Digital Games and Science Learning: Design Principles and Processes to Augment Commercial Game Design Conventions

Douglas B. Clark, Stephen Killingsworth, Mario Martinez-Garza, Grant Van Eaton, Gautam Biswas, John Kinnebrew, Pratim Sengupta, Kara Krinks, Deanne Adams, Haifeng Zhang, and James Hughes

Vanderbilt University
doug.clark@vanderbilt.edu, stephenkillingsworth@gmail.com, kwarizmi@gmail.com, grant.vaneaton@vanderbilt.edu, gautam.biswas@vanderbilt.edu, john.s.kinnebrew@vanderbilt.edu, pratim.sengupta@vanderbilt.edu, kara.krinks@gmail.com, deanne.adams@gmail.com, haifeng.zhang@vanderbilt.edu, jamesh53@gmail.com

Abstract. Digital games have the potential to make unique and powerful contributions to science education efforts. Much of that potential, however, remains unrealized, partly because powerful games for science learning need to synergistically augment commercial game design conventions and principles with design principles specific to the goals and nature of science learning and research on science learning. This paper builds on earlier frameworks outlining the affordances of commercial game design conventions for learning by proposing three design principles to help students explicitly articulate the intuitive science learning inherent in good game play in terms of formal science concepts and representations. We discuss these principles in the context of our recent and ongoing work in the SURGE projects. These projects investigate effective game mechanics to help students organize their tacit understandings about Newtonian mechanics into more formalized concepts.

Keywords: Digital learning environments, prediction, explanation, scaffolding, science education

1 Introduction

Digital games provide a promising medium for science education (Clark, Nelson, Sengupta, & D'Angelo, 2009; Honey & Hilton, 2010; NRC, 2009). In 2006, the Federation of American Scientists issued a widely publicized report stating their belief that games offer a powerful new tool to support education and encouraging private and governmental support for expanded research into complex gaming environments for learning. In 2009, a special issue of Science (Hines, Jasny, & Mervis, 2009) highlighted digital games in their survey of the promises and challenges of educational technology. Much of the initial debate over digital games for science education has focused on whether or not they support learning on science in general terms. This is obviously a simplistic question; well-designed games should produce better learning outcomes than games with unsound design. The NRC report on laboratory activities and simulations (Singer, Holton, & Schweingruber, 2005) supports this view, making clear that the design of physical and virtual learning activities, rather than simply the potential affordances of the medium, determines efficacy for learning. This paper outlines design principles focusing on helping students explicitly articulate the intuitive science learning inherent in good gameplay in terms of formal science concepts and representations.

2 SURGE I: Design and Rationale

SURGE was originally funded by an exploratory NSF DR-K12 grant between Vanderbilt University and Arizona State University (Clark & Nelson, 2008). The original design goal involved developing a game that would integrate formal physics representations and concepts with popular gameplay mechanics. We built SURGE I as a multi-platform game using the Unity3D game engine (unity3d.com). The SURGE I platform was intended to investigate design approaches for connecting students' "spontaneous concepts" (i.e., intuitions about kinematics and Newtonian mechanics) with formalized "instructed concepts." The design approaches integrate (1) disciplinary representations of Newtonian mechanics and explicit connections to its central concepts with (2) popular commercial game mechanics from games such as Mario Galaxy and Switchball that include marble motion. As a result, SURGE I and SURGE II are conceptually-integrated games for learning (Clark & Martinez-Garza, in press), rather than conceptually-embedded games. The science to be learned is thus integrated directly into the mechanics of navigating through the game world, rather than being embedded as an activity to be visited at some location in the game environment. The latter structure is typically present in many virtual worlds designed for science learning.

We focused heavily on popular game-play mechanics from appropriate game genres in the design of SURGE I. Core ideas from commercial game design conventions included (a) supporting engagement and approachable entry (Koster, 2004; Squire, 2011), (b) situating the player with a principled stance and perspective (McGonigal, 2011), (c) providing context and identification for the player with a role and narrative (Pelletier, 2008; Aarseth, 2007; Gee, 2007;), (d) monitoring and providing actionable feedback for the player (Annetta et al., 2009; Garris, Ahlers & Driskell, 2002; Kuo, 2007; Munz, Schumm, Wiesebrock & Allgower, 2007), and (e) using pacing and gatekeeping to guide the player through cycles of performance (Squire, 2006). An extended review of these commercial game ideas would be outside the focus of this paper; they are discussed in full detail in the cited works and other excellent analyses of the affordances of commercial game design for learning (e.g., Annetta, 2010; Gee, 2009; Klopfer, Osterweil, & Salen, 2009).

