Supports for Digital Science Games: Visualizing and Mapping Analogies

Wendy Martin, Megan Silander, Katherine McMillan Culp, Cornelia Brunner, and John Parris

Integrating Digital Games into Instruction to Dislodge Science Misconceptions

More than 10 years ago, our team—consisting of instructional designers, game developers, science education experts, and researchers—began work on a set of four digital science games and instructional materials for middle-school educators. Collectively called *Possible Worlds*, with funding from the US Department of Education's Institute of Education Sciences (Award # R305C080022), and later the National Science Foundation (DRL-1252382), we were motivated by the desire to provide teachers with engaging and easy-to-use resources to help students overcome persistent science misconceptions and gain a deeper understanding of abstract science concepts that can be difficult to visualize. For example, students often struggle to understand the concept that a solid material like plant matter can be made from a liquid (water) and a gas (carbon dioxide). Students (and adults) who cannot imagine processes that take place at the molecular level are likely to hold the misconception that plants "eat" a solid material such as soil and transform that into plant matter, another solid material.

We believed that digital games were particularly well-suited for helping students build an implicit understanding of the invisible forces and interactions underlying difficult science concepts because (1) they encourage players to imagine different realities as they enter into a world of novel rules and situations and (2) they motivate players to gain mastery of those rules and persist through frustration as they solve

W. Martin (✉) · M. Silander · J. Parris
Education Development Center, New York, NY, USA
e-mail: wmartin@edc.org

K. M. Culp · C. Brunner
New York Hall of Science, Corona, NY, USA

M. J. Bishop et al. (eds.), *Handbook of Research in Educational Communications and Technology*, https://doi.org/10.1007/978-3-030-36119-8_36

game challenges (Gee, 2007). We planned to leverage these affordances to create fanciful environments and experiences, analogous to abstract scientific phenomena, that would challenge students' assumptions and present new rules that they would need to master to succeed in the gameworld.

We also wanted to make games that were scalable, that teachers and students could use easily in their classrooms, despite limited time and technical resources. Therefore, we felt that games should focus specifically on misconceptions that normal instruction and curricula tend not to dispel. To help integrate the games into classroom teaching, we intended to design instructional materials that teachers could use to highlight the analogies between the game visualizations and the concepts the games target. We hoped that our games would create compelling, shared experiences that teachers could draw upon using our instructional materials to help middle-school students overcome the misconceptions that prevent them from comprehending abstract concepts that are essential for higher level science.

Initial Rationale for the Design of the Digital Games and Instructional Materials

The initial rationale for our approach to *Possible Worlds* rested on three elements that we felt would be critical to ensure students would learn from using the games: that the games would need to engage students, address a persistent educational challenge (science misconceptions), and be easily scalable and therefore adaptable for use in a variety of classroom contexts that likely vary in access to technology, curriculum requirements, student achievement levels, and teacher expertise and comfort with technology. To meet these needs, we felt we needed to create materials that were engaging, simple, flexible, and targeted to the specific problem. Therefore, we planned to design easy-to-use digital games that provided students with playful visualizations representing abstract concepts and phenomena and instructional materials that enabled teachers to draw explicit analogies between the game visualizations and the science concepts. We hoped that the game experience would be compelling enough to counter the intuitive pull of misconceptions as well as the abstract nature of the phenomena. We also wanted to create materials that could be used by teachers with no support from us to ensure use of the products beyond our grant period.

At the time that we began designing the *Possible Worlds* games and materials, there was great enthusiasm in the educational community about drawing on what commercial game designers do to create experiences that are motivating (Gee, 2007; Squire, 2006). Many of the game-based learning initiatives that were being discussed in the research literature were designed to be used in place of existing curricular units (notably *River City* [Ketelhut, 2007] and *Quest: Atlantis* [Barab, Sadler, Heiselt, Hickey, & Zuiker, 2007]). While we agreed that digital games had the potential to create exciting and memorable learning experiences for students, we also suspected that most schools did not have the capacity to replace full curricular units with digital games. Our plan in 2008 was to build on the lessons learned from those initiatives and create a series of four relatively simple games based on familiar game mechanics (such as puzzle, platformer, and first-person shooter) that would be easy for students to play and that could be integrated into teachers' existing curricula to help them teach only those concepts that students tend to find particularly challenging. We also planned to develop instructional materials that connected the games to those science concepts. The choice to include simple, short games was grounded in our understanding of the challenges teachers face when attempting to integrate complicated digital interventions into teaching and learning—that teachers lack time and technical expertise, that they need help understanding *how* to incorporate technology into instruction, that their curriculum constrains their choices, and that students do not have sufficient access to technology (Blumenfeld, Fishman, Krajcik, Marx, & Soloway, 2000; Culp, Honey, & Mandinach, 2005; Edelson, Gordin, & Pea, 1999; Honey, Culp, & Carrigg, 2000). We planned to design the four games and associated materials so that teachers could select those that were aligned with the existing curricular units that they taught. The games were not intended to replace teachers' curricula, but to supplement it. We believed this was more consistent with how teachers might actually use digital games, increasing the likelihood that the games would be accessible and feasible for teachers to implement.

Our original vision was to make games for the Nintendo DS, which, at the time, had a very large install base among middle-school-aged students. This project began prior to the release of the iPad and before it was commonplace for middle-school students to have smartphones. The Nintendo DS provided a familiar portable platform for digital games that would be easy for students to play at home. Because our goal was to work within the constraints of typical schools, we did not want to design games that required a great deal of instructional time or developer involvement to implement. Rather, we wanted to have students play the games as homework and use precious instructional time for teachers to make connections between gameplay and targeted science concepts using the instructional materials we would design.

