Visualizing Photosynthesis:

Lessons learned from a field trial of a digital game to support science learning

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Abstract

Digital games have the potential to help students engage with challenging concepts, but for this potential to be realized at scale, designers must create game experiences that classroom teachers can implement on their own and that address conceptual content aligned with what teachers are already covering. The authors are involved in a five-year program of research and development known as *Possible Worlds*, for which we created four instructional modules consisting of a game on a handheld device and classroom activities that connect the digital game to typical concepts covered in middle-grade science curricula. This article presents findings from a field test of the module about photosynthesis. The field test was designed to determine whether module implementation was feasible across different classroom contexts, and to explore the contextual factors that influenced how teachers integrated the modules. Findings from the field test demonstrated that teachers in different contexts were able to integrate the game modules with no assistance from the research team, but also that teachers' instructional goals and assessment requirements had a strong mediating influence on how they implemented the modules and what concepts they addressed. These findings have implications for scaling digital game experiences designed to support conceptual learning.

Rationale

Educators, researchers, and policy-makers have stressed the need to find new and more effective ways to support students in learning science (National Research Council, 2005, 2007; National Science Board, 2010). Over the past decade, education researchers have been investigating the potential for digital games to engage students in science, and have offered a range of theoretical models and explanations for how and why games might support learning (Alexander, Eaton, & Egan, 2010; Amory, 2007; Habgood & Ainsworth, 2011; Jin & Low, 2011; Tobias, Fletcher, Dai, & Wind, 2011). There is both anecdotal and empirical evidence of the potential value of game-based learning (Barab, Sadler, Heiselt, Hickey, & Zuiker, 2007; Barab & Squire, 2004; Steinkuehler & Chmiel, 2006). Digital games can motivate students to pursue an activity repeatedly and build mastery through their interactions with complex environments bound by detailed constraints and rules (Squire, 2006). They can enable students to enter imaginary worlds where they can experience conditions and relationships that they otherwise could not in real life, letting them experiment with variables and concepts in an engaging space (Alexander et al., 2010; Habgood & Ainsworth, 2011). Most importantly, digital games invite students to play—to become an active part of a dynamic system that encourages exploration and progress toward greater knowledge within the game world (Gee, 2007a, 2007b).

However, the instructional models and learning goals associated with many high-profile game-based learning initiatives are often positioned as alternatives to the kind of instruction found in most K–12 classrooms in the U.S., and are often implemented with intensive support from research teams, making them difficult to sustain beyond the life of the research project (Fishman, Marx, Blumenfeld, Krajcik, & Soloway, 2004). This also makes it impossible for the research to explore how teacher and contextual factors can mediate the game experience in authentic settings (Alexander et al., 2010; Amory, 2007). Digital game experiences also can serve a more modest function, such as helping teachers tackle specific, challenging concepts that students struggle to understand. Research on these kinds of interventions can explore the ways in which games designed for K–12 settings are used by teachers without the intervention of researchers and designers, and how teachers adapt the materials to their particular instructional contexts.

Our organization received a five-year grant from the U.S. Department of Education's Institute of Education Sciences to explore how digital games might be used to support and enhance key aspects of middle-grades science instruction, and consequently deepen student learning, in classrooms that are not specially structured to focus on game-based learning. One way to describe our project is as an effort to consider carefully how digital games can be understood as opportunities for teachers and students to engage with a "possible world" that then becomes a common point of reference during traditional instruction. This project as a whole is called *Possible Worlds,* a reference to Jerome Bruner's book, *Actual Minds, Possible Worlds* (1986), which presents an approach to negotiating the interpretive relationship among the individual, the material world, and the symbolic or imaginary meanings the individual projects onto that world. Bruner's use of this philosophical construct speaks directly to our concern with science learning, because it has implications for how we think about the role of the not-real, the alternative, and the imaginary in creating opportunities for considering what is and is not possible in the natural world, and what might count as evidence to support or reject propositions about what is possible.

The goal of *Possible Worlds* was to address a broadly recognized, chronic challenge for middle-school science teaching: helping students build scientifically accurate conceptual models of phenomena that are often the subject of scientific misconceptions (Driver, Squires, Rushworth, & Wood-Robinson, 1994; Nussbaum, 1985) or naïve theories (Chi, Roscoe, Slotta, Roy, & Chase, 2011). Each *Possible Worlds* module includes a digital game[1]. The games do not teach the content directly; they are designed to engage players repeatedly with core game mechanics that are analogs to abstract, scientific concepts, furnishing learners with experiences they and their teachers can draw upon to frame and make sense of challenging concepts. Students play each game as homework prior to instruction, and become familiar with a visual analogy of the target science concept teachers want them to learn. Unlike a simulation, the visualizations are not explicit illustrations of the concepts (such as watering a plant to make it grow). Rather, the game uses familiar game mechanics designed to give the player a visceral experience (e.g., "shooting" molecules apart with sunlight and putting the atom "puzzle pieces" together to

[1] The digital game for the photosynthesis module was on the Nintendo DSi. We have since created a Flash version of the game for the Web and a tablet version.

form glucose) that is analogous to the interactions associated with the particular scientific phenomenon (Habgood & Ainsworth, 2011).

The games are explicitly positioned to contribute to a learning process that can achieve its goals only when gameplay becomes part of a broader learning sequence, and when students work with one another and with their teachers to make sense of their gameplay experiences. Each module also includes activities designed to help teachers make connections between key experiences in the game and target concepts, and a consolidation activity that requires students to draw on their new conceptual model to evaluate other, related scientific claims. We designed the game modules with 7th-graders in mind, although the specific content covered in each module is sometimes taught in 6th or 8th grade.

The field test described in this article was designed to test and refine this specific approach to integrating a digital game module into an instructional sequence about photosynthesis in preparation for a randomized controlled trial that we conducted in the following year (Authors, under review). Two of the central questions we posed, however, should be of much broader interest, as they focus on issues that will be confronted by any effort to make digital games a part of ambitious learning and teaching at scale. Given our theoretical framework, these were also questions we need to address before we could begin to look rigorously at the impact of digital games on learning outcomes. The questions were:

1. Is the *Possible Worlds* instructional model feasible across different classroom contexts without the intervention of the research and development team during instruction?
2. What are the key mediating contextual factors that influence how teachers integrate and make sense of the module components with their students?

Keeping these research questions in mind, we designed our field test to collect evidence of whether and how teachers used the game and other instructional materials to make connections between the game analogies and instructional content. We provided teachers with the game, handheld devices, materials, activities, instructional sequence, and professional development. We particularly wanted to see how teachers would adapt the materials and the instructional sequence we had shared with them. We wanted to observe the connections and analogies they would draw out that we could not anticipate. Therefore, we encouraged the field-test teachers to make their own decisions about how, when, and if to use the various materials (with a few key exceptions, described below). This information not only would help our team understand how to make our materials and professional development useful to teachers beyond this study, but also would help us build knowledge about how teachers' own goals and practices mediate the way digital science games, designed to achieve a very particular instructional goal, are used and adapted in authentic classroom settings.

Theoretical Framework

The core mission of the *Possible Worlds* project is to develop supplementary curricular materials, which can be integrated by teachers into standard science curricula to help dislodge misconceptions and support students in developing a conceptually sound understanding of science. Scientific misconceptions have been the subject of a wide-ranging literature. For a succinct and coherent review of that literature, and some of the efforts within the learning sciences to build instructional supports to displace misconceptions, see Reiner, Slotta, Chi, and Resnick (2000). In brief, this project follows Driver et al. (1994) and others in stressing the developmental roots and permeable boundaries of the scientifically inaccurate conceptual models that often are held by people of all ages.

Game-supported conceptual change

Underlying our theory of change is the idea that well-designed digital games can be effective tools for helping learners develop preconceptual mental models in targeted learning domains (Reese, 2007, 2009). Reese argues that game-based instructional design informed by structure mapping theory (Gentner, 1983) can promote the development and practice of analogical reasoning by providing learners with opportunities to have game-based experiences analogous to those in the targeted learning domain. According to Reese (2007), educational games whose features are designed to map to conceptual features in a target domain can become metaphors for abstract concepts learners will encounter in school. This is important because complex, abstract concepts are particularly challenging for novice learners to understand (Reese, 2007). Novices often fail to develop deeper domain understanding when they cannot understand complex introductory concepts, an impediment to integrating future knowledge. As closed systems of interrelated parts, games can afford novices opportunities to develop an initial understanding of the relationships among these parts by operationalizing them: That is, gameplay allows players to visualize and experience conceptual objects and their relations in ways they ordinarily cannot do in real life (Fullerton, Swain, & Hoffman, 2004; Gee, 2007a, 2007b; Reese, 2009). Coupled with the artifacts players can manipulate in the environment, game mechanics can approximate the invisible processes that occur in the targeted learning domain, while feedback and metrics can provide players with indicators of how successful they are in their understanding of the game's objectives (Habgood & Ainsworth, 2011). Further, game rules constrain the set of possible behaviors, limiting the conclusions players might draw from the relationship between play and feedback.