3 Baseline Student Performance in Original Surge I Design

Students playing versions of SURGE I demonstrated high engagement and significant learning gains on items based on the highly-regarded Force Concept Inventory (FCI), which is a widely known benchmark assessment for conceptual understanding of Newtonian dynamics at the undergraduate level (Hestenes & Halloun, 1995; Hestenes, Wells, & Swackhamer, 1992). A study with 208 seventh and eighth grade students in Taiwan and 72 seventh grade students in the United States (Clark, Nelson, Chang, D'Angelo, Slack, & Martinez-Garza, 2011), for example, showed significant pre-post gains, $t(250) = 2.0792$, p (one-tailed)= 0.019, with modest effect sizes. In Taiwan, 62% of the students liked or really liked playing SURGE, 32% thought it was okay, and only 6% did not like it. In the United States, 76% of the students liked or really liked playing SURGE, 21% thought it was okay, and only 3% did not like it. These percentages were similar across gender and previous game-playing experience. These findings mirrored our findings in multiple studies conducted with different populations including: (a) 155 U.S. undergraduate physics students (D'Angelo, 2010), (b) 69 U.S. Title I sixth grade students, (c) 72 U.S. undergraduate educational psychology students (Slack et al. 2010), and (d) 124 U.S. undergraduate educational psychology students (Slack 2011). Those studies showed similarly significant pre-post gains (one-tailed $p = .001$, $p = .02$, $p = .006$, and $p = .01$, respectively).

The downside, however, was that these gains and increasing mastery focused on intuitive understanding (which is what the FCI largely measures) rather than explicit understanding. Essentially, players could more accurately predict the results of various actions, impulses, and interactions (which improves performance in the game and on FCI questions), but players were not being supported in explicitly articulating their mental models and the connections from choices made in game play to formal disciplinary representations and concepts.

Thus these results demonstrated that the players were developing intuitive rather than formal understandings while playing a game built mainly on commercial design principles. This makes sense because the goal of commercial games involves helping players develop robust intuitive understanding that helps them enjoy increasing levels of mastery as they play the game, which naturally increases their engagement and desire to play more. If players are left confused and unable to learn to play the game, or if the learning process is overwhelming or poorly structured, players will disengage, making it very unlikely that they will recommend the game to others or purchase future versions of the game. Repeated designs of this type would naturally drive a game company into bankruptcy. Thus, strong evolutionary pressures in the gaming industry favor design conventions that support intuitive understanding. There is no immediate market need, however, for commercial games to support explicit articulation or connection to formal ideas. The intuitive understandings developed at the heart of commercial games generally are not intended to correspond with important understandings outside of those games.

The use and purposes of the knowledge obtained from gameplay in commercial digital games diverge in some important respects from the goals for science education. Commercial game design conventions thus need to be augmented to meet the educational goals for science education. For learners to achieve the goals of science education, they must be supported in explicitly integrating the intuitive understanding they develop through popular game-play mechanics with formal disciplinary concepts and representations. This is a critical challenge for the design of games for science learning. How do we promote the integration of intuitive and formal learning without sacrificing the engaging intuitive learning encouraged by successful commercial gameplay?

Research in psychology, science education, and the learning sciences suggests a number of ways to support explicit articulation and integration, but the design principles developed through that research focus on contexts and mediums with different characteristics, affordances, and constraints than those of digital games. As result, in order to be synergistic rather than disruptive, these design principles from psychology, science education, and the learning sciences require adaptation and reinterpretation for the digital game medium. Two areas of research are of specific interest in our own work for leveraging explicit articulation in synergy with commercial game design conventions. These areas of research focus on enhancing (1) prediction within navigation interfaces, (2) self-explanation within game dialog.

4 SURGE II Design Approach: Prediction within Navigation Interfaces to Scaffold Model Articulation

Our SURGE II research explores the potential of leveraging the research on prediction and explanation from psychology and science education to engage students in reflecting more consciously and deliberately about the underlying physics models (e.g., Mazur, 1996; Grant, Johnson & Sanders, 1990; Scott, Asoko & Driver, 1991). Prediction and explanation can promote metacognition, learning, and reflection (e.g., Champagne, Klopfer & Gunstone, 1982) and conceptual change (Tao & Gunstone, 1999; Kearney, 2004; Kearney & Treagust, 2000). A growing body of research and scholarship on games and cognition emphasizes cycles of prediction, explanation, and refinement at the core of game-play processes (Salen & Zimmerman, 2004, Wright, 2006).