We decided to design visualizations in the digital games that were analogous to abstract science concepts because a great deal of research has demonstrated that drawing analogies between familiar concepts and novel ones is an effective method for building a solid and lasting understanding of those novel concepts (Gentner, 1983; Gentner, Loewenstein, & Thompson, 2003; Gentner & Smith, 2012). Our design challenge was to create game-based visualizations that were age- and curriculum-appropriate analogies of the concepts at the core of our target misconceptions and to integrate them into games that were compelling to play. Unlike simulations, the visualizations would not be illustrations of the concepts—such as watering a plant to make it grow. Rather, the games would use familiar game mechanics designed to give the player a visceral experience (e.g., "shooting" molecules apart with sunlight and putting the component parts of the molecule together like a puzzle to form glucose) that acts as an analogical source to the target concept—for example, the molecular process of photosynthesis.

From the start of the design process, we had in mind that teachers would need to be supported with materials that would guide them in integrating the student's digital gameplay experiences into regular classroom instruction, as well as limited professional development in the use of the games and materials. Therefore, in parallel with the digital game design, we developed a suite of materials that would enable teachers to connect student gameplay with the conceptual learning that we aimed to help students achieve.

The Design Process

The first priority for this project was to build a team with the expertise necessary to develop four different games that would each have visually realized worlds and characters that would inhabit them but that would also be educationally sound. First, we had an instructional designer with the expertise of a developmental psychologist who could create learning experiences aligned with instructional goals. Our game development partner, 1st Playable, brought years of commercial experience with licensed properties, including creating Nintendo DS games for Disney and Cartoon Network. They had expertise in art direction, character and graphic design, as well as designing mechanics and scoring systems that would make the games fun for middle-school students. Our team had science education experts to ensure the games were scientifically sound, to provide expertise about what middle-school science teachers typically teach, and to help design the instructional materials. We also had a production manager to coordinate the various aspects of the development process and researchers to test iterations of the paper mock-ups, digital games, and instructional materials with students and teachers.

The design and development process for each of the four games followed a similar pattern, although with each successive game the process became more efficient and integrated. First, the full team met with our advisory board, which included game designers as well as experts in science, developmental psychology, and educational media, to select the scientific misconception the game would target. We based our selections on a number of criteria. First, it had to be a persistent misconception identified in the research literature (e.g., we referenced Chi, 2008; Driver, Squires, Rushworth, & Wood-Robinson, 1994; Ozay & Oztas, 2003; Smith III, diSessa, & Roschelle, 1994). Second, the misconception had to be associated with topics addressed in typical middle-school science standards. This project predated the Next Generation Science Standards, so we used standards from New York and Massachusetts, where the research took place. Third, the team needed to be able to imagine a way to translate the abstract concept at the heart of the misconception into entertaining visuals and game mechanics. Fourth, there had to be potential for an engaging narrative into which the visuals and mechanics could be integrated.

The first game was based on the misconception described above—the belief that plants eat soil. The second game focused on misconceptions related to heredity—the idea that "dominant" genes are inherently better or more powerful than recessive genes and that inheritance of traits is not random or independent from what has happened before. The third game addressed the misconception that electricity is matter, and the fourth game focused on heat transfer and targeted the misconception that cold can be transferred just as heat is transferred.

After choosing each misconception to target, our science experts examined existing middle-school science curricula and standards that included the concepts related to the misconception and talked to science teachers to understand how they taught the concepts, what other digital and non-digital games or simulations they used, and how they could imagine integrating games into their instruction. Using this information, our instructional designer mocked up simple digital or paper-based games to serve as analogous visualizations of the concepts that students needed to understand in order to overcome the misconception. The researchers tested these mockups with students in after-school programs and provided rapid feedback about students' responses to the games to the instructional designer, who made revisions. The instructional designer then worked with the game developers to design the learning experiences and interactions that should be included in the prototype DS games. Based on these conversations, the developers created a game-design document to guide the production of the alpha, beta, and final versions of the games.

During the prototyping phase, the instructional designer, game developers, and science education expert met as a group weekly to review each iteration of the prototype and discussed the scientific content, instructional design, gameplay, and visual design. The researchers tested the prototypes with students. The production manager shared the user-testing feedback with the design team, who made changes in response. The designs typically required many iterations, especially with the first two games. With each new iteration the game developers produced, the instructional designer needed to ensure that the game mechanics, graphics, and larger game challenges did not undermine or contradict the analogy, and the science education expert needed to ensure that the game did not introduce scientifically inaccurate information or new misconceptions. At the same time, however, the team understood that the game developers had to have creative license to design games that were as entertaining as possible. The science education expert and the instructional designer also created or found classroom activities and materials that connected the digital game visualizations with the target science concepts. This collaborative process evolved over time, as the team members grew to trust each other and appreciate the various forms of expertise everyone brought to the enterprise.

The Evolution of the *Possible Worlds* Digital Game Design

One of the key components of the original project idea was that, in order to engage students in the game, we wanted to create games that did not look or feel like educational games but that seemed like real DS games that adolescents would want to play. In the beginning, our design team believed that meant that the larger game narrative goals did not have to be related to the core analogy we wanted players to learn. Rather, we planned to create analogous mini-games within the larger narrative that players would have to engage with multiple times to achieve the game goals. This repetition of the analogous mini-game would lead players to develop a deep, implicit understanding of that activity, which teachers could reference during instruction. Only if the game felt like a fun “real game” would players stay interested enough to be exposed to the analogous mini-game multiple times. However, with each successive game, we came to realize more and more that this bifurcation of fun narrative/analogous mini-game was not necessary. By the fourth game, the analogy had been completely integrated into the game narrative and goals.

During the process of developing the first game, *The Ruby Realm*, which addressed the misconception that plants eat soil and turn it into plant matter, prototyping began with testing a number of puzzle-like mini-games that attempted to provide a playful experience of interacting with the transformation of energy during photosynthesis. The main learning goal of the mini-games was to challenge misconceptions about the nature of photosynthesis by having students engage with mechanics, gameplay, and images that help them enact the process of using light energy to break apart carbon dioxide and water molecules and reconfigure them into a glucose molecule. The game developers tried out a number of different ways to visualize the atoms and molecules and different ways to break them apart and regroup them, such as using the DS stylus to separate the atoms from the molecules and then circle groups of them to form new molecules, as well as “shooting” molecules of water and carbon dioxide apart and completing a puzzle by dragging the resultant atoms to form the new molecule of glucose (Figs. 1 and 2). When we tested these two versions, the first-person shooter mechanic proved more popular with a range of students, perhaps because it is more familiar than the circling mechanic.