Providing a shared visualization to prepare students for learning

Though games can provide students with compelling experiences and opportunities to gain mastery of skills and concepts within a game world, it does not necessarily follow that students can then transfer what they have learned to more formalized educational contexts (Alexander et al., 2010). If students are to capitalize on games as "metaphor primers," teachers must provide them with the scaffolding and guidance necessary to make connections between gameplay and targeted learning concepts. We turned to Bransford and Schwartz's (1999) "preparation for future learning" model to inform our approach to sequencing and relating gameplay and instruction. In this framework, shared activities "set the stage" for learning through direct instruction by the teacher by providing students with experiences from which they can draw to make sense of subsequent material.

To increase the likelihood that learners will make conceptually productive connections between the game analogies and the targeted concepts, teachers have to be prepared to help their students by clarifying features the two share and by discussing how the processes in both are alike (Cameron, 2002; Gentner & Smith, 2012; Venville, 2008). Beyond the game, the additional materials we have developed—including PowerPoint presentations and Flash animations that feature images from the game—are designed to provide teachers with visual cognitive supports to help students make those connections during regular classroom instruction (Richland, Zur, & Holyoak, 2007). We also have included a traditional classroom activity that addresses the same target science concept as the game, to help teachers bridge their standard instruction and game concepts. At the end of the sequence, students participate in a consolidation activity in which they have to apply their knowledge of the targeted concepts in a novel context (Schwartz & Martin, 2004). This is an in-class activity that invites students to examine three unlikely stories and determine which one could possibly be true. The exercise meets Bransford and Schwartz's definition of a "future learning" assessment, because to move through the activity successfully, students must be able to activate a scientifically accurate model of the target concept—in this case, the process of photosynthesis—to help them tease out the relevant evidence in the articles.

The rationale for our instructional approach can be summarized as follows: Games can provide students with concrete experiences, in a playful, motivating environment via interaction with core game mechanics, that are structurally analogous to abstract concepts and phenomena. For those experiences to coalesce into functional mental models that can help learners to counter the intuitive pull of scientific misconceptions, teachers must make explicit, varied connections between specific features of gameplay and the target concepts during classroom instruction to help students visualize and develop meaningful analogies between the game's structural features and those of the target concepts. For teachers to be able to do this, they must be provided with instructional supports that connect the game to standard curricula and teaching practices.

Approaches to the research and development cycle

There are multiple theoretical frameworks available to guide the structuring of the research and development cycle for educational interventions. The field test reported on here was grounded in a design-based research approach (Barab, & Squire, 2004; Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003). After initial cycles of formative testing had driven the development of early versions of the digital game and accompanying materials, our goal was to introduce the module to authentic classroom environments and to collect a range of qualitative evidence about how the module was implemented, interpreted, and acted upon by both teachers and students. This approach is consistent with a broad range of design-based research conducted over the past twenty years (see, for example, Barab, 2006; Dede, 2005; McKenney & Reeves, 2013).

At the same time, it may be helpful for the reader to note that this field test was conducted by researchers who also were planning to conduct a fully-powered experimental trial of the impact of the module on student learning in the following year. This randomized controlled trial was included in the overall design of the project to ensure that the sometimes drawn-out, highly iterative design-based research process would lead to the timely development of at least one module that would be ready for a rigorous test of impact within the available project period.

Exploring the complexities of balancing the exploratory and iterative nature of design-based research with the rigors of preparing for a randomized control trial, which requires a highly specified intervention that can be implemented with minimal support or guidance from the research team within a relatively short period of time (in this case, an 18-month period of development informed by design-based research including this field test), is beyond the scope of this article. However, acknowledging these sometimes competing priorities may help to explain why this field test did involve a significant level of discretion and authority on the part of the teachers during implementation, but a limited amount of the kind of truly collaborative exploration that might be found in other design-based research studies. For the purposes of this field test we did encourage teachers to implement the module according to their own priorities, and sought their feedback and reflections on the module's feasibility and utility. On the other hand, we also limited researcher involvement during instruction, as we needed to discover in the course of the field test whether the overall instructional sequence was feasible in terms of technical and logistical hurdles and from a classroom management perspective.

We believe that a more collaborative and exploratory approach to the field test would have been informative and led to further revisions of the module that would have been valuable and ecologically valid for the classrooms in which we were working. However, we also believe that the push to move toward the timely production and testing of a useable, functional intervention was ultimately productive, and reflected our own commitment to creating a game-based intervention that would place minimal burdens on instructional time and on schools' technological infrastructures.

Description of the *Possible* Worlds Photosynthesis Module

Possible Worlds Photosynthesis Module focuses on a core misconception about photosynthesis and plant growth, namely, that plants get their mass from "eating" soil (Anderson, Sheldon, & Dubay, 1990; Driver et al., 1994) rather than by transforming a gas and liquid (carbon dioxide and water), with the help of sunlight, into a solid (glucose). Research has shown that even students who can recite the photosynthesis equation continue to hold onto the belief that plants "take in" (eat) food from the environment (Ozay & Oztas, 2003) and that soil provides this food (Driver et al., 1994), because it is difficult to conceptualize how chemical reactions at the molecular level cause change in states of matter. Photosynthesis involves abstract concepts that are difficult to visualize. Students often are unable to picture the underlying scientific processes, and their preexisting notions seem more consistent with their observations of the world than do explanations presented by teachers or in textbooks or other instructional resources.

The instructional model for *Possible Worlds* Photosynthesis Module includes a digital game to be played as homework before formal photosynthesis instruction, as well as activities and materials designed to help teachers connect the game analogies with the concepts introduced during photosynthesis instruction. The components of the module are as follows.

1. *Ruby Realm, a maze adventure game for the Nintendo DSi.* Set in a cave, the player's objective is to guide "Biobot Bob," an exploration robot, through the cave's maze-like passages in search of friends who are lost, while fending off vampires and bats. Bob runs on a technology modeled on photosynthesis. To keep him moving and to defend against enemies, players periodically produce three resources—food (glucose), fuel (liquid methanol), and the Biobot's weapon against the vampires (tear gas)—all of which are different states of matter, but are composed of the same three elements (carbon, oxygen, and hydrogen). Players create these resources by breaking apart water and carbon dioxide molecules with sunlight (available only in light shafts found intermittently throughout the cave) to release carbon, hydrogen, and oxygen atoms, and then reconfiguring them in different patterns depending on the substance they are building at the time. Figure 1 presents an image of Biobot Bob and the glucose production puzzle; Figure 2 shows the liquid methanol production puzzle; and Figure 3 shows the tear gas production puzzle. These repetitive molecule-building activities provide students with visual analogies that they manipulate themselves of how photosynthesis and changes in states of matter occur in the real world. The games provide concrete images (such as the glucose molecule) and actions (such as breaking apart molecules with the sun, and putting atoms together to form a different molecule) that teachers can draw upon to help students make sense of abstract concepts that are presented in normal instruction about photosynthesis. However, there is nothing in the game that explains the process to students in terms of the photosynthetic process, and students are not expected to understand photosynthesis as a result of playing the game. Though the game includes some photosynthesis terminology, such as glucose, it does not label the water, carbon dioxide, or sunlight, and uses letters to label the hydrogen, oxygen, and carbon atoms.

[INSERT FIGURES 1-3 HERE]

2. *An instructional PowerPoint presentation about photosynthesis.* This PowerPoint (see Figure 4) uses images from the game as it gives an overview of photosynthesis, what materials are required, and how they get into a plant. Teachers can use this to teach the traditional photosynthesis concepts while drawing connections to the images from the digital game (Richland et al. 2007).

[INSERT FIGURE 4 HERE]

3. *A kinesthetic classroom activity, called "Molecules in Motion."* Students hold cards identifying them as carbon, oxygen, or hydrogen. They first form the reactants of photosynthesis by joining together as water (H_2O) and carbon dioxide (CO_2). Sunlight (the teacher shining a flashlight on them, for example) splits them apart, and they then form the products of photosynthesis—glucose ($C_6H_{12}O_6$), and oxygen (O_2). In another session, students first form the reactants (glucose and oxygen) and then the products (water, carbon dioxide) of respiration.

4. *Sense-making activity with Web-based Flash animations.* Teachers are encouraged to hold a sense-making discussion about the relationship between what students do in the "Molecules in Motion" activity and the molecule-building part of the digital game, using Flash animations that show the key visualizations (the molecule-making puzzles) from the digital game to ground the conversation. Teachers with an

Internet connection can access the Flash animations on the *Possible Worlds* website and project them for use during classroom instruction.

5. *A paper and PowerPoint-based consolidation activity, called* No Way![2] This collaborative classroom game prompts students to evaluate claims and evidence in stories about photosynthesis. Students play the role of science fact-checkers working for a fictional website, *NoWay!com*. They must figure out whether three incredible-sounding stories that report on natural phenomena could be true. Each story involves photosynthesis, but the claims made in two of them are based on common misconceptions about the process, specifically having to do with the role of soil in plant growth. One of the stories cannot be refuted if students understand the basic concepts underlying photosynthesis. Students are asked to review a range of available evidence, evaluate how evidence serves to support or refute story claims, and construct an argument for or against the story's validity based on that evaluation.