In terms of scaffolding prediction, SURGE II shifts mechanics to adapt to what we have learned from SURGE I. In SURGE II, players navigate their avatar through the play area to collect Fuzzies and treasures and deliver them to safe locations while avoiding obstacles and enemies (as in SURGE I). Rather than employing the real-time interfaces of the original SURGE grant (where pressing an “arrow key” resulted in immediate application of an impulse or constant thrust in the direction of the arrow key), the new versions incentivize prediction by requiring the player to spatially place all of the commands in advance. This feature has the advantage of requiring the player to make predictions about the results of each command in terms of the motion of the player’s avatar, rather than simply interacting reactively. Furthermore, SURGE II reduces the total number of commands a player initiates in a given level (thereby increasing the salience and impact of each individual command) to encourage players to think more carefully about the outcomes and implications of each action.

Our research with the new predictive interface to date has been promising. In our current study, 96 students played SURGE over three days. Learning outcomes were measured with an 11-item multiple-choice test of Newtonian kinematics modeled after the Force Concept Inventory and the Tennessee Comprehensive Assessment Program (TCAP) high-stakes science test. The pre- and post-test scores were compared using a two-sample paired t-test. The test showed a mean gain in test scores, from $M = 3.48$ to $M = 4.51$, and this result was statistically significant ($t = 5.184$, $p < .001$). The effect size was medium (Cohen's $d = 0.57$). Furthermore, the game was broadly appealing to students, with 92% of the respondents saying they "liked it" or "really liked it." Moreover, 80% of students considered the game appealing for both boys and girls. The sample comprised a cross-section of students who almost never play video games (40% reported playing less than two hours a week) as well as students for whom video games are a daily or near daily activity (33% reported playing an hour per day or more). These increased effect sizes encourage pushing forward with our exploration of leveraging prediction in the navigation interfaces.

5 SURGE II Design Approach: Self-Explanation within Game Dialog to Scaffold Model Articulation.

While the increased emphasis on prediction in the navigation design seems productive, the learning it promotes still focuses on making if/then predictions in the context of the consequences of different actions. We are, therefore, also exploring approaches for integrating explanation functionality into the dialog to leverage the increased intuitive grasp of the physics involved. Few games provide coherent structures for externalizing and reflecting on game-play; more often, such articulation and reflection occur outside the game, through discussion among players or participation in online forums (Gee, 2007; Squire, 2005; Steinkuehler & Duncan, 2008). We are now working to develop supports for this articulation and reflection by encouraging explanation and self-explanation in the dialog between the players and the characters within the game.

Research on self-explanation by Chi and others provides insight into the value of explanation for learning (e.g., Chi, Bassok, Lewis, Reimann, & Glaser 1989; Roy & Chi, 2005; Chi & VanLehn, in press). A recent review of research on students' self-explanation reports that self-explanation results in average learning gains of 22% for learning from text, 44% for learning from diagrams, and 20% for learning from multimedia presentations (Roy & Chi, 2005). Encouragingly, research by Bielaczyc et al. (1995) shows that instruction that stresses generating explanations improves performance even after the prompts that drive the explanations are discontinued. Mayer and Johnson (2010) have conducted preliminary work in embedding self-explanation in a game-like environment with encouraging results, including gains on transfer tasks. This emphasis on explanation is mirrored in research on science education. Work by White and Frederickson (1998, 2000), for example, demonstrates the value of asking students to reflect on their learning during inquiry with physics simulations.

Our design plan involves leveraging game dialog, which is a very popular aspect of conventional game design. Interestingly, while many aspects of commercial game design are currently very sophisticated, dialog in commercial games tends to involve relatively simple "multiple-choice" dialog trees that are not difficult to create. In fact, dialog in games is an area where educational games could take the lead. In SURGE II, after a player has completed a set of missions in the core game, a computer-controlled character in the game contacts the player and asks for help in mounting a similar rescue mission. The plan is for the resulting dialog tree to scaffold the player, requiring him or her to construct a solution for the character and to convince the character to try the solution by explaining how it fits a larger pattern of phenomena related to Newton's three laws of motion. Our goal is to present these invitations for dialog as puzzles that are engaging in their own right (Clark & Martinez-Garza, in press; Clark, Martinez-Garza, Biswas, Luecht, & Sengupta, in press). We will conduct our first studies of this approach later this year and will continue to explore its affordances for explicit articulation.

