A Development Process Focused on Pedagogy-Centered Design

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This paper discusses the importance of instructional design to the creation of games for learning. It distinguishes instructional design — the process of defining the topics to be addressed, the form of the desired learning outcomes, and the kinds of learning activities that games will support — from game play design, and illustrates one approach to integrating the goals of these two processes.

This approach to game development is guiding the development efforts for *Possible Worlds*, one of two National Research and Development Centers on Instructional Technology funded by the U.S. Department of Education, Institute of Education Sciences. *Possible Worlds* focuses on the use of portable gaming devices to support teaching and learning about some of the most difficult scientific content, particularly persistent scientific misconceptions, and on the challenges of designing to address the developmental needs of specific age cohorts of students.

The paper illustrates this approach by describing the development of a game intended to support students' exploration of the process of photosynthesis. It presents a case for the critical importance of strong instructional design to the production of electronic games that succeed in engaging young people in thinking and learning. It argues that games can only move beyond the delivery of content knowledge to act as spaces for rich exploration, critical engagement with evidence, and true conceptual learning when game designers invest in detailed instructional design prior to initiating the game design process.

Pedagogy-Centered Design

User–centered design attempts to make it possible for the designers of the innovation to keep the variety of needs, interests and interpretations of the appropriate range of customers in mind when deciding among alternatives in the design process. It puts the customer's experience at the center of the formative research supporting the innovation, helping designers to remember that people's interpretation of even the most elegantly designed product or process differ markedly but, if their needs and purposes are known, always make some kind of sense.

Pedagogy-centered design is a form of user-centered design, but is more narrowly focused on educational innovation, specifically on the design of learning materials and supports. The specific pedagogical approach, the method of teaching, which we want to support with innovation, has as its core a belief in the active learning process, and in the learner's ability (and need) to construct knowledge. This process, grounded in a developmental and sociocognitive view of how learning unfolds, includes the following elements:

1. Active engagement with rich, provocative materials;
2. Materials that that enable different types of learners to make sense of them;

3. Apparently loose but carefully structured guidance of a teacher;
4. The provision of tacit and explicit structuring and supervision of the experience, both to support progress and to ensure individualization of the experience for different students.

The formative research needed to support that kind of design is specifically focused on how customers interpret the innovation so that developmentally appropriate and conceptually relevant guidance can be provided, both in the structure and content of materials and in guidance to teachers about the roles they can and should play as children interact with the resources they have access to.

A fundamental aspect of the notion of active learning is that we learn what we *do*, rather than what we are *told about,* as in the more traditional transmission model of learning. *Doing*, in this context, includes the act of interpretation, of sense-making. In entertainment games, a good deal of information is being transmitted, much of it about fantasy environments, but some of it is about important social issues. Frequently there is a disconnect, however, between the information conveyed in the narrative content of a game and the game-play action in which the player is engaged. In the most typical version of this disconnect, a loose narrative ties together a set of unrelated puzzles. In Professor Layton, for instance, a popular (and excellent) puzzle game, there is a narrative about helping someone in a town solve a mystery, but the *actions* in which the players engage to move through the game require some strategic navigation through the world but mostly solving a set of logic puzzles. The logic puzzles are not integrated, that is, the problem to be solved in the puzzle bears no real relationship to the point in the narrative at which it is encountered.

In some games there is more thematic integration. It makes sense, for instance, that get into a building, you need to know a code to unlock it □ and so you engage with a logic or skill puzzle whose solution yields that code. Sometimes the action is more directly related to the narrative, when you have to find the key by carefully examining the surrounding terrain, for instance. In that case, the activity (searching for the key by looking at places and objects) is a direct solution to the narrative problem of unlocking the door.

In educational gaming conversations, we tend to refer to both types of integration, thematic and direct, as if they were interchangeable, because both involve problem solving. The pedagogical approach underlying them is profoundly different however, both in its use of narrative and of action. Thematic integration means that students can make sense of the narrative flow, can interpret usefully what the problem is and can therefore think about what might constitute a solution. That knowledge, what you have to do to get the key, for instance, is highly prized by gamers and shared in a variety of ways. Most of the time, what makes it possible to get the code or the key, to move on in the narrative, has to do with a set of gaming skills, either speed, accuracy or timing □ or, in the case of logic puzzles, a kind of "cleverness." The need for skill means that you can get a hint from another player, but you still get to do the action and achieve the solution, the achievement is still yours.