Method

We conducted a field test to determine whether teachers could implement the module without help from the research team, and to see how teachers adapted the instructional model and materials to their specific contexts. In this field trial we sought to strike a balance between pushing the innovation of using digital games as a common base for sense-making around challenging science concepts, and stepping back to examine how this innovation is leveraged by teachers as they teach their standard curriculum. There were a few non-negotiable components of the intervention derived from the preparation for future learning theory (Bransford & Schwartz, 1999) that shaped our instructional model. First, the digital game had to be played before the teacher covered the relevant topics in class, preferably as homework so no class time would be taken up with gameplay; and second, the intervention had to conclude with the *NoWay!* consolidation activity. However, in accordance with a design-based research approach (Cobb et al. 2003), we also encouraged the field-test teachers to integrate the rest of the materials as they saw fit so that they could provide iterative feedback on how they might be adapted or revised to support instructional goals. This created more opportunities to see both new possibilities and unintended challenges that can arise in the course of a variety of instructional choices.

Sites and participants

The field test took place in four public middle schools in urban and suburban areas of the Northeast. Because we wanted to observe implementations with a range of student ages and ability levels, we included all middle-school grade levels, and both special and general education students. One 6th-, five 7th-, and five 8th-grade science teachers and 496 students participated in the field trial. Four of the 17 classes we observed were inclusion classrooms, in which approximately half (10–15) of the students had Individualized Education Programs (IEPs). We also wanted to observe a variety of classroom contexts, so we worked in schools with small (17 students) and large (35 students) classes, classes in which the materials were integrated into standard plant function units as well as classes where photosynthesis was covered as part of units on

[2] This activity is now available for tablet devices.

energy transfer and climate, and schools where teachers had a great deal of flexibility in what they taught and others in which teachers had to follow a very specific curriculum.

[INSERT TABLE 1 HERE]

Intervention

The instructional sequence involved (1) play of the digital game as homework for at least 30 minutes; (2) regular instruction in photosynthesis, including some or all or the photosynthesis instruction PowerPoint presentation we provided; (3) use of the "Molecules in Motion" linking activity; (4) a sense-making discussion using the Flash animation; and (5) use of the *NoWay!* consolidation activity. We provided all of the handheld devices as well as all of the paper and PowerPoint materials for the study. Teachers asked the students to play the digital game for homework before photosynthesis instruction began. Teachers used class time for their regular instruction and module activities described above. All teachers received six hours of professional development over two days, from one to two months prior to the intervention. The intervention lasted between 6 and 10 instructional days at each site. Because the materials were designed to be used in conjunction with existing curricula, the intervention added from two to four days to teachers' normal units covering photosynthesis. Most of the additional time was for the *NoWay!* activity.

[INSERT TABLE 2 HERE]

Data collection and analysis

Two researchers observed classes during every day of the intervention, including regular instruction and the module activities, and took detailed field notes. Researchers conducted interviews with students after they played the digital game and at the end of the intervention, and interviewed teachers at the end of the intervention. We designed the instruments to capture evidence of what materials teachers used, how they used them, how teachers and students referred to the game visualizations and other instructional materials during class time, and what connections teachers drew between their normal instruction and the module materials.

When a field test ended at a site, researchers synthesized all of the observational and interview data collected over the two-week period, along with publicly available demographic data about the school, using a standardized form that asked for the following information:

- details about the class (grade, number of students, curriculum used, inclusion or not);
- a description of the school demographics;
- a description of what took place in the class each day of the intervention (materials used, topics covered, activities engaged in by students);
- all instances of the teacher and students making reference to the digital game during photosynthesis instruction;

- a description of how the teachers conducted the “Molecules in Motion” activity, and the connections made to the digital game; and
- a description of how the teacher conducted the *No Way!* activity, and the connections made to the digital game.

Because of the standardized format for these syntheses, researchers could identify evidence across all interventions about which materials the teachers used, for how long, and in which order, and how they were used in relation to their other curricular materials. Using the research questions as a guide, researchers first focused on coding for fidelity to the instructional model and materials (what components teachers used and did not use, the order in which they used them, how long they used them), then coded for how teachers integrated and adapted the materials, whether they drew connections between the visualizations and abstract concepts related to photosynthesis (structure of glucose, role of glucose, transformation of matter, role of sunlight, difference between photosynthesis and respiration), and the similarities and differences in classroom context that might influence how the materials were used. We looked across cases to understand whether the game module was feasible to implement in different contexts, and to determine which factors were related to difference in implementation. We then selected two contrasting cases to illustrate these differences.

Findings

We conducted the field test in diverse middle-school classrooms (a) to see if the instructional model could be implemented with fidelity, without intervention from researchers, by teachers working in authentic classroom settings, and (b) to understand what key factors influence how teachers in different contexts mediate the module experience. Below we give an overview of what we found across the sites about feasibility and factors influencing implementation, and then focus on two cases that highlight how those contextual factors impact module integration.

Implementation fidelity across sites

Our analysis of implementation fidelity demonstrated that, on a procedural level, teachers across the different sites were able to integrate most of the module materials into their photosynthesis instruction on their own (see Table 3 below). All 11 teachers had the students play the game before they covered photosynthesis in their classes. Ten out of 11 teachers had students take the handheld devices home with them, and one had students play the game in class. Ten of the teachers used at least some parts of the photosynthesis instruction PowerPoint we provided, with seven teachers showing the entire slideshow. Nine teachers had students do the Molecules in Motion activity. All teachers incorporated our sense-making questions in some way into their instruction, and all teachers implemented the complete *No Way!* activity at the end of photosynthesis instruction, as we recommended. The only module component that fewer than half of the teachers implemented was the Flash animation. One teacher had no Internet access in his classroom and therefore could not use the animation. The other five teachers chose not to use that resource.

[INSERT TABLE 3 HERE]

Although most teachers used the majority of the resources we provided in the order we recommended, teachers also made adaptations to the instructional model and module materials. As we detail below, teachers' adaptations of the materials and the instructional sequence exposed a series of divergences between the conceptual targets the intervention had been designed to address and the local curricular goals, classroom management concerns, and school and district policies driving teachers' day-to-day instructional decisions.

Digital gameplay prior to instruction

In accordance with the preparation for future learning model, we designed the game to be played as homework or in some out-of-class setting before a teacher covers the target concept, so students would have a shared experience of interacting with relevant analogies prior to instruction. As noted above, all teachers provided students with the opportunity to play the game prior to photosynthesis instruction. (One had students play in class rather than sending the devices home with students.) The special education teacher had students take the game home, but also allowed them to play during their pull-out periods. Teachers who did send the devices home varied in the length of time they allowed students to keep them. Four teachers allowed students to have the devices for the whole length of the intervention (about two weeks); seven allowed students to have the devices for only two or three days before they began photosynthesis instruction. These decisions were based both on school policies and on teachers' levels of comfort with having students responsible for the devices.

Though some of the teachers worried that the devices would be lost or stolen, or that students would not play the game at home, these concerns proved to be largely unfounded. Students returned the devices in a timely matter. We collected gameplay data, saved onto the game cartridges, from a sample of 322 students[3]. Our analysis of gameplay data showed that students who had the game for more than a week (a total of 249) played for an average of 80 minutes, with a range from one student who did not play at all to a student who played for over three hours. Among students who had the game for only two days (a total of 73), average playing time was 42 minutes, which still exceeded the 30 minutes we recommended. There were eight students in this group who did not play at all, but 22 students who played for over an hour. These findings indicate that, on the whole, students played through enough levels to be exposed to the molecule-making puzzles dozens of times, giving them exposure to the visualizations that teachers could reference in their instruction.

Photosynthesis instruction PowerPoint presentation

The photosynthesis instruction PowerPoint presentation was developed as a resource for teachers to provide them images that could serve as cognitive supports (Richland et al., 2007) for drawing explicit analogies between game visualizations and standard photosynthesis instructional content. We found that teachers drew upon this resource based on what they needed to cover and the materials they already had. Four teachers who used a very structured living environments curriculum already had PowerPoint

[3] We did not collect the data from all students because some devices had to be turned around quickly and sent home with another class before the data could be downloaded from the cartridges.

presentations that addressed the specific photosynthesis content they needed to cover, so they chose not to use much of our presentation. However, these teachers did insert into their own presentations a slide that used images of atoms and molecules from the game in an animation of the glucose production process (water and carbon dioxide splitting up into carbon, hydrogen, and oxygen and reforming into glucose and oxygen). Because their living environments curriculum did not cover chemistry, they did not have their own visual representations that clearly showed the interactions between the three atoms as they form different molecules. These teachers observed that this representation was an effective way of illustrating what the photosynthesis equation signifies. They also liked that the images provided a visual cue that helped them connect back to the game. The teachers who did not already have a PowerPoint on photosynthesis, who had flexibility in the way they could teach their curricula, or who integrated the materials into a unit that was not specifically about photosynthesis, used the PowerPoint presentation in its entirety, either because they did not have any other presentation on this topic, or because they thought it provided a coherent introduction to the subject and the materials that they would be using with students.

