# Using Students' Naïve Theories to Design Games for Middle-Grades Science

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## Abstract

This paper reports on one phase of a long-term research and development project that is creating video game modules for middle-school science classrooms. The games are intended to help teachers address common scientific misconceptions by providing students with opportunities to interact with visualizations of otherwise abstract or inaccessible concepts or phenomena that are the source of those misconceptions. The visualizations serve as metaphors for natural phenomena, and linking activities help teachers build connections between the visualizations and the targeted concepts. Findings presented here are derived from formative research conducted to inform the development of a game and associated classroom materials that address genetics and heredity. The paper discusses how teachers in our sample typically teach this material in seventh grade, student expressions of common misconceptions about genetics and heredity, and how an initial design for the game responds to and addresses those misconceptions. Students' misconceptions were associated with the concepts of randomness of inheritance, gene expression, and natural selection.

## Introduction

This paper reports on emerging findings from a five-year program of research and development funded by the U.S. Department of Education's Institute of Education Sciences. Education Development Center's Center for Children and Technology (EDC/CCT) is conducting this work, the goal of which is to create and assess a series of four game modules that support middle-school science and literacy learning. Collectively known as *Possible Worlds,* each game module consists of a game on the Nintendo Dual-Screen handheld game console (DSi) and classroom activities that draw connections between the DSi game and existing science curricula.

The particular affordances of mass-market games are different from those of other technologies that can be used to support education. Games motivate students to pursue an activity repeatedly, and to build mastery through their interactions with complex systems. Games invite students to engage simultaneously with both rich narrative or visual context and detailed technical constraints and rule systems. Most importantly, games invite students to *play*—to become an active part of a dynamic system that, by definition, motivates both exploration and progress toward greater knowledge or broader experience within the game world.

A core mission of this project is to explore how to make these potential values of digital games broadly useful to traditional classroom-based teaching and learning. We are pursuing this goal with a focus on particularly difficult concepts taught in middle-grades science and on the needs of teachers who are willing to devote some class time to create innovative or resource-intensive classroom experiences. We are also designing with an eye toward the common teacher practice of "cherry picking" bits and pieces from large curriculum sequences by making modules that work as *supplements* to widely adopted middle-grades science curricula.

Each of the four game modules is designed to address common misconceptions about a particular science topic. The first is about photosynthesis and chemical change, the second is about genetics and heredity, the third is about electricity, and the fourth has not yet been specified. The findings discussed here describe one portion of the early research conducted to inform the development of the second module on genetics and heredity.

Before detailing this research and its findings, a description of our game design approach and theoretical underpinnings is necessary.

## Instructional Approach

Our approach to designing the game modules involves focusing on the aspects of a science topic that give students the most trouble. We ask:

- How is the subject taught?
- What aspects of the domain are most difficult for students to grasp?
- What misconceptions do students bring to or take away from instruction?
- How can we design a game and supporting materials to support teachers' efforts to instill in students a true understanding of the most complex science concepts?

Our efforts to address these questions begin with two strands of formative research. The first involves in-depth interviews with teachers to identify their content priorities within a particular scientific domain, strategies when teaching the target content, and concepts they find are most difficult for students to grasp. The second engages students in hands-on activities and one-on-one discussions that elicit their theories and misconceptions about the topic.

Insights drawn from this exploratory research, as well as reviews of the existing research based on teaching and learning in this content area, are shared with the game development team. This team then can begin to design an instructional core for the game that responds directly to one or more of the central misconceptions students harbor. Further rounds of formative testing and elaboration and revision of the game design follow.

The goal of this process is to create games that give students opportunities to interact with a visualization of a complex science concept about which they have a persistent misconception. The visualization is not expected to teach the content, in the sense that it does not deliver explicit information or ideas, or guide students through the process of building, recognizing, and consolidating a new understanding of the phenomenon in question. Rather, the visualization is part of the game mechanic—something a player does to keep playing, and whose function in the game is clear. The games provide repeated opportunities for students to interact directly with the visualization, and at times to construct them rather than merely to inspect them visually. The games require about an hour of play to complete and to internalize the important elements of the key visualization. The teacher's role in implementing a module is to provide scaffolding and guidance to help students explore the visualization as a metaphor for the targeted natural phenomenon.

In short, the games are designed to serve as "metaphor primers." Bransford and Schwartz's (1999) "preparation for future learning" (PFL) model effectively frames our thinking—educational interventions are followed by a form of direct instruction, which should increase the likelihood of transfer. In the PFL framework, activities "set the stage" for learning with direct instruction by providing students with experiences from which they can draw to make sense of subsequent material. In *Possible Worlds*, games are designed as analogs to abstract, scientific concepts, furnishing teachers and learners with experiences they can draw upon to frame and make sense of challenging concepts.