Direct integration is a different kind of challenge for the designer. If we stay with the example of finding the key to open a door, one kind of game might encourage, even necessitate, systematic clicking on every part of the screen to "find" the key. Random clicking might produce the key more quickly than systematic clicking, of course, but if there are multiple keys to be discovered, systematic clicking is the better strategy in the long run. If we wanted this "finding" of the key to be instructive, to require planning on the part of the player, for instance, instead of trial and error, we would have to penalize the player for clicking too often. You might have to locate the key in 5 clicks, for instance, or fail to find it after multiple attempts and have to come back to the screen later. A player can try to figure out where the key can't really be, given the narrative (like floating through the air), and eliminate those areas of the screen from the search. As designers, we can challenge the player by hiding the key in a possible but not prominent place, or make the game easier by hiding the key in a more obvious place.

If we want to involve the player in some kind of "higher order" thinking, however, we have to frame the problem differently. There might be hints in some previously discovered object that eliminate some things in the current scene and the player has to make sense of that information to relate it appropriately to the current problem. Alternatively, there might be hints in the scene itself that can serve as clues for the careful player. If you know that the door recently been opened, for instance, any objects with a heavy layer of dust or spider webs on it is not likely to be where the key is hidden.

What the player is *doing*, in the latter case, is *figuring out* what the implications of the information contained in the hint are for the current problem. Clicking is the result of that action. In the example where the key can be anywhere, what the player is *doing* is *clicking*. If the narrative puts the player in the role of a detective, for instance, both types of activity are "realistic." Detectives do have to make sense of information, figure out the implications of existing clues for the next phase of the investigation and they also have to look carefully over a crime scene to identify clues. The sense-making activity is more cognitively challenging, of course, than the finding activity, both for the player and for the game designer.

A game in which there are two pictures and you have to identify the minute differences between them, for instance, might be one way to play at processing a crime scene. If the differences between the two images can be identified by systematically clicking on everything, no thinking is required. If you get a score for the number of clicks and the lowest number wins, the game is encouraging a more thoughtful approach and, if the differences are meaningful in the narrative rather than random, thinking should help guide the player make reasonable guesses and therefore get a better score. In a crime scene littered with beer cans, liquor bottles and cigarette stubs, a baby bottle might be a clue because one would not expect it to be there. A difference in the color of a beer can in the two versions of the image requires careful attention to notice, honing observation skills, but it requires no "figuring out."

Designers often talk as if they could be certain that every player plays the game as intended. In other words, if the clues in a crime scene game are reasonably meaningful – the baby bottle is, in fact, a clue – designers may assume that players will examine the scene carefully and only bother to click on possible clues rather than clicking on every beer can, for example. Unless the player is motivated by getting a lower score for clicking on beer cans, however, random, intense clicking might seem more fun to a player than careful perusal. And even if a player is fully aware that random clicking will lower the score, some players might be imagining themselves in the scene and they might decide what to "touch" and what not to "touch" based on very different criteria than the ones imagined by the designer – a squeamish player might resist "touching" garbage until every other nook and cranny has been explored, for instance.

Possible Worlds: Our Game Design Process

To create the pedagogically rich games we wanted required creating a development team that brought together three areas of expertise: game design, science learning, and pedagogy. Specifically, we needed a game shop with talented, imaginative game designers who know lots of game mechanics and can make games fun to play. We needed experts in science teaching and learning to make sure that the metaphors in the game world are congruent with the scientific concept we are illustrating and are related to persistent misconceptions in the target audience. And we needed psychologists to make sure that the pedagogy embedded in the game activities is both appropriate to the cognitive development of the target audience and supports the kind of thinking the innovation is intended to foster and support. In order to design active learning games, we needed to create an iterative process involving each expertise in turn and culminating in a set of design decisions that maximize the contributions from each expert domain.

We started with the science experts identifying the kinds of misconceptions that might arise in 7th grade science and that are particularly difficult to address because they make so much sense and nothing in ordinary life helps to dispel them, even for good students, who may learn the scientific explanation but fall back on their naïve, pre-teaching theory when confronted with a real-life situation. Our science experts decided that photosynthesis is a topic covered in most 7th grade curricula and that it is well documented that even college graduates who know the formula for photosynthesis by heart, do not use that knowledge when trying to figure out how an acorn grows into a tree. The misconception that soil is an important element in how plants make food is just too appealing to common sense: matter turning into matter makes a lot more sense than gas turning into matter.