"Molecules in Motion" activity

Teachers made adaptations to this activity based on the number of days available to cover the topic, the length of their class period, the number of students in the class, and the size of their classrooms. Faced with the challenge of shepherding students from one state (playing the role of water and carbon dioxide) to another (glucose and oxygen), four teachers projected the image of the atoms and molecules from the photosynthesis instruction PowerPoint presentation to serve as a cognitive support for the activity. The teachers pointed to the different atoms and asked students to raise their hands if they were supposed to represent those atoms. Then they ran the animation to show the students what they would have to do with their bodies. This strategy was used both by teachers who had little time and wanted to do the activity efficiently, and teachers who had enough time to conduct the activity over two days, but who wanted to reinforce what students were enacting. One teacher who had a flexible curriculum but a crowded classroom decided to have students make the molecules with their cards on tables because there was not enough room for students to move around easily. One of the teachers who taught the highly structured curriculum chose not to do the "Molecules in Motion" activity at all, stating that she had a different activity that she preferred to do with her students and did not have time for an additional one.

Sense-making activity using Flash animation

Teachers integrated the sense-making questions and Flash animations in ways that reflected their access to classroom technologies and the normal classroom practices they used for checking on what students know. We provided six questions for teachers to ask to draw explicit links between the digital game and the "Molecules in Motion" activity. Four teachers who regularly used "Do Now" questions to start classes used these for that purpose. Six teachers created quizzes with these questions. They did not grade the quizzes, but used them to see what students did and did not understand, and then went over questions that students had not answered correctly, such as the difference between atoms and molecules. Half of the teachers used the Flash animation to illustrate their discussion of the questions, while the other half (including one teacher with no Internet access) did not show the Flash animation.

No Way! ***consolidation activity***

Teachers spent from two to three class periods on this activity. Teachers with double periods used the entire double period for the activity. All of the teachers in the trial followed the recommended sequence and used the paper resources involved in this activity. The main differences across teachers lay in how the students were grouped to discuss the resources—in most classes students worked in groups of four, in two classes students worked in pairs, and in one case the whole class was split into three groups and each discussed a story— and in how students presented findings—by voting on what to publish (or not), creating and presenting posters on conclusions, and reporting out by group.

Case studies of two sites

Site 1:Highly structured living environments class

One set of field tests took place at a large suburban public school, serving 1200 6th–8th graders. The school's student population was 65% white, 19% Hispanic, 13% African-American, and 2% Asian. Thirty percent of the students in the school were eligible for free or reduced-price lunch. We selected one focal class to follow for each of the three 8th-grade science teachers. All of these teachers followed a highly structured living environments curriculum designed to prepare their students to take the New York State Living Environments Regents Exam, which is normally given to 9th graders. Ms. M had taught this curriculum for three years, so she had clear goals for the unit, reflecting the content the students were required to know about photosynthesis for the exam. She had a laptop connected to a Smart board and access to a database of digital resources related to photosynthesis, compiled by her district, that she drew upon regularly in her already fully developed unit.

The intervention began in early December, just after Ms. M covered plant cell structures and organelles. The students took the handheld devices home over a weekend and returned them on the following Monday, though the devices remained available in the classroom throughout the two-week intervention. On that Monday, the students came in talking about the game with each other and the teacher. Although she had other plans for the day, the teacher took time out at the beginning of class to debrief with the students about the game.

> *Ms. M:* What did you find out in the game?
>
> *Student:* You had to make those cell things.
>
> *Ms. M:* Did you have to make cells?
>
> *Student:* Molecules.
>
> *Student:* Glucose.

Ms. M: Daniel is bursting at the seams because he memorized all the molecules. How many different molecules did you make in the game?

Student: Three—tear gas, methanol, and glucose.

Ms. M: Why were you able to make three?

Student: Glucose fed Bob and tear gas fought the vampires.

Ms. M: Did you have to add things to those molecules?

Student: No.

[*Ms. M* asks a boy to come up to the white board to draw methanol from memory. He makes the molecule using the shapes used in the game.]

Ms. M: What are those letters?

Student: Elements.

Ms. M: What is C?

Student: I don't know.

Student: Chloroplasts?

Student: Carbon dioxide?

Student: Carbon?

Ms. M: Each element has a symbol. Carbon is C. What is H?

Student: Hydrogen.

Ms. M: What is O?

Student: Oxygen.

Ms. M: How many carbons in methanol?

Student: One.

Ms. M: How many hydrogens?

Student: Four.

Ms. M: How many oxygens?

Student: One.

[Another boy goes up to the white board and draws glucose from memory.]

Ms. M: What were the elements in glucose?

Student: Same thing.

Ms. M: Same thing! Were they the same amount?

Student: No.

Ms. M: How many carbons?

Student: Six.

Ms. M: How many hydrogens?

Student: Twelve.

Ms. M: How many oxygens?

Student: Six.

Ms. M: Yes, the formula for glucose is $C_6H_{12}O_6$. Who wants to draw tear gas?

A number of students: Me!

[She picks a boy to draw tear gas from memory.]

Ms. M: Who wants to write the formula for glucose?

[She chooses a student to go up and write the formula.]

Teacher: What did you have to do to make the glucose? What were those yellow things you were shooting?

Student: Energy.

Student: It was the sun.

Ms. M: What were you shooting? You were shooting energy at what?

Student: The molecules.

Ms. M: What were those molecules?

Student: The oxygen and hydrogen.

Ms. M: Were they together or separate?

Student: Together.

Ms. M: Was it two hydrogens?

Student: Two hydrogens and one oxygen.

Student: Water?

In this exchange, Ms. M. built on the enthusiasm her students showed about engaging in a novel kind of science homework. Though she had other content she planned to cover that day, she not only allowed the students to talk about their experience and even "show off" their mastery of game content, she also saw an opportunity to use the game visualizations to introduce and review science content they would need to learn during their unit. Holding this kind of debrief discussion after gameplay was not something we had explicitly trained teachers to do. This instance provides an example of how a teacher who knew exactly the content she needed her students to understand (the formula for glucose, the role of water and sunlight in photosynthesis, the photosynthesis equation) could quickly capitalize on student enthusiasm for the game, using the game visualizations to structure a question-and-answer session about the science content she wanted students to learn, though she did not ask the students to think about how the visual analogies represented more foundational photosynthesis concepts, such as how plants make solid food out of gaseous and liquid substances.

On day two, Ms. M started off the lesson showing her own PowerPoint introduction to photosynthesis, explaining the process and products of photosynthesis. She then introduced the Molecules in Motion activity. She went over to a table where there were cards with long strings on them and told them she needed 6 molecules of carbon dioxide. Six students got up, and the teacher handed them C cards to wear around their necks. She then asked, “If I have 6 carbons. How many oxygens do I need to make 6 carbon dioxides?”

A student responded, ”six,” and Ms. M asked, “What's the formula?” again highlighting the relationship between what they were doing and the chemical formulas they would need to know. The same student replied, “oh, twelve.” Ms. M told the boy to pick 11 other oxygens. Those students came up and got their O cards. Once students got their cards they moved to the hallway. Students were in a mass rather than linked up as molecules, with water components on one side of the hall and carbon dioxide components on the other. Ms. M asked students repeatedly what the reactants of photosynthesis were, but the students struggled to answer, even though they were supposed to be forming those molecules with their bodies. Ms. M flashed a light and instructed them to combine to make glucose and oxygen. After the students finally formed glucose with a great deal of help from Ms. M, a number of students with O cards around their neck stood apart from the glucose group. When the teacher asked these students what gas is a product of photosynthesis, they could not answer, even with the cards around their necks, which provided a clear indication of how non-intuitive the connection between substances and letters was for students.

Despite their confusion, at no point during the Molecules in Motion activity did Ms. M ask students to think back to what they did in the game, nor did she, as some other teachers did, show the glucose production slide of the PowerPoint to provide a visual guide to the process. This was her first attempt at the activity, and it was apparent that neither the professional development nor the instructional sequence made clear to her how to organize the activity effectively for her students. Understanding her role as a collaborator in the design of the intervention, Ms. M revised her approach, which she said worked better for her. She told the researchers that with other classes she had students link up into carbon dioxide and water molecules rather than just being a mass of atoms at the beginning of the activity. By having students focus first on what molecules they were making at the beginning, they could be clearer about what materials are needed for photosynthesis, and what materials are produced.

On days three and four Ms. M engaged in her normal photosynthesis instruction. She presented different digital materials and activities from a district database of resources that all revolved around the specific photosynthesis content that would be on the Regents Exam. Ms. M began the class by asking students to come up to the Smart board and answer multiple-choice questions about the products and reactants of photosynthesis. The software tallied the student responses and displayed them in a graph. She then presented a simulation on her Smart board in which she measured carbon dioxide in a bell jar containing a plant during a 24-hour period. She showed an animation that illustrated why photosynthesis does not require soil, and one that showed that a mouse can live in a bell jar with a plant as long as there is light. The students then played a quiz game on the Smart board that asked questions about plants. Finally, she showed a simulation of an underwater plant in a test tube producing oxygen bubbles. The more light it got, the more oxygen bubbles were released. Ms. M made no reference to the game or Molecules in Motion activity, suggesting that she felt that her existing resources adequately addressed the content.