6 Bibliography

1. Aarseth, E. (2007). I Fought the Law: Transgressive Play and The Implied Player. Proceedings of DiGRA 2005 Conference: Situated Play.
2. Annetta, L. A. (2010). The “I’s” have it: A framework for serious educational game design. Review of General Psychology, 14(2), 105.
3. Annetta, L. A., Minogue, J., Holmes, S. Y., & Cheng, M.-T. (2009). Investigating the impact of video games on high school students’ engagement and learning about genetics. Computers and Education, 53(1), 74-85.
4. Bielaczyc, K., Pirolli, P., & Brown, A. L. (1995). Training in self-explanation and self-regulation strategies: Investigating the effects of knowledge acquisition activities on problem solving. Cognition and Instruction, 13(2), 221-252.
5. Champagne, A. B., Klopfer, L. E., & Gunstone, R. F. (1982). Cognitive research and the design of science instruction. Educational Psychologist, 17(1), 31.
6. Chi, M. T. H., Bassok, M., Lewis, M. W., Reimann, P., & Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. Cognitive Science, 13(2), 145–182.
7. Chi, M. T. H., & VanLehn, K. A. (in press). The content of physics self-explanations. Journal ofthe Learning Sciences.
8. Clark, D. B., & Nelson, B. (2008). Scaffolding Understanding by Redesigning Games for Education (SURGE). Exploratory DR-K12 grant funded by the U.S. National Science Foundation, 2008-2012
9. Clark, D. B., Nelson, B., Sengupta, P., D’Angelo, C. M. (2009). Rethinking Science Learning Through Digital Games and Simulations: Genres, Examples, and Evidence. Paper commissioned for the National Research Council Workshop on Games and Simulations. Washington, D.C.
10. Clark, D. B., Nelson, B. C., Chang, H.-Y., Martinez-Garza, M., Slack, K., & D’Angelo, C. M. (2011). Exploring Newtonian mechanics in a conceptually-integrated digital game: Comparison of learning and affective outcomes for students in Taiwan and the United States. Computers & Education, 57(3), 2178-2195. doi:16/j.compedu.2011.05.007

11. Clark, D. B., & Martinez-Garza, M. (in press). Prediction and explanation as design mechanics in conceptually-integrated digital games to help players articulate the tacit understandings they build through gameplay. C. Steinkuhler, K. Squire, & S. Barab (Eds.), Games, learning, and society: Learning and meaning in the digital age. Cambridge: Cambridge University Press.
12. Clark, D. B., Martinez-Garza, M., Biswas, G., Luecht, R. M., & Sengupta, P. (in press). Driving Assessment Of Students' Explanations in Game Dialog Using Computer-Adaptive Testing and Hidden Markov Modeling. In D. Ifenthaler, D. Eseryel, & G. Xun (Eds.). Game-based Learning: Foundations, Innovations, and Perspectives. New York: Springer.
13. D'Angelo, C.M. (2010). Scaffolding vector representations for student learning inside a physics game. Unpublished doctoral dissertation. Arizona State University.
14. Garris, R., Ahlers, R., & Driskell, J. E. (2002). Games, Motivation, and Learning: A Research and Practice Model. Simulation & Gaming, 33(4), 441 -467. doi:10.1177/1046878102238607
15. Gee, J. P. (2007). What Video Games Have to Teach Us About Learning and Literacy. Second Edition: Revised and Updated Edition (2nd ed.). Palgrave Macmillan.
16. Gee, J. P. (2009). Deep learning properties of good digital games: How far can they go. Serious Games: Mechanisms and Effects. Taylor & Francis Group, Routledge.
17. Grant, P., Johnson, L., Sanders, Y., & Science Teachers' Association of Victoria. (1990). Better links : teaching strategies in the science classroom. Melbourne: Science Teachers' Association of Victoria.
18. Hestenes, D., & Halloun, I. (1995). Interpreting the Force Concept Inventory: A Response to March 1995 Critique by Huffman and Heller. Physics Teacher, 33(8), 502–506.
19. Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force Concept Inventory. Physics Teacher, 30(3), 141–158.
20. Hines, P. J., Jasny, B. R., & Merris, J. (2009). Adding a T to the three R's. Science, 323, 53.
21. Honey, M. A., & Hilton, M. (Eds.). (2010). Learning Science Through Computer Games and Simulations. National Research Council. Washington, DC: National Academy Press.
22. Kearney, M. (2004). Classroom Use of Multimedia-Supported Predict–Observe–Explain Tasks in a Social Constructivist Learning Environment. Research in Science Education, 34(4), 427–453.
23. Kearney, M., & Treagust, D. F. (2000). An investigation of the classroom use of prediction-observation-explanation computer tasks designed to elicit and promote discussion of students' conceptions of force and motion. Presented at the National Association for Research in Science Teaching, New Orleans, USA.
24. Klopfer, E., Osterweil, S., & Salen, K. (2009). Moving Learning Games Forward. Cambridge, MA: The Education Arcade.
25. Koster, R. (2004). A Theory of Fun for Game Design (1st ed.). Paraglyph Press
26. Kuo, M.-J. (2007). How does an online game based learning environment promote students' intrinsic motivation for learning natural science and how does it affect their learning outcomes? Digital Game and Intelligent Toy Enhanced Learning, 2007. DIGITEL '07. The First IEEE International Workshop on (pp. 135-142). Presented at the Digital Game and Intelligent Toy Enhanced Learning, 2007. DIGITEL '07. The First IEEE International Workshop on. doi:10.1109/DIGITEL.2007.28
27. Mayer, R. E., & Johnson, C. I. (2010). Adding instructional features that promote learning in a game-like environment. Journal of Educational Computing Research, 42(3), 241–265.
28. Mazur, E. (1996). Peer Instruction: A User's Manual (Pap/Dskt.). Benjamin Cummings.