Once the science topic and the way it is conventionally taught were identified, it was the turn of the instructional designers (in this case developmental psychologists) to identify the appropriate learning goals for each game. It was clear that even the best illustration of the process would not be enough, would not really dispel the underlying belief that the leaves of plants transform nutrients in the soil into "food." Students would continue to hold both theories and learn that this process of turning nutrients into food happens in the presence of sunlight and requires water to keep the plant alive. If pressed, students might remember that oxygen plays a role and assume that oxygen is also necessary to keep the plant alive and to perform this "nutrient-to-food" process called photosynthesis.

We knew we would need a larger concept, something that would help focus their attention on the counter-intuitive idea of the transformation of gas into matter. Relevance seemed important to motivate learners to wrestle with counter-intuitive information. The instructional designers decided that the larger concept would be the transformation of energy, making it relevant to current social concerns. We decided to "shake up" robust beliefs about nature by using a narrative about vampires, which are particularly popular with girls, and robots, which are popular with boys. Fantasy, whether a fascination with the glamorous "undead" or with futuristic technology, seemed a vehicle for shaking up assumptions by capitalizing on students' willingness to suspend disbelief, and to accept that their assumptions (their persistent beliefs about nature) may not be to the point in this game world.

The next major contribution of the collaboration between the science teachers and the instructional designers was to focus on active learning, on insisting that the player cannot be a passive observer of the phenomenon but rather has to take an active part, in this case, to *be* the energy. We considered more traditional scenarios, in which the player is a gardener or farmer trying to use a correct understanding of photosynthesis to grow more, better plants. We decided against those scenarios partly because they have been done (there are many excellent illustrations of photosynthesis) and, more importantly, because we wanted to avoid making the kind of game in which learners get an opportunity to display their knowledge, but in which they are not actually learning anything new.

Many educational games provide learners with an opportunity to study some content, transmitted to them either in the background or in the foreground of the game, and then to answer questions that, in effect, assess their knowledge of that content. One could argue that they are learning something new, new content, but we were trying for a pedagogical alternative to the transmission and assessment approach. We wanted learners to amplify the content they were encountering in their science classes (e.g., the photosynthesis formula) by experiencing the process from the inside, by *doing* photosynthesis in addition to learning about it. We wanted teachers to be able to use that shared experience – playing the game – as a form of shared prior knowledge they can refer to in their lessons about photosynthesis.

Since we understood from the science educators that students are confused about the difference between food and energy and tend to think that energy gets used up, like food, rather than that it is transformed but conserved. So we asked the game designers for a game in which the player *is* energy and *does* photosynthesis, i.e., breaks down carbon dioxide and water and produces glucose and oxygen. The game designers produced a first person shooter variant, in which the player "shoots" energy in the form of sunlight toward floating molecules. When the energy blast hits a molecule, the molecule breaks up into its constituent parts. The central parts bond with each other if they touch as they float around, released by the energy blast. When a certain number of parts have bonded into a chain, watery molecules appear and when I shoot energy at them, they also burst apart and parts of them become glued onto the chain. If the player keeps doing that, after a set number, the chain transforms into a solid and floats away. After a while, the screen gets darker and the player can now shoot oxygen from the bottom at the stately solids floating past. Each shot that finds a target adds a kind of glow to it. After several oxygen blasts, the solid breaks up into its component parts and a whoosh of energy is released, which causes the plant to flourish. If the player breaks up enough of the solids constructed during daylight, the plant that is trying to grow in the top screen grows flowers. If there are not enough solids or they are not broken up, the plant withers.

Negotiating the game

Prototype software development began in early March 2009. The team holds weekly teleconferences to enable the instructional designer, the production manager, the game designers, and the science content experts to review each new iteration of the prototype and discuss science, instructional design, game play, and visual design as a group. These calls are followed by reviews by individuals and small groups within the EDC/CCT team with the resulting comments, questions, and concerns collected by the production manager and forwarded on to the game designers.

1st Playable Productions uses the PC-based game authoring tool Game Maker (see Figure 1), that allows for visual emulation of the Nintendo DS and the interactions and mechanics of the Nintendo DS on the screen of a PC. Button functionality can be mocked-up and players use a mouse instead of a stylus on the bottom touch screen. This rapid prototyping environment makes it easy to iterate mechanics and artwork for evaluation by the designers, and play testing before coding begins on the proprietary and less flexible Nintendo development environment.