On day five, Ms. M gave students a handout of questions from the Regents based on the previous days' lessons. They reviewed the reactants and products of photosynthesis. Before she transitioned to the *No Way!* activity, she reviewed homework they did about glucose and how it is turned into energy in the plant. Ms. M told them they were going to do an activity to decide if things are true or not true. She presented the *No Way!* PowerPoint. At the first introductory story, she asked what a claim was, and students said, "It's like a hypothesis," and "Something someone says to be true." She asked how they would go about proving that what someone says is true and the students said they would run "experiments" or go to Google. They voted on whether they believed the introductory stories, and Ms. M revealed the answers. She held up different kinds of publications (*Newsweek*, *National Inquirer*) and asked students if everything in them had to be true.

Ms. M then handed out the three *No Way!* stories and presented the headline of each, e.g., "In this story, this man *claims* that he grew 32,000 tomatoes." Students worked in groups of four, with two groups per story. Within their groups, they were asked to fill out the chart and use the resources to decide if the stories could be disproved. They were given about 15 minutes to work in groups. Ms. M stopped the class at one point and told them to identify the supporting and disconfirming facts for the claims. While they worked, the teacher moved around the room to answer questions or refocus them on the activity.

When Ms. M brought the class back together, she reviewed what they had learned about photosynthesis. She asked, "What are the raw materials?" "What's the waste gas?" "Is there nitrogen?" and "Is there soil?" Then she read the headlines and the class voted on whether or not to publish the stories. She pointed out that there is no soil in the photosynthesis equation, and explained the connection to the issues in the articles. Students did not have to say which resources from the activity materials they used to decide which stories might be true. Student comments indicated that they were making decisions based on prior knowledge, rather than drawing upon on the activity resources provided by the research team. For example, students said that mushrooms do not photosynthesize because they are in forests where there is not strong sunlight. Ms. M asked them to remember what she had taught them about fungi in prior months, and did not ask them to supply evidence from the activity resources.

On day six, Ms. M led a question-and-answer session on photosynthesis and respiration. She began the class with a question about whether or not soil is needed for photosynthesis. With each activity, she went over the reactants and products of photosynthesis and where it takes place in a plant. When pushed, some students were able to answer her questions correctly. In this lesson she talked about real-world implications of photosynthesis, such as global warming. She showed a video about how scientists discovered that soil was not needed for photosynthesis, and then had the students do an activity that required them to paste images onto a sheet of paper to "tell the story" of photosynthesis. She made no reference to the game or to the Molecules in Motion activity.

On day seven, Ms. M continued to go over the same key components of photosynthesis and respiration, though she went at it in different ways each time. This time she talked about whether soil was necessary or not, which was touched on in the last class in the video, but she had the students use the photosynthesis formula to answer the question. This was her own review of photosynthesis and respiration, but she included the online Flash animation of the game to illustrate the different components of the processes. The students were eager to use the Flash animation and some talked about their favorite parts of the game. Ms. M had expressed concern in previous classes that the students were just throwing out terms and did not really understand the photosynthesis and respiration processes, so she gave a quick assessment using some of the sense-making questions we had provided for use with the Molecules in Motion activity to see if individual students understood key terms in photosynthesis and respiration. Because her students take many quizzes in preparation for the Regents, it was consistent with her typical instructional practices to turn some of the sense-making questions we provided into a quiz to assess what students understood.

On day eight, Ms. M led a discussion about respiration being the opposite of photosynthesis, and she referred to the Molecule in Motion activity in her lesson. “You should know cold the process of photosynthesis, we talked about how they kind of cycle each other, so the products of respiration are going to be the raw materials of photosynthesis.” She asked them to describe the processes of photosynthesis and respiration and she walked around rows checking to see what students wrote. She had them write on the whiteboard the formulas (in words) for photosynthesis and respiration, and introduced the Molecules in Motion activity to model respiration. She called on students to come up and wear C, H, and O cards with strings around their necks, and the class went out into the hallway to arrange themselves as glucose and oxygen, and to transform into water and carbon dioxide. This was the final day of the photosynthesis instruction.

When Ms. M began this field test she already had a detailed, media-rich photosynthesis unit and a clear vision of her instructional goals, based on what she knew her students would be required to learn about photosynthesis to be prepared for the Regents Exam—knowing the photosynthesis equation, the reactants and products of photosynthesis, and how photosynthesis occurs and where it takes place in a plant. She adapted our materials to reinforce essential vocabulary and to help students visualize confusing aspects of the photosynthesis and respiration processes. Her initial discussion about the game zoomed in on the reactants and products of photosynthesis, and both the image of glucose as well as the chemical formula for glucose. During the Molecules in Motion activity, she repeatedly asked what were the reactants and products of photosynthesis, and used the Flash animation and sense-making questions once again to go over this content. Her comments and questions during the *No Way!* activity kept the students focused on the photosynthesis equation and how that helped to answer the question about the specific claims, rather than on researching the resources provided as part of the activity, or digging deeper into what is meant by a claim and the difference between supporting and disconfirming evidence.

In this teacher's view, one of the key differences she saw in the students who had played the game compared to students in previous years was in their reaction to chemical formulas and the photosynthesis equation. She and her colleagues who also implemented the module told us that their students usually "shut down" when they show the photosynthesis equation during instruction. The equation typically lacks meaning for students because they have little or no background in chemistry, so the letters (H, O, and C) and subscripts indicating the amounts are confusing. When this equation was shown in class after gameplay, however, she was surprised to find that students remained attentive and were able to follow along. Comments from students support Ms. M's assessment of what students took away from the game.

> *Student 1*: When I was playing, I noticed how the molecules are put together and how they broke apart and then how you have to put them back to a certain order so it would have the robot have more energy. We kind of went over the game and on the Smart board [Ms. M] let us play it, and then she was talking as the student would go up there and put the molecules together.
>
> *Student 2*: Yeah, she was really talking about the equation for photosynthesis and respiration, and when we were talking about respiration and photosynthesis, that kind of reminded me of the game, too, because you would have respiration failure and we would have to shoot oxygen molecules at the glucose and then break it apart.
>
> *Student 1*: I felt like it was easy for her to connect to [photosynthesis] because we already tried playing the game. … She went over it, connected it to the game, I kind of could make a connection a little more. She was talking about how you break the molecules down and how many molecules are in glucose with the elements, she would ask us, "Remember when you did the game?"
>
> *Interviewer*: So how many elements are in glucose?
>
> *Student 2*: $C_6H_{12}0_6$… you can kind of picture it as when you're at the end and you finally put it all together, you get so used to doing it that when she asked you how many are in there, you could just remember what it looked like.

According to Ms. M, the game helped students became familiar with the components involved in photosynthesis, so that when she introduced into instruction the chemical formulas and equations that are crucial to understanding photosynthesis, rather than shutting down, students drew upon an experience that many of them had enjoyed and mastered.

Site 2: Small urban school with flexible curriculum

Another field test site was a relatively small urban public school that serves 678 6th–12th-grade students. Thirty-six percent of the students in the school are eligible for free or reduced-price lunch. The school is very ethnically diverse. Thirty-four percent of students are white, 26% Hispanic, 20% African-American, and 18% Asian. About 25% of the students receive special education services, and there is a strong focus on supporting those students, especially by emphasizing literacy across the disciplines. The school has a commitment to small class size, so classes have no more than 25 students, and students have the same teachers for two years.

Researchers observed two 7th-grade science classes taught by Mr. S, who had been teaching science for five years. He used Prentiss Hall curricular materials along with many other instructional resources he gathered himself, rather than a district-created database of resources, as was the case with the previous teacher. Though Mr. S was required to meet state science standards for 7th grade, he had the flexibility to design his own lessons and the overall curriculum. Consistent with the literacy emphasis of the school, having students keep a science notebook into which they write responses to curriculum-related questions each day is an important component of his instruction. One class (Class A) had 25 students, with seven struggling readers. The other class (Class B), with 23 students, was an inclusion class with 10 students with IEPs, including one girl who was deaf and two boys with autism. An aide attended classes to help struggling students. In both classes, students sat at tables in groups of four. At the time of the intervention, the classes had completed a unit on chemical change, followed by a unit on the chemistry of the atmosphere. Mr. S, covered photosynthesis as part of a unit about climate. One of his key instructional goals was for students to develop an understanding of the science behind climate change. Though he had a laptop and projector, Mr. S had no Internet access in his classroom.

Students received their handheld devices on a Tuesday in January and kept them over the course of the two-week intervention. The day after they received the devices, Mr. S had a day of normal instruction. Students measured plants that they had been observing for the past nine days and recorded the data point on their individual plant height charts. With some guidance from Mr. S, students plotted their data points on a graph to include in their lab reports. There was no discussion of the game during this class. However, in a later reflection on the game, one student described how his experience with the game related to this lab activity. To emphasize the role that light plays in photosynthesis, one of the challenges in the game was finding the shafts of light in the cave where photosynthesis can take place. This game mechanic had an impact on how he took care of his plant. “My plant was dying,” he explained. “I had the runt. I had the underdog. It was dying. It was like, O.K., what if I move all those plants to the darker area who don’t need as much sunlight, and I put mine right in the sunny spot? It actually did help, because mine ended up growing the fastest. But I think I realized, oh, wait, if [Bob’s] just like a plant and he responds better to more sunlight, I can just put [my plant] near more sunlight and it’ll grow faster.”