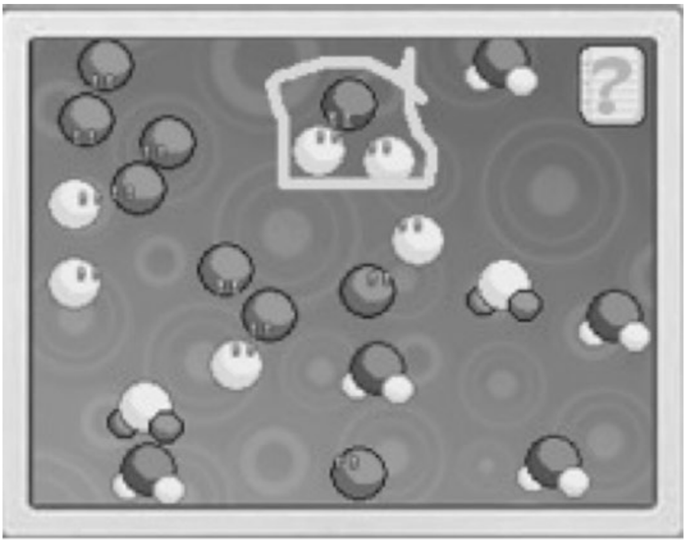

Fig. 1 Early iteration showing a circling mechanic to combine particles

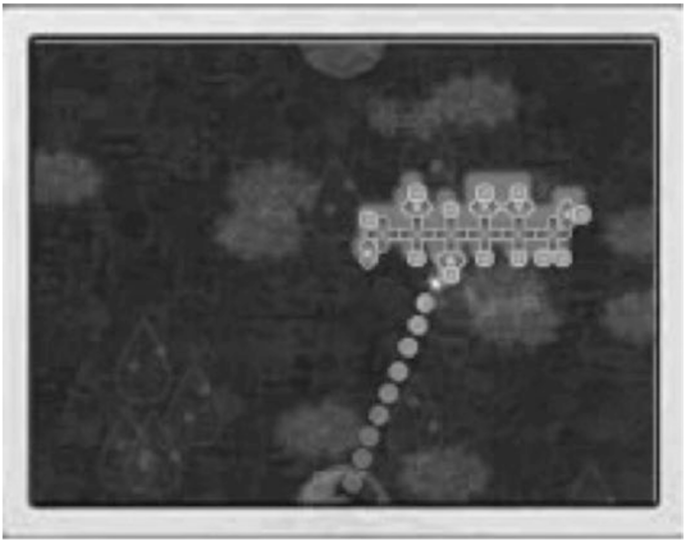

Fig. 2 Later iteration showing a shooting mechanic that directs energy toward particles

After the team agreed upon the design of the mini-game that served as the visual analogy to the concept, we conceived of a narrative surround. The first iteration of the photosynthesis game centered on the task of keeping a plant healthy. The game took advantage of the dual screen design of the DS; in an effort to aid a plant in its photosynthesis process, players shot apart and built molecules on the lower screen, while the resulting effects on a plant took place on the upper screen (Fig. 3). Although the team thought that the premise of caring for a plant would be engaging for our middle-school audience, we encountered two challenges. First our science experts objected that the game might give students the impression that plants controlled their own photosynthesis, creating a new misconception that plants have agency over this process. The second challenge with the prototype was engagement. When we tested this iteration with students, they enjoyed the action of shooting and building the molecules but were not very engaged by the "keeping a plant healthy" narrative.

At this point, we realized that our team lacked a crucial component—we did not have a storyteller who could make the game narratives compelling enough to keep students engaged. We were fortunate to find a writer with years of experience in developing children's media who could create interesting stories. Adding this person to the team transformed the photosynthesis game. Instead of keeping a plant healthy, the narrative centered on a group of kids who send a robot into a cave full of vampires to save their lost friends. At the time, vampires were popular in films and fiction aimed at our target middle-school-aged audience. In the game, titled *The Ruby Realm,* players control a robot called BioBot Bob, who relies on a process analogous to photosynthesis to produce the energy he needs to travel through a cave (Figs. 4 and 5). When players navigate Bob to a light shaft in the cave, they are able