Figure 1: GameMaker DS Emulator shown on PC screen

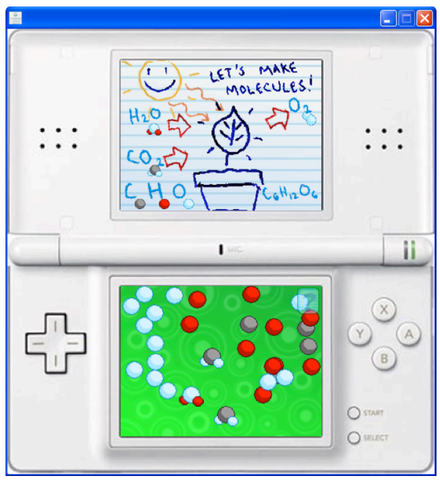
The initial production schedule called for an approximately six month development period for Module 1, with two iterations in the Game Maker environment and one iteration for Nintendo DS development for each mini-game.

The first prototype attempted was the “cell puzzle,” in which a player manipulates the process of photosynthesis on the cellular level on the touch screen and sees the effects of that manipulation on the plant in the status screen.

In the game, students direct the sun’s energy into a plant leaf. By blasting the sunlight toward molecules of carbon dioxide (a gas) and water (a liquid), they initiate the break down of these materials and the subsequent reassembly of atoms into sugar, or glucose, molecules (a solid). Later in the game, they can explore the process of respiration. By blasting oxygen molecules toward the glucose, students witness the breakdown of glucose and the consequent release of stored energy. When energy is released, students are able to see the impact on the overall health and size of the plant represented on the upper Nintendo DS screen. Through repeated manipulation of the photosynthesis process, we believe students will deepen their understanding of chemical change. They will also begin to internalize the understanding that there is no "eating" involved a plants' production of food, and that soil has no role in photosynthesis.

1st Playable's initial approach was to create a game challenge on the touch screen that was at the molecular level, where users would have to break apart CO_2 and H_20 and then re-assemble the resulting particles into glucose. Players could see feedback in the form of animations of plant health and growth on the top screen. The particles had a lively bouncing action and the challenge entailed organizing, grouping and circling needed particles with a lasso-like use of the stylus/mouse. (Figure 2)

Figure 2: First Game Maker iteration of cell puzzle



It was during the review of this first iteration that the team began to delve deeply into one of the central challenges of creating games for science education: what tradeoffs must be made in natural verisimilitude in order to create compelling game play? Careful review of science content is needed to preclude the establishment of new misconceptions, but artistic license must be allowed to simplify and amplify mechanics that can sustain player interest.

Rather than two iterations of the first mini-game, the production team went through four versions. The team encountered challenges pertaining to scientific accuracy and appropriate visual representation in the early prototypes. Creating thinking games that address concepts rather than delivery of content information on a game platform raised several key design questions that are discussed below.

Question 1: Are the game mechanics relevant to the content and the learning? E.g. does the player manually and conceptually enact a process that reinforces the phenomena being represented?

In Figure 3, an early prototype shows one carbon and two oxygen particles being circled by the stylus to combine to make $C0_2$.

Figure 3: Early iteration showing a circling mechanic to combine particles

After review, the team determined that the circling mechanic had no metaphorical connection to the energy transformation and did not really promote thinking about energy's role in photosynthesis. Figure 4 shows a later iteration of the game where a "shooting" mechanic was introduced to give the feeling to the player that they were enacting energy being directed at the particles in order to break them apart.

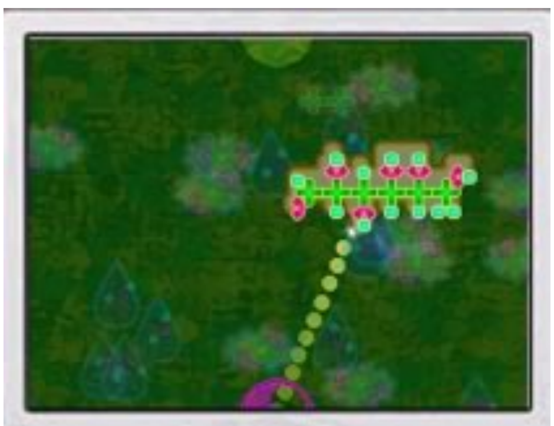
Figure 4: Later iteration showing a shooting mechanic that directs energy towards particles

Question 2: Are particles represented in a meaningful way that helps students understand the forms of matter involved in photosynthesis? E.g. Gases being transformed into solids.