On day two, students began the class writing individual responses to Do Now questions based on the sense-making questions we provided related to the reactants and products of photosynthesis, and Mr. S called on students to share their answers. He then projected the photosynthesis instruction PowerPoint and had different students read each slide aloud. In keeping with the focus on supporting literacy, he paused frequently to clarify information on a slide, to rephrase information, and to check for understanding. When he got to the slide with the glucose production process animation, which uses the atom and molecule images similar to the *Ruby Realm* game, some students noticed that there were slight differences between the molecule in the digital game and the photosynthesis instruction PowerPoint. (For example, in the game carbon is shaped like a cross and in the PowerPoint it is an X, and one of the oxygen atoms is on the opposite side). In Class B, students made the following comments when they saw the glucose slide projected.

> *Student*: How come the game looks different from that? They're not the same.
>
> *Student*: Besides, the crosses are different.
>
> *Student*: That one at the other end isn't there.
>
> *Student*: The purple one goes diagonally.
>
> *Student*: I know that because I shot those for a long time.

In Class A, students were also curious about what the images of the molecules from the PowerPoint represented.

> *Student*: Is oxygen really shaped like that? Did they use this shape just to help us understand or is oxygen always in that shape?
>
> *Teacher*: It's just a symbol that they came up with, but it's not actually in this shape or in this color. Where else do you find oxygen in this shape?
>
> *Student*: In the game.
>
> *Student*: It looks like the game.
>
> *One student spoke softly, and Mr. S paraphrased what he said to the rest of the class*: Lee is saying that the video game makers may have chosen to make this shape (a horseshoe) for this atom because oxygen has two spaces to bond. It's missing two valence electrons. Carbon is missing 4 so maybe that's why it's shaped like the plus sign. Hydrogen just has one, so they made it just a circle. (The developers did not, in fact, design the images to reflect the number of valence electrons.)

Mr. S capitalized on the students' interest in the game visualizations and their excitement about demonstrating their mastery of the game to encourage a discussion about atomic structure. Students reflecting later on the game said that the action of breaking apart water and carbon dioxide and making glucose helped them see that the atoms needed to be arranged in a specific way to form the different molecules. "I learned that when you break everything down there's a certain pattern you have to put it and if you put it randomly, it might not make the right [molecule] but if you make it the right way, it will make what you want it to make." Because these students had recently completed a chemistry unit, they were familiar with the concept of atoms forming molecules, so they could put the game visualizations into that context. One student said, "We were making glucose … that represented the chemical change … first you would split [molecules] apart, and then you'd put them back together in, like, the code, I guess you could say, for the molecule." A number of students mentioned that the need to repeat the process over and over as part of the game is what enabled them to figure out this "code" or pattern for glucose. "I really got out how the different molecules and stuff are put together, because I had to do that so many times," one student reported. Another said, "We do [molecule-making] so many times before it becomes auto and you really got it."

Mr. S then began the Molecules in Motion activity. He handed out cards with a C, O, or H, and instructed students to, "Find people to bond with so you can make molecules that are in the photosynthesis equation." Unlike students in the previous case, these students had recently completed a unit on chemistry and were not as confused by the notion that letters represented elements that combined with others to create substances. Students with certain letters made comments such as, "I'm looking for an oxygen," and "I need a carbon." Small groups of kids gathered to form CO_2 and H_2O molecules.

Once the students had formed water and carbon dioxide, Mr. S instructed students to form glucose. In his small, crowded classroom, this resulted in a lot of noise and disorganization, so he collected the cards, arranged piles on tables, and asked groups of kids to form a glucose molecule with the cards on the tabletops. Groups gathered around the tables and students lined up their paper atoms to make the glucose molecule. Some students stood around the periphery and did not actively contribute to this effort, but almost all students at least observed as other students formed the glucose molecule correctly. Mr. S noted that he had not introduced the glucose molecule in class, so it was likely the students who did know the correct structure knew it from the game.

Mr. S then had students independently write responses to questions about the Molecules in Motion activity, based on sense-making questions provided in the instructional sequence.

1) How does this activity remind you of the DSi game?
2) How do you know this showed a chemical change?

He called on a few students to share their answers.

> *Teacher*: How does this activity remind you of the DSi game?
>
> *Student*: You break up all the atoms and in the game they're floating around and you have to put them in order to make glucose.
>
> Student: You're making glucose.
>
> *Teacher*: How do you know this showed a chemical change?
>
> *Student*: Because the bonds broke and formed new bonds. A new substance is created.
>
> *Teacher*: What are the new substances?
>
> *Student*: Glucose and oxygen.

On the third day of instruction, students were asked to respond in their notebooks to Do Now questions created by the teacher that related to the game.

> 1) Describe what you have to do in the game.
>
> 2) How is photosynthesis part of the game?

Then they spent 40 minutes working on a graph for a regular class assignment; there was no discussion around the questions. During the last 15 minutes of class, students were given time to play the DSi game and write answers to four additional questions, some of which came from the sense-making questions we provided, and some of which Mr. S had made up himself.

1) How do you make photosynthesis occur?

2) How is this photosynthesis different from real life?

3) What do you like about the game?

4) What do you dislike about the game?

There was no discussion about students' responses to these questions.

On the fourth day, Mr. S began the *No Way!* consolidation activity. When Mr. S saw this activity during his PD session, he was enthusiastic, mentioning that he already did science literacy activities, such as having students compare science articles that present the same issue from different points of view. He also liked its focus on evaluating claims by looking at evidence. He said that one of his key goals for the year was helping students understand the role of evidence in understanding science issues. In their lab reports, he required students to identify what claims they were making and the evidence to support them. On his walls he had posters that provided definitions of claims and evidence.

Mr. S began the class asking students to write definitions of evidence and counterevidence in their notebooks, and had students share their answers. Then he introduced the *No Way!* consolidation activity, showing sample stories and asking students to record in their notebooks whether they would or would not publish the stories. Before resuming the slide show and showing which stories could be refuted, Mr. S took a vote about whether the students thought each story was true. Mr. S then handed out one of the three main stories. He asked kids to record the central claims from the story in their notebooks. In the final minutes of class, students shared the claims they identified and Mr. S explained that they would look for evidence or counterevidence to support or refute those claims the next day.

On day five, Mr. S handed out the story from the day before and called on volunteers to read each paragraph. He told students they would receive a claims chart and five different resources that would help them determine if the claims in the story were true or false. A copy of the claims chart was written on the board. He modeled how to fill out the chart, and then handed out charts to the students, asking them to fill in the other claims. Some students worked independently and some in small groups. After about 15 minutes, Mr. S selected students to write their answers to specific claims on the board; they were asked to specify whether each statement was true or false and to identify the resource that supported their decision. If they did not find a resource to refute a claim, students were told to say it could be true because there was no counterevidence. Even though most students concluded that this story could be true, most said they would not publish it because there was not enough supporting evidence. Finally, Mr. S asked the students to record in their notebooks whether they thought the story should be published and why.

On day six, students at each table had copies of one of the two remaining articles, a resource packet, and claim sheets. Students read the article independently and then Mr. S told them to go through each claim in the article and use the resources to decide if there was evidence to refute the claim in the resources. In Class A he explained why the article itself could not be used as evidence. He did not explain this in Class B until he noticed students using the article to defend claims. He said if they could not find anything to prove a claim wrong, they should write that it could be true because there was “no counterevidence.” Students worked in groups for about 20 minutes and then individually wrote responses to the following questions:

1) Is the story true? Why or why not?

2) Should NoWay.com publish it? Why or why not?

Then Mr. S put up the PowerPoint. He went through each story, asked students to raise their hand if they thought it should be published, and asked for explanations. Then he showed the reveals. This was the last day of the intervention.

Although Mr. S did not have a rigid curriculum to follow, he had a specific teaching style and instructional goals that shaped how he integrated the Photosynthesis Module materials into his teaching. Because his school has a relatively large percentage of students with IEPs or who are struggling readers, infusing literacy into content areas such as science is a high priority. This can be seen in his regular use of Do Now questions that his students respond to in written form, as well as their using a science notebook full of their own writing as an organizing tool. Presented with the sense-making questions we provided to connect the game with the classroom activities, it was natural for him to use these as Do Now questions. Because he did not have Internet access, Mr. S was not able to use the Flash animation, so he could not use this tool to reinforce the game visualizations, though he did make use of the PowerPoint glucose production animation to connect the game images to content they had recently been covering.

As noted above, Mr. S integrated the module into a unit on the atmosphere and chemical reactions related to the atmosphere. Unlike the living environments teacher, his students came to the intervention familiar with chemistry, so they were not as confused by chemical formulas as were the living environments students. Mr. S described a different benefit of the *Possible Worlds* Photosynthesis Module in relation to his goal of teaching the science of climate change:

> I think that photosynthesis is normally framed in a way that is plants taking in carbon dioxide and releasing oxygen. Some of the students think, “Oh, plants help us, because we reuse the oxygen.” And even if I were to teach the chemistry and show all the atoms, “Oh, look, there’s six oxygen molecules,” they might think that glucose is just the leftover stuff that formed, and in the ecological sense that glucose is not significant. … I think that the game made glucose seem way more important, and it showed that oxygen is actually just the waste, that oxygen should be the afterthought for the plants. That’s huge, because in reports that [students] wrote [in previous years], they would say, “photosynthesis produces oxygen,” and in all these science reports, it’s “photosynthesis produced

> glucose so the plant can grow, and have energy, and it just gets rid of the oxygen as waste." I think the game did a lot to help.