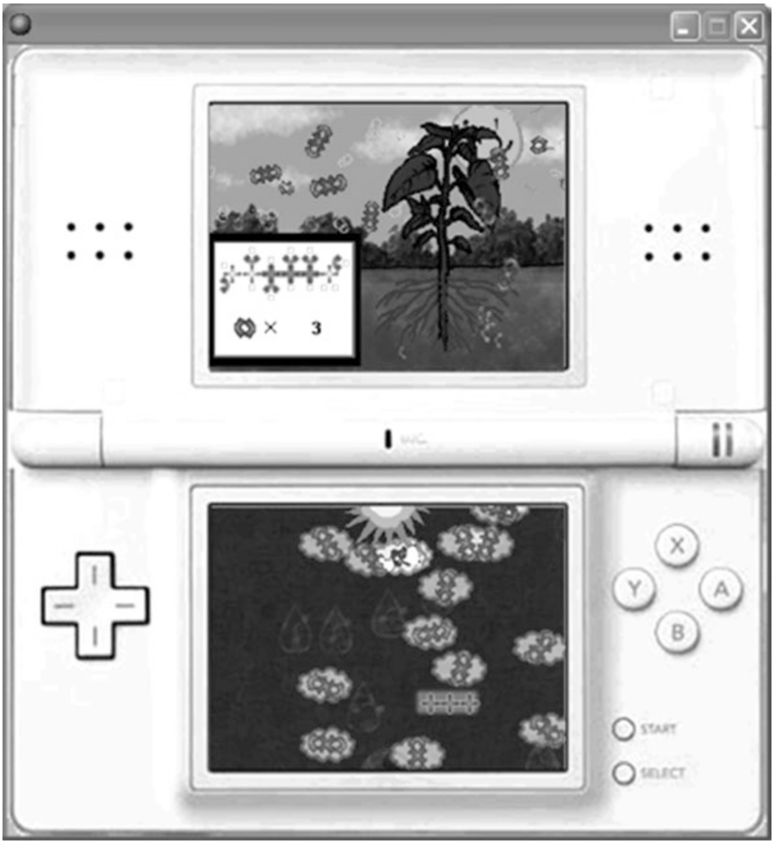

Fig. 3 Early DS game

to play the mini-game in which they break apart clouds (carbon dioxide) and droplets (water) into oxygen, hydrogen, and carbon atoms and then construct glucose (to give Bob energy), methanol (to fuel his jet pack), and tear gas (to ward off vampires). We hoped that having a robot engaged in an artificial form of photosynthesis would help students understand the process of breaking apart and putting together molecules, without having them believe that plants do this intentionally. When we tested this game with students, they were far more interested in playing through the levels than they were with the "keeping a plant healthy" game, which meant that they experienced the mini-game multiple times. In keeping with our initial belief, the mini-game was a task that students had to complete to achieve the game goals, but was not a main point in the narrative, which was to get through the cave to find friends and collect treasure.

For the second game, we sought to address the misconception that dominant traits are "stronger" or more desirable just because they are more likely to be expressed and the misconception that individual instances of a trait being expressed

Fig. 4 *The Ruby Realm* title screen

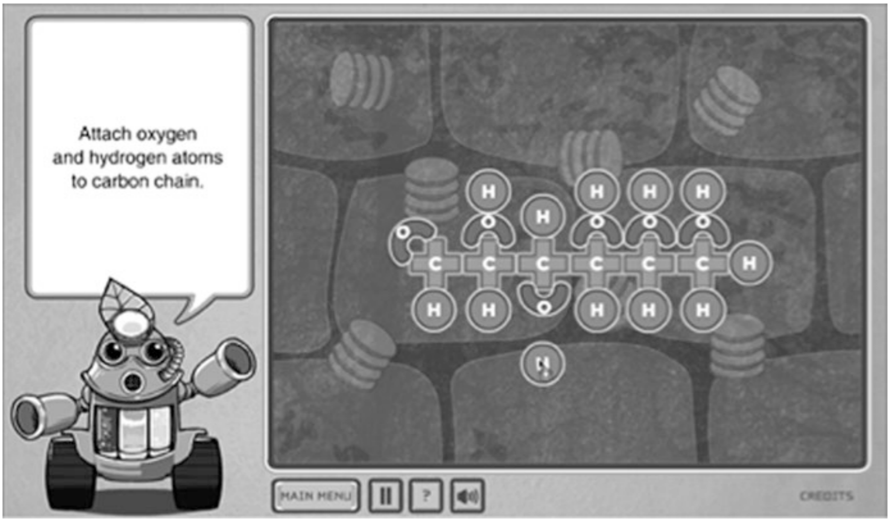

Fig. 5 BioBot replicator mini-game

are dependent on what came before (i.e., not random) just because there are overall patterns in the emergence of traits across a population over time. Therefore, we wanted to design a game in which players need to develop an understanding of randomness and dominance to help them achieve game goals. The instructional designer originally had the idea of using a pachinko machine/lottery mini-game to convey the idea of randomness and a rock-paper-scissors mini-game to convey the idea that different traits can be beneficial under different conditions.

Our writer and game developers took these ideas for analogous mini-games and extended them to the broader narrative and game goals, creating *RoboRiot*, a game about robots that become infected with a virus. The player must create a team of robots to disable infected robots so that the anti-virus software can be installed. There are a variety of environments in this world, and the robots have different basic "traits," such as fire, ice, water, and electricity. Each robot has two alleles—fire and water, for example—and the one that is functional or "expressed" determines its job. For example, a water robot is useful as a firefighter, a fire robot makes a good cook. Each type of robot is powerful against some robots and weaker in relation to others. The trick to winning the game is to deploy the robots so that they can "fix" the infected ones; this means that the robot sent to fix a specific infected robot has to be more powerful so that it can temporarily capture and reprogram it. To create a specific type of robot, the player can send two robots to a recycling machine and create a new one that has one allele from each of the original pair (Fig. 6). Because each allele is randomly selected, there is no way of predicting which two of the four alleles it will get, just as alleles from each parent are randomly selected in reproduction. We used robots again rather than biological creatures in this game to simplify heredity to something based on a single trait and to avoid the issue of biological reproduction. By using robots, which do not mate, have no life span, and exist to