The PFL model does not adequately account for the quality of the direct instruction, however. That is, in order to increase the likelihood that learners make connections between the game as a metaphor and the targeted concepts, teachers will 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; Venville, 2008). Beyond the game, additional materials are designed to assist teachers in helping students make those connections. Additionally, curriculum linking activities are designed to help teachers engage learners in making playful use of the new conception (as opposed to the initial misconception), to reflect on its import, and to consolidate their understanding.

Our rationale for our game development approach can be summarized as follows: games can provide students with concrete experiences of abstract concepts and phenomena in a playful, motivating environment. For those experiences to coalesce into functional mental models that enable learners to counter the intuitive pull of scientific misconceptions, teachers must make explicit connections between the game play experience and normal classroom instruction in order to help students visualize and develop concrete analogies between the game's features and those of the target concepts.

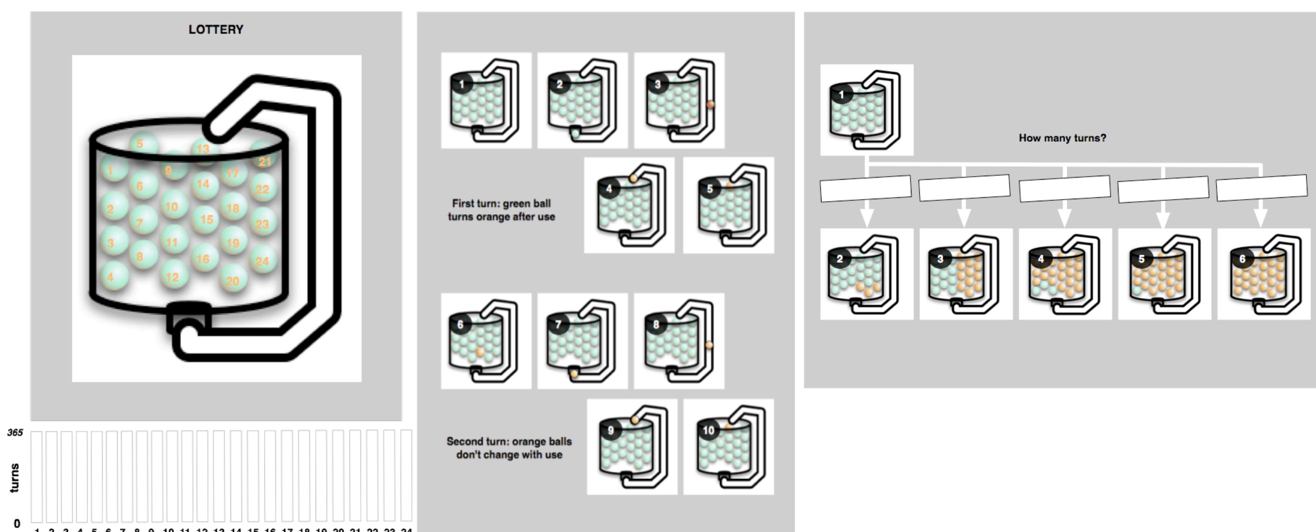
## The Current Study

The purpose of the research initiated in spring 2010 was to identify core aspects of student misconceptions to prioritize in the design of the second module, which focuses on genetics. The first step in this process involved two strands of formative research. The first involved in-depth interviews with teachers to identify their content priorities, instructional strategies, and areas where they felt additional support and approaches were needed when teaching genetics. The second strand engaged students in hands-on activities and one-on-one discussions that elicited their theories about three topics related to genetics—heredity, adaptation, and randomness—in order to identify the persistent misconceptions upon which to base the Module 2 game and teaching materials.

To elicit students' theories relating to heredity and adaptation, for example, we presented images of relatively obscure animals such as the Leaf katydid and Stick bug, shown below.

We asked students to describe the physical characteristics of the animals and asked questions that elicited their theories about the animals' likely living environments and behaviors, as well as the origins of and reasons for their unique physical characteristics. Questions also prompted them to predict how those individual animals and those animal species may respond to environmental changes (e.g., "If all of a sudden the leaves of all the trees became red, what do you think would happen to the Leaf katydid?;" "Now let's imagine that a few thousand years passes in which Leaf katydids are living in this environment with red leaves. What do you think katydids in that future time would look like?").