The game visualizations convey the idea that the glucose produced by Biobot Bob is a source of energy, and also forms a tangible substance that can be used to get past obstacles (the bats). Students in Mr. S's class, in their notebook responses to Do Now questions, regularly mentioned glucose production as central to the game. One student wrote, "Basically you had to save your friend from inside a cave. You could not go inside the cave so you used a robot. The robot was almost like a plant and ran on glucose." Another student wrote, "Bob makes glucose; you have to break apart CO_2 and H_2O with sunlight. Then you have to put the remaining atoms together to make glucose." When another student was asked what he took away from the game, he replied, "I got out of it glucose. I learned how to write glucose and realizing how much plants actually need glucose and water and sunlight."

Because Mr. S taught photosynthesis in the context of the chemistry of the atmosphere, it is not surprising that his students in the past have primarily seen photosynthesis in terms of what it contributes to the atmosphere. The use of the game allowed students to have a visceral experience of making the glucose molecule, and the game narrative enforced the importance of glucose in driving the action of the characters. By referring back to the game regularly through his Do Now questions, students were constantly reminded of the glucose-making visualization, which likely gave glucose a more prominent role in how they understood photosynthesis.

Discussion

We began *Possible Worlds* with the idea that we would create digital games to address a specific instructional need—to help dislodge persistent science misconceptions that even high-quality traditional instruction and curricula fail to dislodge. We believed that digital games would be particularly appropriate for this purpose because they could both motivate and present students with alternative realities or "possible worlds" (Bruner, 1986), in which it might be easier to accept non-intuitive concepts. As Alexander and colleagues (2010) note, gameplay on its own, though it can produce a certain kind of mastery, does not in itself translate into mastery of the kind of content and concepts that are relevant for formal educational purposes. However, by strategically mapping game metaphors to particularly challenging, abstract concepts, we sought to create a gameplay experience that could prime students to engage productively with those concepts in more traditional instruction (Habgood & Ainsworth, 2011; Reese, 2007). Our instructional model follows on Bransford and Schwartz's (1999) preparation for future learning model, in which students have a shared experience (in this case, gameplay) prior to instruction that is intended to prime them to understand a particular concept. Because we predicted that teachers might need additional support to make links between gameplay and instruction, our model also includes scaffolded materials that make explicit connections between the game metaphors and science concepts encountered during instruction, and a consolidation activity that asks students to apply their new conceptual knowledge in a different context. Teachers can use these cognitive supports (Richland et al., 2007) to leverage students' enthusiasm for and mastery of the gameplay to promote science learning (Cameron, 2002; Venville, 2008). Once a beta version of the materials was developed, we field-tested the modules to investigate how different teachers would integrate these materials to meet the unique instructional needs of their school and classroom contexts. At the same time, the field tests were trials of the feasibility of our implementation model, as this work also sought to produce an intervention that could be implemented broadly and uniformly, and potentially have an impact on student outcomes with minimal training for, or support of, the teachers involved (Cook, 2007).

Our field test demonstrated that teachers in a broad range of instructional settings were able to integrate the materials into their instruction without the help of the research team. We also saw that the module experience was strongly mediated by key contextual factors, such as the degree of flexibility teachers had in designing their curriculum, and their typical instructional practices. The two implementation cases presented here in detail demonstrate that the materials are flexible enough for teachers to adapt to support their particular instructional goals. The teacher who needed her students to understand specific vocabulary, equations, and formulas related to photosynthesis and respiration used each Photosynthesis Module resource to reinforce those key ideas. Adding these to her already media-rich repertoire gave her students many different experiences to draw upon to make sense of and remember the content she needed them to learn. In contrast, the teacher who was concerned about supporting literacy and an understanding of the role of claims and evidence used the materials to create multiple writing opportunities for his students, took the time during the consolidation activity to carefully model how to identify claims and evaluate them using evidence, and gave the students adequate time to engage in that process themselves.

What sense do we make of these two functionally successful, but very different, implementations? Students in both schools played the game prior to instruction, and both teachers made use of the additional materials in the sequence, generally in the order recommended by the research team. From a design-based research perspective, these teachers have provided us with valuable insight into the diverse priorities and emphases teachers bring to their instruction of even very narrowly defined topics and concepts. "Teaching photosynthesis" involved quite distinct means, and led to different ends, for each of them. From the perspective of researchers preparing an intervention for a randomized controlled trial, this variation in the methods, goals, and purposes of photosynthesis instruction suggested that it would be difficult to anticipate how "controlled" the experiment actually would be.

What was notable from both cases, and from the larger set of observations in general, was how infrequently teachers, with or without our materials, addressed the specific misconception that our module was designed to target, namely, the concept that plants create solid food (and their mass) out of air and water. This observation should lead us to revisit what may be a missing piece in this intervention—an adequate opportunity for teachers to explore whether and how consideration of states of matter and conservation of energy can help students to understand the process of photosynthesis and how it creates plant matter out of "thin air." This finding challenges us to reconsider our definition of the instructional challenge we set out to address. We continue to believe, as is well-documented in the literature, that scientific misconceptions are persistent and widespread, and that teachers believe they do not teach to them effectively. However, in practice, teachers are working in the context of assessment requirements and curricular sequences that prioritize other instructional goals, such as covering content or supporting literacy. Helping teachers to teach challenging concepts that they are not held accountable for is a problematic proposition, even if teachers acknowledge that in theory it would be worthwhile to achieve these instructional goals.

From a preparation for future learning perspective, however, the lessons to be learned from this field test are somewhat different. If our intervention is a truly effective "black box"—if it is expected, from a particular theoretical perspective, to work without regard to contextual variation—then these variations in teachers' points of emphasis in their implementation of the module should not be particularly important. A strict reading of the theoretical basis for this project suggests that by providing students with the grounds for analogical reasoning about the nature of photosynthesis, we should be able to help them reason through the process of transformation of matter that underlies photosynthesis, regardless of other features of their teacher's instructional process.

A third alternative for making sense of this finding comes from the articulation of "design-based implementation research" as a new alternative for guiding the creation of educational interventions. This approach (Penuel, Fishman, Cheng, & Sabelli, 2011) suggests that these findings should lead the research team into much more sustained discussion with practitioners about how the target concepts might best be integrated into their instruction, with a more comprehensive focus on considering the intervention as one element in a complex implementation environment that the teacher is orchestrating in collaboration with her students as well as with the larger community of her school and district. This approach might lead us to reconsider how we structure the curricular relationship between these modules and the highly diverse, decentralized process of sequencing science-topic coverage during the middle grades.

In practice, we took several lessons from this field test. We redesigned elements of the materials to make them more streamlined and user-friendly for the teachers. More importantly, we redesigned the one-day professional development experience to focus more explicitly on the nature of students' common misconceptions and to help teachers explore the ideas about states of matter and conservation of energy that underlie *Ruby Realm* and the actual process of photosynthesis in nature. It remains to be seen whether these adjustments were adequate.

The other major finding of this field test was the rarity of teachers' explicit references to the digital game during regular instructional time. The theoretical promise of the digital game as an effective tool for dislodging misconceptions is dependent on teachers explicitly using visualizations from the game as cognitive supports for analogies that clarify the targeted science concepts (Gentner, 2010; Richland et al., 2007). We did not see teachers make these kinds of connections very often between the visual analogies and the science concepts they were mapped to, although they did make some references to the game when using the instructional materials provided by the research team. Though the teachers in this study participated in professional development and had the games in advance of the intervention, at least two of the teachers admitted they had not played the game beyond what they played in the training, which may have been the case with others. Therefore, it is likely that some of the teachers were not yet comfortable enough with the game to initiate their own connections between their existing unit materials and the game visualizations. To use the game visualizations more effectively, teachers will require focused professional development during which they play the games and are shown explicitly how the visualizations map to concepts they address in their teaching. The instructional materials supplied by the research team provided teachers with cognitive supports in the form of consistent images (the atoms and molecules) and actions (breaking apart and making molecules) designed to help them draw connections to the game, but the field-test findings suggest that a more explicit mapping of visualizations to concepts is necessary for teachers to leverage the game to its full potential. The research team intends to create such a resource for teachers in the final year of the study. We will then have to conduct research around the use of that resource to determine how to balance simplicity, clarity, and depth in the design.