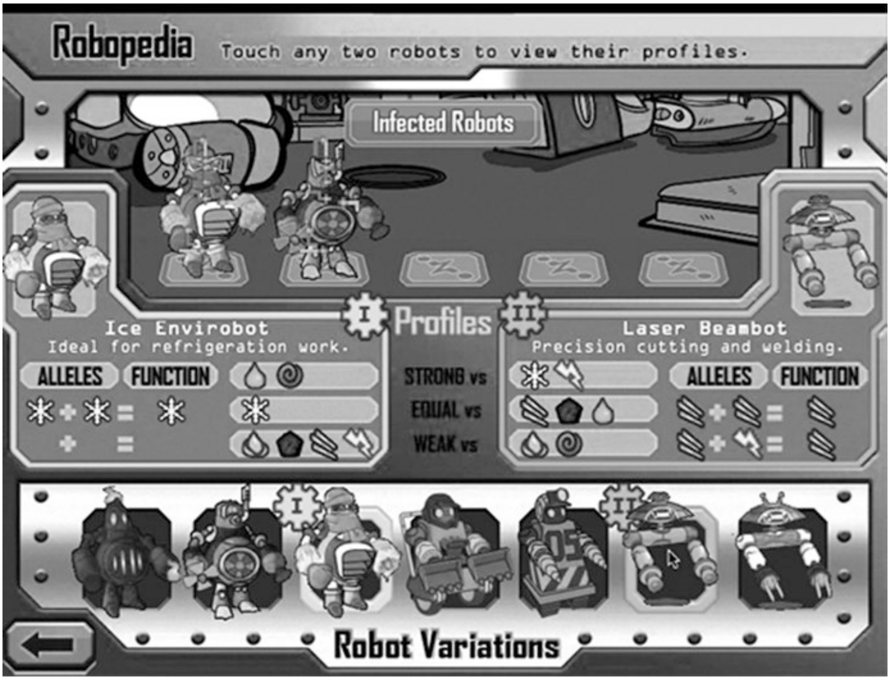

Fig. 6 *RoboRiot* "Robopedia" showing robot attributes

fulfill a single function, we could maintain our focus on the key ideas of random combinations and relative dominance.

The design team stayed with the original idea of an analogous mini-game that visualizes the concept of randomness (the recycling machine) but also saw the narrative potential of a rock-paper-scissors scenario, where different kinds of traits are valuable in different environments and in battle against other robots. Mastering the concept of relative dominance is important for developing a successful strategy for winning the whole game, not only a mini-game that a player needs to complete to get back to the action.

Our third game took on the misconception that electricity is matter rather than energy, a misconception often perpetuated by the common analogy of electricity flowing through wires like water through a hose. The design team's first idea was to visualize the flow of electrons jumping from positively to negatively charged atoms, but our science expert observed that the middle-school curriculum rarely treats electricity on an atomic level and that this approach might not be very useful in the classroom. Instead, the design team decided to use music as the central analogy for understanding electricity. Like electricity, music is not matter, but it can be a source of energy, at least metaphorically. To create the game *Monster Music*, the design team used an approach similar to that of game two, which combined an analogous mini-game that targeted one aspect of electricity (alignment of positive and negative charges) within a larger game narrative centered around the analogy of music as a source of energy. The premise of the game is that the player has to make musical recordings to reenergize the exhausted citizens of Harmonia, a platformer gameworld. The platformer is a widely used and popular commercial game genre dating back to Donkey Kong in the 1980s. Gameplay involves the player moving an avatar through a side-scrolling landscape of obstacles and surfaces that require jumping, ducking, and sliding to avoid danger and make forward progress. Selecting this genre was in keeping with our strategy of using game design patterns that were easily recognized by our target audience. Using these common platform mechanics, players move throughout this fanciful city looking for studios where they can make the recordings.

To record music, a player needs to complete an alignment puzzle mini-game in which they have to turn monster musicians situated in a grid in different directions so that they are holding hands (Fig. 7). Each monster has an open and closed hand, representing positive and negative charges. Before they are properly aligned, each monster makes a noise, but the sounds are incoherent. When the monsters are aligned, they make recognizable music together. Monsters were chosen as characters mainly on the basis of visual appeal, as many movies and children's media use cartoon monsters to represent strange but non-threatening forces. We thought this would work well for the premise of organizing a group of unruly musicians.

Our final game dealt with the misconception that cold can be transferred just as heat is transferred ("don't leave the refrigerator door open, you'll let out the cold!"). By the time this game was developed, the iPad had replaced the DS as a popular small, portable device, so we decided to develop the game for that platform. The larger touch screen of the iPad made it possible to create a navigation game with

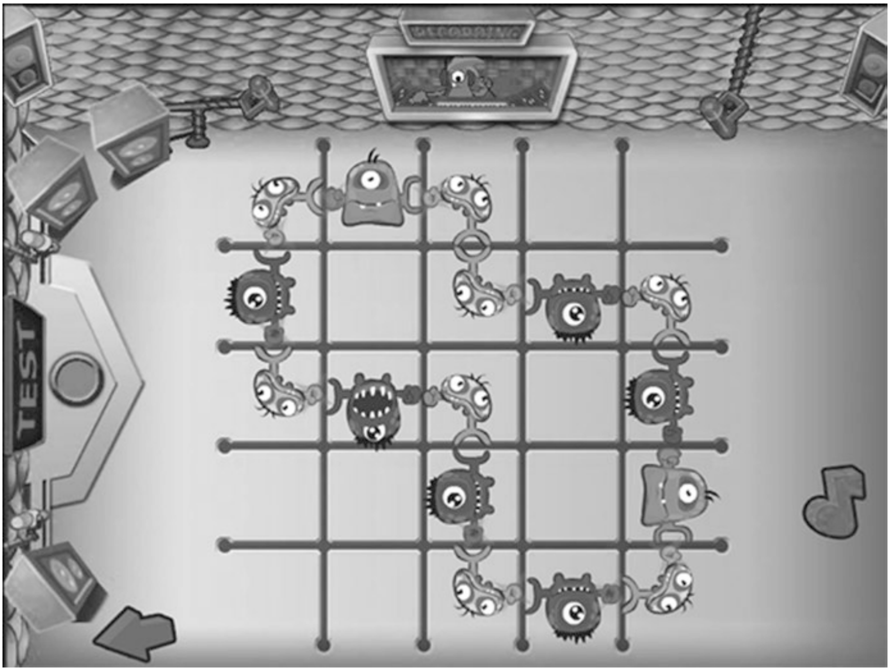

Fig. 7 *Monster Music* alignment puzzle

many different obstacles and places to move on a single screen, which would not have been possible on the smaller Nintendo DS screen. In addition to having more visual real estate to work with for game four, we also abandoned the notion that we needed analogous mini-games to visualize the concepts within the larger game narrative. Instead, with this game, *Galactic Gloop Zoo*, our design team had figured out how to move players through a leveled world that structured repetition of challenges analogous to heat transfer that were embedded in the narrative. We created a game with a story that centered on the need to distribute heat to achieve game goals by moving avatars around the screen and gaining and losing heat via radiation, convection, and conduction (Fig. 8).

