by gravity" (NGSS Lead States 2013). This idea connects to the dynamical properties construct map (Figure 1) because of the focus on gravity and how the formation explains the relative flatness of the solar system. Although there are conceptual connections between the formation construct map (Figure 2) and the dynamical properties construct map (Figure 1), we would not expect middle school learners to be able to make these connections without significant instructional support.

The formation construct map (Figure 2) could be used before instruction to identify the information that should be assessed to determine students' initial understanding of the solar system formation process. For example, a teacher could ask students the following question to determine their understanding of how the planets formed: How is it possible for a rocky planet, such as the Earth, to form out of a cloud of dust and gas?

When we asked this question during pre-instruction interviews, we found many of the sixth-grade students described vague accretion-like processes and elaborated on the specific types of materials that came together to form the planets. These students were at level 4 on the formation construct map (Figure 2) because they were able to describe the specific materials that planets formed from along with a general accretion-like process. In order to help these students progress toward the most sophisticated level of understanding, instruction would need to focus on the specific mechanism that drove the formation of the planets in the solar system. However, many of the sixth-grade students were at level 1 because they believed that the solar system has always existed. Rather than having a broad spread of ideas, we found that these students were mainly in two groups in terms of their understanding. This demonstrates how a teacher could use the construct map to determine before instruction whether students are all at one level or on multiple levels. A teacher could then target instruction to work with just those levels of understanding. See Active Accretion in Resources for one example of an instructional activity that can move students along the formation construct map (Figure 2).

The teacher could continue to use the formation construct map (Figure 2) to develop assessments to measure students' progress toward the upper level throughout the instructional unit. The results of these assessments could then be used to guide instructional choices and to determine where remediation efforts may be needed for individual students. Post-instruction interviews using this question indicated many sixth-grade students were able to describe the accretion of microscopic materials, but not the accretion of macroscopic materials, during the solar system formation process. These students specifically mentioned gas, rock, or dust particles coming together to form the planets but did not indicate gravity would continue the formation process at the macroscopic level once the objects gained enough mass; therefore they only progressed to level

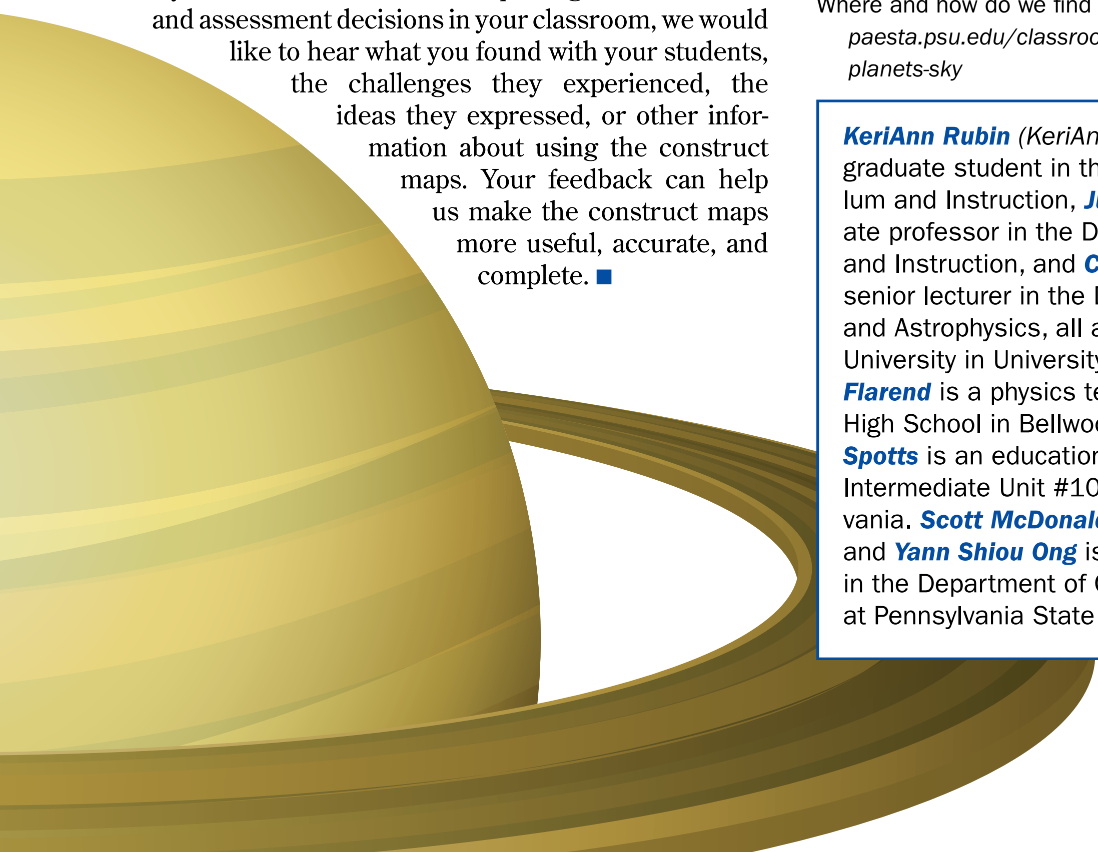


5A on the formation construct map (Figure 2). Further instruction would be needed to support students' understanding of how gravity continued the accretion process at a macroscopic level in order to move students to level 6. Reaching the upper level of this construct map would position students to learn the more quantitative understanding of the solar system's formation addressed in the high school *Next Generation Science Standards* (NGSS Lead States 2013) levels.

Conclusion

Construct maps are a promising tool to guide assessment around the *Next Generation Science Standards* (NGSS Lead States 2013) because they help teachers focus on intermediate levels of student understanding leading toward a big idea, rather than whether students' ideas are simply right or wrong. However, students' developing understanding is dependent on the instruction they receive. Where middle school students enter these construct maps may depend on their prior experiences in elementary school, such as learning about how the Moon orbits the Earth and the Earth orbits the Sun. However, much of this material will be new to middle school students. In addition, these construct maps may be helpful in determining whether students are ready for the more quantitative ways of understanding the solar system and its formation in high school.

We found these construct maps worked in the particular sixth-grade classroom in which we used them, but we recognize the instruction was designed to support student progress along our learning progression. If you use these construct maps to guide instruction and assessment decisions in your classroom, we would like to hear what you found with your students, the challenges they experienced, the ideas they expressed, or other information about using the construct maps. Your feedback can help us make the construct maps more useful, accurate, and complete. ■



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Resources

Active accretion: An active learning game on solar system origins—*https://solarsystem.nasa.gov/docs/ActiveAccretion.pdf*

Pennsylvania Earth Science Teachers Association activities

The role of gravity in planetary orbits—*www.paesta.psu.edu/citation/role-gravity-planetary-orbits*

What do craters on solid planets tell us about the history of the solar system?—*www.paesta.psu.edu/classroom/what-do-craters-solid-planets-tell-us-about-history-solar-system*

Where and how do we find planets on the sky?—*www.paesta.psu.edu/classroom/where-and-how-do-we-find-planets-sky*

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