Finally, this field test gave us encouraging, but limited, indications of how students grappled with key photosynthesis concepts that suggest how to design support materials to help teachers leverage the game visualizations to make more explicit connections to instruction. Certainly students did show evidence of mastery over the core game mechanic of breaking apart molecules and building new ones, and that mastery did reflect some understanding of the molecular structures of the reactants and products of photosynthesis, most significantly glucose. Though students' knowledge of the glucose structure is not remarkable given that they had to create glucose many times during gameplay, what is important is that this finding suggests that the game gave students a familiarity with the process of molecule-making that teachers could potentially build on to help them understand that the atoms in that glucose molecule are the same atoms that originally were in carbon dioxide and water molecules, a concept that is abstract and often hard to grasp (Reese, 2007; Richland et al., 2005). Moreover, this suggests that the game gave the students a direct, felt experience with molecule-making so that they had a concrete understanding of the pieces that make up the molecule, how they are split apart, how they are put together, and the purpose of the process. After playing the same puzzle over and over, students became very familiar with the images. In many of the classes we observed, the students wanted to know why the atoms looked like they did, asking if the graphic reflected what the atoms look like in real life. In some classes, students decided that the game had it "wrong" when they saw a slightly different image on the photosynthesis instruction PowerPoint presentation, suggesting that they assign more credibility to the instructional materials than to the game. It also suggested that, while the game experience may give them a foundation for understanding the structure and components of glucose, the concreteness of the representation and the repetition of the glucose-making process may make it difficult for them to conceive of glucose or photosynthesis being represented in any other way. This represents a crucial moment when teachers must provide explicit instruction to translate the gameplay experience to a more abstract understanding of the process (Venville, 2008). For this to occur, teachers must have a clear understanding of how to connect the game metaphors to their curricular content, in the form of instructional materials accompanying the games that make those connections obvious, training that focuses on making those connections, or a guide that maps the game metaphors to standard curricula.

Because the only data we collected from students were observations of classroom interactions and interviews with subsets of students, we are not able to say what students as a whole gained from the experience. We can only report on what those students who participated in class and who offered to be interviewed could tell us. What these findings do suggest for the larger research and development community seeking to understand how digital games can enhance science instruction in typical classrooms is that digital games that offer visualizations designed to be analogous to specific science concepts do show some promise for helping students engage in a playful way with those concepts. Importantly, the games do not have to be elaborate, immersive experiences, but can be relatively simple games that are played at home. However, playing the games alone will not lead to the kind of conceptual change necessary for learning to take place. Teachers must use visualizations with which students have become familiar to support learning around the challenging concepts.

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Visualizing Photosynthesis

Figures 1-4

Figure 1: BioBot Bob and the glucose production puzzle

Figure 2. Liquid Methanol Puzzle Detail

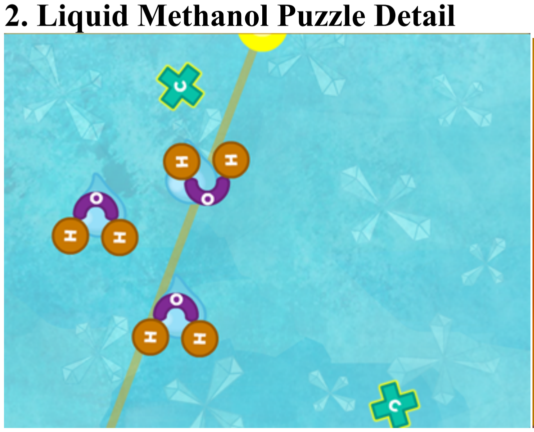


Figure 3. Tear Gas Puzzle Detail

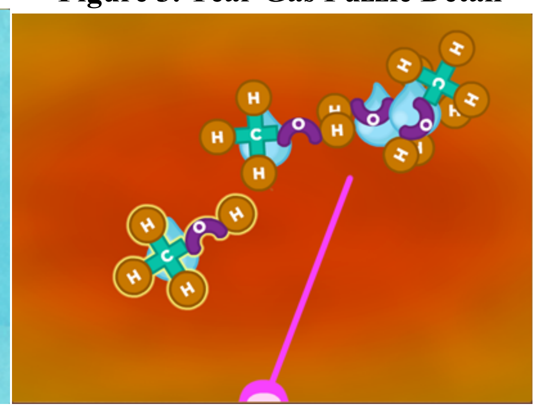
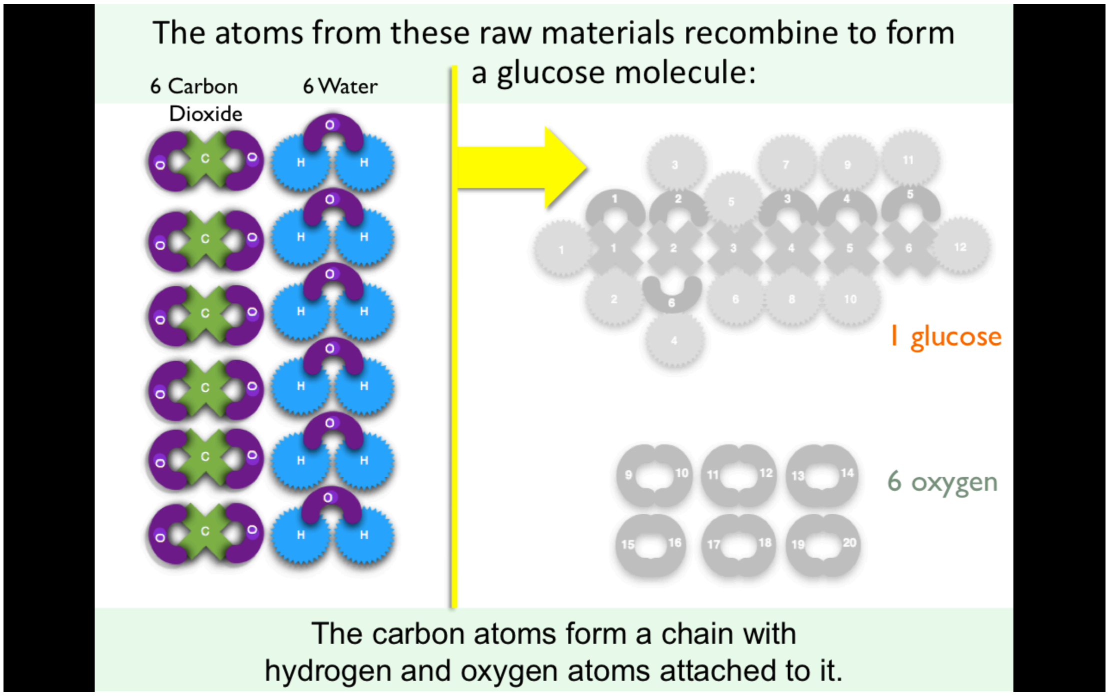


Figure 4. Image from photosynthesis PowerPoint presentation



Visualizing Photosynthesis Tables 1-3

Table 1. Site demographics

	Setting	Grade levels	Class size (approx.)	% FRL*	Number of Teachers	Number of Classes	Number of Inclusion Classes	Number of Students
1	urban	7, 8	35	10	2	8	2	265
2	urban	7	25	36	1	2	1	47
3	suburban	7, 8	27	30	7[4]	6	1	167
4	suburban	6	17	0	1	1	0	17
Total					11	17	4	496

* Percentage of students eligible for free or reduced price lunch, an indicator of low income level.

Table 2. Intervention sequence

Hand out devices and introduce digital game	1 day	Teachers handed out the devices (can be done in last 10–15 minutes of class) and instructed students to play at home for at least 30 minutes
Regular classroom instruction, student interviews	1–3 days	Days when teacher covered a topic as s/he usually would teach it, integrating some or all of the photosynthesis instruction PowerPoint presentation Researchers interviewed students about the digital game
"Molecules in Motion" activity	1 day	Days when teacher completed the "Molecules in Motion" activity.
Sense-making activity	1 day	Days when class discussed the similarities and differences among "Molecules in Motion," the digital game, and the content covered in class using the Flash animations (can be done in conjunction with other photosynthesis coverage)
NoWay! activity	2–3 days	Days that teachers had students do the consolidation game
Teacher interviews, student interviews	1–2 days	Researchers interviewed teachers and students about the experience

[4] Includes a special education teacher who co-taught a class.

Table 3. Summary of module implementation across teachers

	Unit content	Instructional goal	Digital game	PPT	Molecules in Motion	Flash animation	Sense-making questions	No Way!
Teacher 1	Plant structure and function	Photosynthesis vocabulary and equation	At home	Did not use	Used	Used	Quiz	Used
Teacher 2	Plant structure and function	Photosynthesis vocabulary and equation	In class	Used one slide	Used	Did not use	Discussion, quiz	Used
Teachers 3 & 4	Plant structure and function	Photosynthesis vocabulary and equation	At home and in class	Used one slide	Did not use	Did not use	Written questions	Used
Teacher 5	Ecology	Role of photosynthesis in environment	At home	Fully used	Used	Used	Written questions, discussion	Used
Teacher 6	Climate	Role of photosynthesis in climate	At home	Fully used	Used	Did not use	Written questions, discussion	Used
Teacher 7	Climate	Role of photosynthesis in climate	At home	Fully used	Used	Used	Written questions	Used
Teacher 8	Climate	Role of photosynthesis in climate	At home	Fully used	Used	Did not use	Quiz	Used
Teacher 9	Climate	Role of photosynthesis in climate, role of evidence in science	At home	Fully used	Used	Did not use (no Internet)	Written questions	Used
Teacher 10	Chemical change	The reactants and products of photosynthesis, and conservation of matter	At home	Fully used	Used	Used	Quiz, discussion	Used
Teacher 11	Plant structure and function	Photosynthesis process, terms, equation	At home	Fully used	Used	Used	Written questions, discussion	Used
Total			10 at home	7 fully used	9 used	5 used	11 used	11 used