The player is a zookeeper who cares for Gloops, blob-like creatures that interact with each other and the zookeeper avatar and have specific abilities that are activated based on their temperatures (which are indicated by color and animation). The player must solve each puzzle-based level by transferring heat energy to different Gloops using the three types of heat transfer. Visual cues such as arrows show that heat moves from a hotter object to a colder one, but not from colder to hotter, until the two objects reach thermal equilibrium, and the player can see the temperature of the avatar increase or decrease depending on what it is touching and for how long. As each level becomes more challenging, the player must make more precise temperature adjustments and strategically change the temperatures of the avatar and Gloops to solve puzzle challenges and achieve game goals. The final objective of

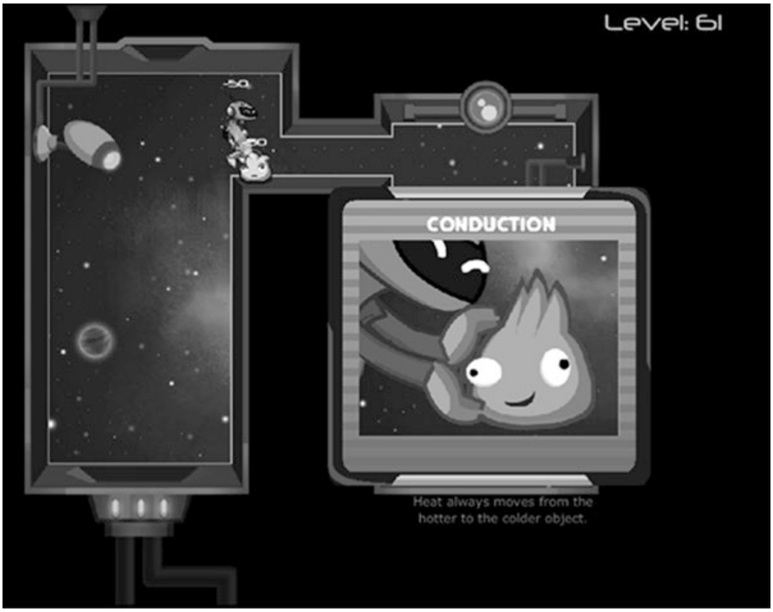

Fig. 8 *Galactic Gloop Zoo* screen showing conduction

each level is to raise or lower the temperature of an incubating egg so that it will hatch a group of baby Glooplings. With Galactic Gloop Zoo, our design team finally realized that we could create a compelling game narrative that itself was analogous to a challenging science concept, with game goals and strategies that required players to build a deeper understanding of that concept, rather than using analogous mini-games as the instructional tools within a more entertaining game narrative.

The Evolution of the Design of the *Possible Worlds* Instructional Materials

As noted above, from the very beginning we intended to create instructional materials to go along with the digital games to help teachers integrate them into their classroom teaching. This design decision was based on our years of experience working with teachers to use technology and our understanding (also reflected in the research literature) that children need scaffolding from adults in order to make sense of and learn from media-based experiences. Therefore, once the design team had a good sense of what each of the digital games was going to be like, the instructional designer and science expert, with input from teachers who participated in the early formative testing, created instructional sequences that included what we called "linking activities" to be used in conjunction with the games. The sequences stipulated the order in which certain components of instruction should occur and suggested ways to connect the game to the concepts. In our original sequences, we had students play the game as homework before receiving instruction about the subject matter. After students played the game, teachers then taught the subject matter the way they normally did. Afterward, they had students do a linking activity we provided that addressed the target concept, but which was a more typical classroom activity that did not involve technology. We incorporated linking activities in order to provide teachers with an experience that they could draw upon to explicitly connect the game analogy to the science concept it was intended to address. For example, in the case of *The Ruby Realm* photosynthesis game, we provided a kinesthetic activity in which students played the role of atoms forming water and carbon dioxide and then breaking up and reforming into glucose and oxygen. This activity allowed students to embody the exact process that they engaged in when they did the mini-game in which they broke apart water and carbon dioxide with light and put the atoms together to make glucose and then to talk about and make sense of the process together through classroom discussion.

We created other teacher support materials to encourage teachers to make references to features of the digital games during instructional time. We gave teachers instructional PowerPoint presentations that provided an overview of the specific target concepts that we addressed in the digital games. We also made it easy for teachers to share and reflect on specific visuals from the games. Because the first three games were designed for the Nintendo DS, a small handheld game console, they could not be projected to view as a class. It was also logistically unrealistic for teachers to have students open up the games and navigate to specific screens to support discussion. To respond to this challenge, we developed a web-based Flash version of the core mini-games that could be easily displayed for whole-class discussion.

We also knew that teachers needed to be very familiar with the specifics of the game in order to have the fluency to integrate them into instruction. This fluency would come from having time to play the game. We addressed this need by building a substantial amount of time (30 minutes) into the professional development for teachers to play the game. Therefore, even if they did not play the game again, we believed they would still be familiar enough with it to see how it related to the science concepts. In addition, the professional development demonstrated how the game images and mechanics were connected to concepts presented in the instructional PowerPoints.

We field-tested all four of our games and the related instructional materials in middle-school classrooms and conducted a randomized controlled trial (RCT) of *The Ruby Realm* (Culp, Martin, Clements, & Presser, 2015). We provided teachers with the games, handheld devices, linking activities, instructional sequences, and professional development. We designed our field test and RCT to collect evidence of whether and how teachers used the game and linking activities to make connections between the game analogies and instructional content and how students responded to the games and activities.