After review of the early prototype (Figure 5) by the science team, we decided that students would be better served by the particles being illustrated in a way that conveyed the form of matter they represented. For instance, carbon dioxide would be shown as a cloud shape, water a droplet, and carbon as four-sided polygon shape, to represent a solid. Glucose would be shown as a collection of particles (Figure 6).

Figure 5: Early iteration showing oxygen molecules as balls and glucose represented as a sugar cube.

Figure 6: Later iteration showing glucose in a schematic form, representing how the component particles bond to form a molecule.



Question 3: Is the scale of the illustrations appropriate? Will conflicting representations of size create or reinforce misconceptions (e.g. depicting molecules visibly floating around in a cell organelle)? Does relative scale need to be consistent or realistic?

After review of early iterations, the science team decided that invisible particles could be shown as visible to reinforce the main components of photosynthesis. To a certain extent all depictions of atomic particles are conceptual and our theory is that students will be able to understand that these illustrations are not to scale. These representations will be tested with teachers and students before final Nintendo DS programming begins (see Figure 7).

Figure 7: A later prototype showing on the top screen carbon dioxide, oxygen, and water represented as visible particles in the atmosphere in order to reinforce the main components of photosynthesis.

Tweaking The Design

There are trade-offs in the game design, where the instructional designer has to mediate between the needs of the science educators and of the game designers. A few examples:

There is no real context for the inside the organelle view presented by the game.

We experimented with introductory screens that focus in on a leaf and then present a "zoom" into the cell and from there into the organelle. To make sure that players really understand the sequence, however, a lot would have to be explained. We decided that the game designers were right in worrying that it made the game too didactic and that we would take advantage of the lack of context in how we integrate the game into the conventional curriculum.

Respiration (breaking down the glucose solids) can happen during daytime, but it makes no difference if you spend the day just making glucose and all night breaking it up, as if plants do not perform respiration in the presence of sunlight.

We decided that in the interest of clarity, of helping kids understand the process that takes carbon out of carbon dioxide and combines it with hydrogen from water in a particular way to produce oxygen and glucose, and that energy from sunlight is powers that process, we would make it a stepped rather than simultaneous process but we would find some way to call the students' attention to the flaw in the game's representation of the process.

The effect of sunlight is the same all day long, making no difference between the amount of light energy available at different times of the day.

This is the kind of problem that game designers were eager and able to fix. They could speed up the shooting or provide gauges of the amount of energy available at any point.

We decided, however, that this would require an explanation, a way to make sense of the relationship between "amounts" of energy and sunlight and that it would overburden the clarity of the focus on the process of using carbon dioxide to make glucose and release oxygen. So we decided to live with the problem and find a way to help teachers discuss it in a fruitful manner.

In the end, we decided that we needed two major changes in the game: to integrate the shooter better into the narrative (about vampires, robots and energy) we would add another level, one in which the player does the equivalent to photosynthesis by helping a robot perform artificial photosynthesis, transforming sunlight into methanol and focusing on the important difference – the production of the toxic byproduct, carbon dioxide. The pedagogical point, however, was less a focus on the difference between the natural and the artificial process (though that can lead to good classroom discussions), but, instead, on their similarity because seeing two different versions of a patterns makes it easier to attend to what makes it a pattern. The use of artificial photosynthesis also creates a bridge to our fantasy content about robots and vampires and lost explorers…

We also decided that we would like a way to play the game that called no attention at all to the content, a way to turn the labels of the molecules on or off, so that students can play without ever realizing that this is in any way analogous to a natural process. The reason for this feature was that we are hoping to make it possible to integrate the game into the conventional curriculum as an example of a representation. We are designing a "teaching" process, an activity guide, which asks students to play the game "blindly" for a time and then to note down how they think it works, what it is made up of, what a winning strategy might be, etc. After an analysis of the game's components and mechanics, we would like the students to critique the game as an illustration or simulation of the process of photosynthesis about which they are learning in class. In other words, one assignment using the game would have students log their observations of the process and a second one would ask them to play again with the labels turned on and to compare those components and mechanics to what they are learning about photosynthesis and, perhaps with some guidance, discover the "flaws" in the representation or the "cheats" the game designers used.

The main reason for this way of integrating the game into conventional curricula was to address a common misconception about illustrations and simulations: that they show what it (nature, in this case) really looks/works like rather than that they are theory-based symbolic representations of what scientists think the process must be.