While the activities such as the one just described also relate to the concept of randomness, we correctly anticipated that we would need to address randomness more directly in order to elicit students' theories about it. To do so, we developed an activity involving a hypothetical daily lottery in which one ball out of 24 is selected randomly from a container each day for one year (each ball is labeled with a number from 1–24). Once a ball is selected, it turns from green to orange and is put back in the container. It remains orange even if it is picked again.




Students were asked questions to predict how many times each ball would be picked over the course of the year, as well as how many days would have to pass for three, 12, 20, 23, and 24 balls to turn orange. We intended for these questions to elicit students' ideas about whether past outcomes (whether one particular ball was picked) influence future outcomes (whether that ball would be likely or unlikely to be picked again). This issue of randomness relates to genetics in that, contrary to what we knew to be common beliefs among kids and many adults, genes are equally likely to be inherited regardless of whether they are dominant or recessive.

The spring 2010 research took place in three afterschool settings—two in New York City and one in a New Jersey suburb. Afterschool sessions included an average of six sixth- and seventh-grade students, with a total of 18 active participants. Sessions were held twice weekly, with four one-hour sessions dedicated to genetics topics occurring at each site. Four science teachers participated in individual one-hour interviews, which took place before or after student sessions.

## Research Findings

Teachers spent anywhere from three to 16 weeks on their genetics unit during the 2009–2010 school year. Teachers who devoted several months to genetics used it as an umbrella topic with which they covered a broad set of science concepts, such as evolution, natural selection, and inherited diseases. Regardless of time spent, their content priorities converged around four central questions:

1. What is a trait?
2. How are traits passed along?
3. How do traits and the environment interact?
4. What are the biological structures behind traits?

The teachers followed similar teaching approaches to address these questions. These involved readings and a history lesson about Mendel's plant experiments, discussions and lectures about dominant versus recessive genes, and the use of Punnett squares to convey that probability and randomness determine the traits passed along from one generation to the next. To help students grasp what they feel are the most difficult concepts, teachers also used a range of hands-on activities that employed popsicle sticks (pink to represent the mother's genes and blue to represent the father's), shoes (one for mom and one for dad), and two-sided coins representing various phenotypes (one side for mom and one for dad). In a typical instantiation of these activities, the props used represent the genes. Students select two "genes" to represent the father and two for the mother. They put the four genes together and arbitrarily select one from each parent; this selection determines the trait that the offspring will have. The purpose of this activity is to communicate the ideas that the inheritance of genes is random (in this case based on their arbitrary selection), genes are passed down from both parents, and some traits are more likely to appear in offspring than others.

While the teachers believed that their instructional approaches conveyed the central concepts to some students, they felt most learners came away from the genetics unit with short-term, surface understandings or, worse, the same misconceptions they started with. As one teacher put it, "Genetics is still tough for kids to understand." She expressed doubt that her use of Punnett squares and physical objects really helped students visualize the abstract concepts or be able to apply any understanding of genetics developed from those activities: “I don’t know if they can apply the Punnett square stuff to other situations. If you were to ask a kid from this program why we did Punnett squares, I’m pretty sure they wouldn’t be able to tell you…It’s not the math, that’s not the problem. It’s that it’s showing something that is physically passed down from generations. They don’t equate the nice letters that represent the genes with the actual physical gene that’s passed down.” Because the teachers we spoke with recognized limitations in their current approaches, they responded enthusiastically to the idea of a game and supporting materials to help students visualize complex genetics processes.

The persistent genetics misconceptions that emerged from our formative work were consistent with other research on children’s understanding of genetics. However, to inform design decisions we needed to understand not only what students do *not* understand accurately, but the quality and character of their *mis*understandings. This is why conducting our own interviews and asking students to respond to various scenarios was so important.

Interactions with students during this formative work revealed that, despite having completed the genetics unit, most held onto several misconceptions. One misconception was demonstrated most often when we asked kids to look at the following images and predict the features that a child of this couple would have:

Looking at these images, one boy said, “From him it gets the skin and nose and hair…and from her the skin, her eyes, her eyebrows and mouth.” The student guessed that the child’s skin color - the only trait that would come from both parents - would be “the average” of that of the man and woman. Other students theorized that the relative strength of a parent’s genes dictates what traits get passed down. According to one boy, “If the mother’s genes on her nose are stronger than the father’s genes, then the child’s nose will be like the mother’s nose. If the father’s genes on his nose are stronger, then the child’s nose would be like the father’s nose.” Other students believed that the same-sex parent would pass on more of his/her traits to the child. A student articulated, “If it’s a boy then the first kid will look like the father. With the second kid, she would look like half the mother and half the father.” These comments reveal the common belief among these students that genes for certain traits come from only one parent; we either get that parent's observable trait or we do not have that gene.