In the field tests and RCT, students reported that the games were fun (although not quite as fun as their favorite commercial games), and most played them to high levels, although up to 22% in the RCT did not play the game as homework; this may reflect a lack of interest in the game or the proportion of students who do not do homework in general. A critical finding was that the games were technically reliable and bug-free. However, we also learned that our instructional materials had not scaffolded discussion of the analogies between the games and science concepts. Teachers rarely referred to the game during instruction, and if they did, it was primarily to ask the students if they liked the game. A third important finding from this study related to student learning. Specifically, the results of the RCT found that student learning was moderated by teacher instructional quality—students who played the games did not learn more compared those who did not play the games unless they were taught by a high-quality teacher. This finding suggested to us that what needed changing was not the games but the instructional surround.

Instructional Material Design Guided by a New Theory: Analogy Mapping

The findings from the RCT and the field tests led us to a second project, funded by the National Science Foundation (DRL-1252382) that focused on the games that addressed topics related to energy transfer (*The Ruby Realm*, *Monster Music*, and *Galactic Gloop Zoo*). We investigated how to design materials and professional development that help teachers make more explicit connections between digital science games and science instruction. Because the *Possible Worlds* games were designed to be analogous to science concepts, we turned to the research literature to identify effective ways to support student learning with analogies. Most relevant was the research of Gentner and colleagues about analogical reasoning (1983, 1997, 2003, 2010, 2012) and Reese (2009) framing gameplay as the source for a series of relational analogies to be mapped to target concepts during instruction. However, our own research showed that creating digital games that were analogous to science concepts did not mean that teachers would reference them during instruction. To help us create better scaffolding materials for teachers, we drew upon the work of Richland, Zur, and Holyoak (2007), which offered practical guidance. Their research identified seven techniques teachers use to map analogies effectively during instruction:

1. Use a familiar source analog to compare to the target analog being taught.
2. Present the source analog visually.
3. Keep the source analog visible to learners during comparison with the target.
4. Use spatial cues to highlight the alignment between corresponding elements of the source and the target.
5. Use hand or arm gestures that signal an intended comparison.
6. Use mental imagery or visualizations.

Building upon this and later work by Richland and colleagues (Richland & Simms, 2015; Vendetti, Matlen, Richland & Bunge, 2015), and the guidance of Richland, who served as an advisor on this project, we redesigned the instructional sequences and created new instructional materials. One important difference in this project was that the games were now more easily accessible for a typical school. During the last year of the original *Possible Worlds* project, we transferred all of the games to Flash and created a website that made all of the games and instructional materials freely available. In addition, based on our finding that 22% of students did not play the game at home, we decided not to ask teachers to use the game as homework as we had done under the prior design, but rather had students play the game in class—before and after instruction in the science content. We provided professional development that focused specifically on the analogy mapping instructional techniques that Richland described. We also created two sets of PowerPoints that used game visuals to anchor student discussions about the games and analogies. The first PowerPoint was used after gameplay and gave students and teachers a chance to debrief about what they did in the game and to cement students' understanding of the game mechanics and goals. The second PowerPoint was used after science instruction and scaffolded analogy mapping between the game visuals and visuals showing the target science concepts. We placed the analogy mapping sequence after instruction based on feedback from Richland and other advisors, who noted that students would need some prior knowledge about the topic in order to make the analogies between the games and the concept of focus. We pilot-tested all of these materials with middle-school science teachers and students in low-income public middle schools and tweaked them over the course of the year based on teacher feedback and observations of classrooms and student interactions with the materials. We then conducted an exploratory comparison study in 11 classrooms in low-income communities. We found that the training and materials we provided helped teachers reference the analogies in their instruction (Fig. 9). Treatment teachers incorporated almost six times as many analogies as comparison teachers. We also found that students in the treatment classes performed better on assessments of energy transfer and electricity, suggesting that these techniques show promise in helping students learn the science concepts and overcome the misconceptions the games were designed to dislodge (Martin, Silander, & Rutter, 2019). We did not find that student assessment scores varied based on teacher quality, suggesting that the professional development and materials designed to scaffold analogy mapping enabled a wide range of teachers to integrate digital games effectively into instruction—in contrast to the findings from our previous design.

Fig. 9 Teacher using analogy mapping technique

Lessons Learned over Ten Years of Game and Materials Design and Development

This multiphase effort to help students overcome science misconceptions has provided us with important lessons about digital game design and the design of instructional materials to support the integration of games into instruction that our team will apply to future efforts.

Science can provide compelling rule systems for gameworlds Our team started this endeavor with the idea that digital games could help students dispel misconceptions in science because they encourage players to open their mind to new “possible worlds” that present novel challenges to overcome. We felt that it was essential that the games engaged students and that a compelling narrative was central to this engagement, particularly to hold their interest for sufficient time to support learning. We used the affordance of popular games to create fanciful visualizations that were analogous to difficult science concepts, thus opening up students’ minds to the possibility of a world in which those analogous concepts hold true (in fact, the real world at the molecular level). However, in the beginning we were not confident enough in this theory to design a whole game around an analogy. Instead, we used mini-games that students had to play repeatedly to achieve game goals as the analogy source. These mini-games were situated within more conventional recreational game narratives and mechanics that we thought were necessary to actually engage middle-school-aged players. Over time, however, we became more comfortable with our design team's ability to make analogous visualizations that were both scientifically sound and narratively compelling. Similar to the experience reported by the team that created the Surge game series (Clark et al., 2016), we discovered that creating a "true game" that can achieve educational goals does require that we value imagery and mechanics found in popular recreational games over disciplinary representations of science concepts. We always held to the premise that digital game visualizations were good source analogies to target science concepts, but by game four we discovered that, in fact, a science concept such as heat transfer can serve as the basis of a rule system for a compelling gameworld, not just a mini-game within a conventional gameworld with more familiar rules, rewards, and obstacles.