29. McGonigal, J. (2011). Reality Is Broken: Why Games Make Us Better and How They Can Change the World. New York, NY: Penguin Press.
30. Munz, U., Schumm, P., Wiesebrock, A., & Allgower, F. (2007). Motivation and Learning Progress Through Educational Games. Industrial Electronics, IEEE Transactions on, 54(6), 3141-3144. doi:10.1109/TIE.2007.907030
31. National Research Council. (2009). National Research Council Workshop on Games and Simulations. October 6-7, 2009, Washington, D.C.
32. Pelletier, C. (2008). Gaming in Context: How Young People Construct Their Gendered Identities in Playing and Making Games. In Y. B. Kafai, C. Heeter, J. Denner, & J. Y. Sun (Eds.), Beyond Barbie and Mortal Kombat: new perspectives on gender and gaming. Cambridge, Mass: The MIT Press.
33. Roy, M., & Chi, M. T. H. (2005). The self-explanation principle in multimedia learning. In R. E. Mayer (Ed.), The Cambridge handbook of multimedia learning (pp. 271-286). New York: Cambridge University Press.
34. Salen, K., & Zimmerman, E. (2004). Rules of play: game design fundamentals. 2004.
35. Scott, P. H., Asoko, H. M., & Driver, R. H. (1991). Teaching for conceptual change: A review of strategies. Connecting Research in Physics Education with Teacher Education, 71–78.
36. Singer, S. Hilton, M.L., & Schweingruber, H.A. (Eds.) (2005). America's lab report: investigations in high school science. Washington, DC: National Academies Press.
37. Slack, K., Nelson, B., Clark, D. B., & Martinez-Garza, M. (2011). Model-Based Thinking in the Scaffolding Understanding by Redesigning Games for Education (SURGE) Project. Poster presented as part of a structured poster session at the American Educational Research Association (AERA) 2011 meeting. New Orleans, LA.
38. Slack, K. Nelson, B., Clark, D. B., Martinez-Garza, M. (2010). Influence of visual cues on learning and in-game performance in an educational physics game environment. Paper presented at the Association for Educational Communications and Technology (AECT) 2010 meeting. Anaheim, California.
39. Squire, K. (2005). Changing the game: What happens when video games enter the classroom. Innovate: journal of online education, 1(6), 25–49.
40. Squire, K. (2006). From content to context: Videogames as designed experience. Educational Researcher, 35(8), 19.
41. Squire, K. (2011). Video Games and Learning: Teaching and Participating Culture in the Digital Age. New York: Teachers College Press.
42. Squire, K. D., DeVane, B., & Durga, S. (2008). Designing centers of expertise for academic learning through video games. Theory Into Practice, 47(3), 240–251.
43. Steinkuehler, D., & Duncan, S. (2008). Scientific habits of mind in virtual worlds. Journal of Science Education and Technology, 17(6), 530-543.
44. Tao, P.-K., & Gunstone, R. F. (1999). The process of conceptual change in force and motion during computer-supported physics instruction. Journal of Research in Science Teaching, 36(7), 859–882.
45. White, B., & Frederiksen, J. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. Cognition and Instruction, 16(1), 3-118.
46. White, B. Y., & Frederiksen, J. R. (2000). Metacognitive facilitation: An approach to making scientific inquiry accessible to all. In J. A. Minstrell & E. H. Van Zee (Eds.), Inquiring into Inquiry Learning and Teaching in Science (pp. 331-370). American Association for the Advancement of Science.
47. Wright, W. (2006). Dream machines. Wired 14(04).