A second misconception was most evident when students responded to questions based on the following images:


Students were told that the image on the left represented one generation of beetles and the image on the right was that species 10 generations later. We asked them to explain why these differences may have emerged. A student theorized that there are more green beetles in the second image "because they adapted to the background, the leaf. They got used to green stuff and so they started to turn green so they could live longer." Responses like this suggest the notion that creatures adapt to their environment by consciously changing their appearance or capacity in order to be better suited to the environment, and those useful traits would be passed along to their offspring. In this fashion, changes in the genetic make-up of a species happen quickly and in a linear, predictable fashion.

Finally, the lottery activity previously described illuminated students' theories about randomness. Recall that balls, numbered 1–24, were selected one at a time and returned to a container. When prompted to predict when and how often particular balls would be selected, a girl stated that the existence of "lucky" numbers would influence the outcome. According to this student, "I'm pretty sure out of all the numbers 1 would come out first…2 would come out like not that many times." Another student theorized, "The more the number got picked, the better the chance you get it. If 12 got picked the most, I'd pick 12." These predictions reveal a common belief among students that inherent rules, rather than a random process, would govern the selection of balls, and that past outcomes would influence future selections. These ideas, by extension, are likely to influence students' conceptions of how genes are passed down and expressed over generations.

## Game Development

During summer 2010, the research team shared findings from our work with students and teachers with the development team, which includes an instructional designer, writers, graphic designers, and game designers. This section describes the key misconceptions the team focused on and how they were initially translated into a core instructional activity and an initial game design. We conclude the section with a brief explanation of how the design and development process has continued to progress during fall 2010 and winter 2011.

The development team focused initially on four core ideas about genetics that students persistently misunderstood and about which they expressed clear but inaccurate beliefs.

1. Randomness of inheritance. Randomness is an inherently difficult concept to master and is critical to understanding genetic inheritance. At heart, randomness of inheritance refers to the principle that even though there are overall patterns in the emergence of traits across a population and over time, each individual instance is independent of the ones before it and of other instances within the same generation in a population.
2. The relationship between dominant and recessive genes. Students often believe that when a gene is dominant, it appears more frequently in the population or is expressed in an individual because the trait it represents is more desirable, stronger or tougher, or more easily reproduced than is its recessive counterpart (i.e., it is an inherent, essential aspect of the trait). For these students, as for many adults, the idea that a "dominant" gene is *more likely to be transmitted* makes semantic and even empirical sense. But actually, "dominant" is a description of a relationship rather than a characteristic; it refers only to the allele's relationship to its counterpart in heredity, rather than to the adaptive quality of the trait in an environment. Students need opportunities to play out the relationship between the random nature of individual events (inheriting a recessive or dominant gene from a parent) and the regular patterns that emerge over time and across populations. This is consistent with the experiences teachers attempt to provide students through the hands-on activities previously described.
3. The relationship between genotype and phenotype. Genes exist in pairs, one from each parent. Some are dominant and expressed in the individual, while others are recessive and may or may not be visible, but can still be passed on to the next generation. The *genotype* is the combination of these two – all of the genetic information, whether dominant or recessive. The *phenotype* is the observable characteristic of the organism. Students need opportunities to experience the range of relationships that can exist between genotypes and phenotypes, to build fluency with the idea that multiple genotypes can underlie an apparently consistent phenotype.
4. Natural selection. Certain traits enable organisms to survive and procreate under particular environmental conditions, but traits are not passed from generation to generation *because* they are valuable in the environment; dangerous traits also are passed along, and valuable traits may appear infrequently if they are recessive. Evolution of new genotypes requires many generations because it is the balance of genotypes with the valuable characteristics in the population as a whole that determines the survival of the species. It is typically difficult for students to hold in mind the time span involved in evolution, and to avoid ascribing intentionality or teleology to the process of evolution. They need opportunities to trace the emergence and recession of maladaptive traits, the interaction of emergent traits and the environment, and the passage of time during evolution in order to support the construction of a coherent understanding of this complex process.

Initial Game Concept

During the fall of 2010, the development team created an initial prototype of a game that sought to address each of these challenges. This initial design was a quest game that sent creatures out to travel through various challenges and threats. The player observed alleles combining randomly to produce creatures with different characteristics, and then sought to guide those creatures through a quest. In different settings, different phenotypes were advantageous, and over multiple generations, players would begin to observe how different characteristics led creatures to thrive in different environments.