Provide teachers with instructional materials and professional development that explicitly demonstrate how to integrate digital games into their teaching The design challenges we had to address to achieve our intended outcome of helping students dispel misconceptions were not limited to game design issues, but also encompassed the design of instructional materials and professional development experiences for teachers. From the beginning, we knew that students needed support to connect the game to real life in order to learn. However, our strategies changed over time. Our first attempt was not successful because we gave teachers all of the ingredients to make those connections except the most important part—the actual analogies. When we redesigned the instructional materials we asked ourselves, what analogies do we wish the teachers and students had made? Then we created instructional materials that, in fact, included those specific analogies, designing presentations that also included the visual supports necessary for teachers to use the analogy mapping techniques described by Richland and colleagues and that supported student discussion to further scaffold learning. Providing such explicit materials did not limit teachers' creativity. We saw teachers use a wide variety of teaching styles using these materials, from question and answer sessions, to small group work, to students coming to the board to point out connections.

This 10-year enterprise of iterative design, development, research, and redesign started with the ambitious goal of helping middle-school students overcome persistent science misconceptions. The reason the misconceptions persist (often into adulthood) is because standard science instruction does not dispel them. Innovative techniques are required for students to learn these difficult concepts. In the beginning, we thought that digital games designed to be analogous to science concepts, and instructional materials connecting the game visualizations to the concepts, could be the innovation that helped address this problem. What we found was that even carefully designed games and materials are not likely to have an effect on students unless they are purposefully leveraged by teachers as part of an explicit process of building robust understanding of complex concepts through gameplay, discussion, instruction, and reflection. Such work required innovative teaching and professional development combined with innovative digital game and materials design and the contributions of designers, developers, storytellers, researchers, and many educators and students along the way.FundingThis work was generously supported by the US Department of Education's Institute of Education Sciences (Award # R305C080022) and the National Science Foundation, Division of Research on Learning in Formal and Informal Settings (DRL-1252382).

References

Barab, S. A., Sadler, T. D., Heiselt, C., Hickey, D., & Zuiker, S. (2007). Relating narrative, inquiry, and inscriptions: Supporting consequential play. *Journal of Science Education and Technology, 16*(1), 59–82.

Blumenfeld, P., Fishman, B. J., Krajcik, J., Marx, R. W., & Soloway, E. (2000). Creating usable innovations in systemic reform: Scaling up technology-embedded project-based science in urban schools. *Educational Psychologist, 35*(3), 149–164.

Chi, M. T. (2008). Three types of conceptual change: Belief revision, mental model transformation, and categorical shift. In S. Vosniadou (Ed.), *Handbook of research on conceptual change* (pp. 61–82). Hillsdale, NJ: Erlbaum Associates.

Clark, D., Virk, S., Sengupta, P., Brady, C., Martinez-Garza, M., et al. (2016). Surge's evolution deeper into formal representations: The siren's call of popular game-play mechanics. *International Journal of Designs for Learning, 7*(1), 107–146.

Culp, K. M., Honey, M., & Mandinach, E. B. (2005). A retrospective on twenty years of education technology policy. *Journal of Educational Computing Research, 32*(3), 279–307.

Culp, K. M., Martin, W., Clements, M., & Presser, A. L. (2015). Testing the impact of a pre-instructional digital game on middle-grade students' understanding of photosynthesis. *Technology, Knowledge and Learning, 20*(1), 5–26.

Driver, R., Squires, A. R., Rushworth, P., & Wood-Robinson, V. (1994). *Making sense of secondary science: Research into children's ideas*. London: Taylor & Francis, Ltd..

Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences, 8*(3–4), 391–450.

Gee, J. P. (2007). *What video games have to teach us about learning and literacy* (2nd ed.). New York: St. Martin's Griffin.

Gentner, D. (1983). Structure mapping: A theoretical framework for analogy. *Cognitive Science, 7*(2), 155–170.

Gentner, D. (2010). Bootstrapping the mind: Analogical processes and symbol systems. *Cognitive Science, 34*(5), 752–775.

Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology, 95*(2), 393–408.

Gentner, D., & Markman, A. B. (1997). Structure mapping in analogy and similarity. *American Psychologist, 52*(1), 45–56.

Gentner, D., & Smith, L. (2012). Analogical reasoning. In V. S. Ramachandran (Ed.), *Encyclopedia of human behavior* (2nd ed., pp. 130–136). Oxford, UK: Elsevier.

Honey, M., Culp, K. M., & Carrigg, F. (2000). Perspectives on technology and education research: Lessons from the past and present. *Journal of Educational Computing Research, 23*(1), 5–14.

Ketelhut, D. J. (2007). The impact of student self-efficacy on scientific inquiry skills: An exploratory investigation in River City, a multi-user virtual environment. *Journal of Science Education and Technology, 16*(1), 99–111.

Martin, W., Silander, M., & Rutter, S. (2019). Digital games as sources for science analogies: Learning about energy through play. *Computers & Education, 130*, 1–12. https://doi.org/10.1016/j.compedu.2018.11.002

Ozay, E., & Oztas, H. (2003). Secondary students' interpretations of photosynthesis and plant nutrition. *Journal of Biological Education, 37*, 268–270.

Reese, D. D. (2009). Structure mapping theory as a formalism for instructional game design and assessment. In D. Gentner, K. Holyoak, & B. Kokinov (Eds.), *New frontiers in analogy research: Proceedings of the 2nd international conference on analogy (Analogy '09)* (pp. 394–403). Sofia, Bulgaria: New Bulgarian University Press.

Richland, L. E., & Simms, N. (2015). Analogy, higher order thinking, and education. *Wiley Interdisciplinary Reviews: Cognitive Science, 6*(2), 177–192.

Richland, L. E., Zur, O., & Holyoak, K. J. (2007). Cognitive supports for analogy in the mathematics classroom. *Science, 316*(5828), 1128–1129.

Smith III, J. P., diSessa, A. A., & Roschelle, J. (1994). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences, 3*(2), 115–163.

Squire, K. (2006). From content to context: Videogames as designed experience. *Educational Researcher, 35*(8), 19–29.

Vendetti, M. S., Matlen, B. J., Richland, L. E., & Bunge, S. A. (2015). Analogical reasoning in the classroom: Insights from cognitive science. *Mind, Brain, and Education, 9*(2), 100–106. https://doi.org/10.1111/mbe.12080