Formative testing of this early iteration of the game showed us that tackling all of these issues within a single game was too ambitious. Among other issues, for this game to function effectively as an analogy for all four of these target concepts, players would have to attend to widely varying elements of the game. This was unrealistic to expect of students. Additionally, the management of multiple timeframes for the game (to allow players to trace the progress of individual creatures and their evolution over multiple generations) became technically difficult and beyond the scope of the project. Given the results of these initial formative tests, the development team began to create a second approach for this game.

Second Iteration of the Game

In the current (not yet final) version of the DSi game, players try to win and collect robots by entering their robots in competitions against other robot teams. The challenge is to figure out the strengths and weaknesses of their robots relative to those of their adversaries' robots.

As in the prior iteration of the game, our characters are intentionally whimsical and imaginary, which allows us to clearly illustrate the core concepts and to avoid conflating the principles of genetic heredity with broader notions about reproduction and familial relationships. The game now addresses only two of the four misconceptions we originally focused on: randomness and the relationship between dominant and recessive genes.

In this version of the DSi game, players trade, collect, and combine different types of robots. Students must figure out what kinds of robots to collect and how to combine them in order to form a robot team that is capable of overcoming a variety of challenges. In order to collect robots, the player goes to Bot Fests where owners buy, trade, and recycle robots. A popular feature of these festivals is a game in which people pit their robots against each other. Whoever wins gets to keep the other person's robot. The player pits his/her robots against others in the hopes of being able to claim and free the other robots.

Winning is determined by a simple "Rock-Paper-Scissors"-type scheme. Robots have two "work" modules and the expressed one is determined by module dominance. So, for instance, the water module (used for laundry) is dominant over the fire module (used for cooking), and the fire module is dominant over the ice module (used for smoothie-making). Players deploy their robot without knowing which type of robot their opponent has, and the winner is determined by this dominance scheme.

Players can also recycle robots in order to try to acquire a particular type of robot. They place two robots, each of which has two work modules (or alleles) into the recycling machine, and one new robot is produced. The resulting robot will contain a randomly chosen module from each of the parent robots. Depending on which two of the four work modules the robot "inherits," the player may or may not end up with the type of robot they were hoping to get.

As they play, we intend for players to become aware of how randomness and dominance affect game play, and to rely on that awareness to make decisions that will help them achieve their goals. We expect them to realize that "dominant," in this context, refers only to which work modules (traits) are expressed, because none of the traits are explicitly "better" than all others. There are situations in which each trait/work module is the optimal one.

Players will also gain an understanding of randomness and how it relates to reproduction. By combining robots through recycling, players will learn the value of a pure dominant parent, a pure recessive parent, and a hybrid parent. The game will provide a visualization for how randomness affects which work modules or traits are passed down to the next generation.

## Developmental Factors

The results of our exploration of students' misconceptions about genetic inheritance were consistent with our understanding of the developmental transitions young adolescents are moving through in the middle grades. During this period, young people are capable of considering and manipulating abstract information, but it is a difficult process that requires significant scaffolding and support. Concurrently, in middle-grades science courses, students are expected to shift their thinking away from interpreting direct experience and toward the acquisition and manipulation of abstract concepts. In this context, research by Kuhn (1991) and others has demonstrated that students resist evidence that counters their preexisting beliefs, either by ignoring it or by assimilating it into their existing knowledge, rather than allowing novel evidence to challenge their theories about how the world works. Adolescents are ripe to develop skills of inquiry and higher-order thinking, but their prior beliefs often act as obstacles to learning.

Students' preexisting theories are difficult to displace because those theories are parsimonious, have explanatory power, and are consistent with their observations of the world. Both our teacher interviews and work with students suggest that students are able to acquire procedural knowledge about difficult concepts such as genetics and heredity while also maintaining their existing misconceptions and tolerating potential inconsistencies between these two strands of knowledge. Lacking a robust and accurate conceptual understanding of the topic, they will be unable to draw accurate inferences or form effective hypotheses about new situations as they arise.

## Significance

A distinguishing feature of our approach to game design is our commitment to understand the developmental factors that contribute to students' thinking about complex scientific concepts. We embrace the following notion articulated by Bransford, Brown, and Cocking (1999, pp.14-15): "Students come to the classroom with preconceptions about how the world works. If their initial understanding is not engaged, they may fail to grasp the new concepts and information that are taught, or they may learn them for purposes of a test but revert to their preconceptions outside the classroom." Games can provide students with concrete experiences of abstract concepts and phenomena in a playful, motivating environment. With the teacher's help, these experiences can set the stage for theory revision and the emergence of true scientific understanding.

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