Kong, S.C., Ogata, H., Arnseth, H.C., Chan, C.K.K., Hirashima, T., Klett, F., Lee, J.H.M., Liu, C.C., Looi, C.K., Milrad, M., Mitrovic, A., Nakabayashi, K., Wong, S.L., Yang, S.J.H. (eds.) (2009). *Proceedings of the 17th International Conference on Computers in Education [CDROM]*. Hong Kong: Asia-Pacific Society for Computers in Education.

Game-based Learning as a Vehicle for Developing Science Inquiry Skills using the Centauri 7 Learning Program

Yam San CHEE and Judy Lai Har LEE
[a]*Learning Sciences Lab, NIE, Nanyang Technological University, Singapore*
[b]*Learning Sciences & Technologies, NIE, Nanyang Technological University, Singapore*
yamsan.chee@nie.edu.sg

Abstract: In this paper, we describe how game-based learning can be used as a vehicle for developing students' science inquiry skills. Based on the theoretical foundation of the Play–Dialog–Performance model of game-based learning, we outline the Centauri 7 learning program and the learning processes that are entailed. Drawing upon a sample of post-intervention student reflections as a data source, we illustrate how enaction of the learning program challenges students' conceptions of what it means to learn physics. We also show how student how students' disciplinary and epistemic understandings are fundamentally transformed. Student learning is no longer just conceptual but also developmental. Learning is authentic as students imbibe the attitudes, values, and beliefs of scientists.

Keywords: Game-based learning, science inquiry skills, Centauri 7 learning program, Play–Dialog–Performance model

Introduction

The challenges that students face in understanding Newtonian mechanics are well known [10] [15]. While conceptual deep understanding of scientific principles and laws remains highly valued as an educational outcome, learning science through inquiry has come to characterize good science education [1]. It is increasingly recognized that science education conceived of as *learning about science* has the tendency to lead to inert knowledge [16] and brittle understanding. In contrast, a robust understanding of science can arise as the outcome of *doing science* [14] in a manner that realizes the Deweyan dialectic of action and reflection [3].

In this paper, we describe how we used the computer game, *Escape from Centauri 7*, to enact a learning program for developing students' science inquiry skills in the domain of physics. The game was developed by the Learning Sciences Lab of the National Institute of Education, Singapore. The Centauri 7 (C7) learning program comprises the game together with curricula materials and pedagogical learning processes that enact a specific learning curriculum. Students' science inquiry skills were developed in relation to the dynamics of charged particles in the presence of electric and magnetic fields.

The paper is organized as follows. In the next section, we articulate the conceptual model of game-based learning upon which the C7 learning program has been enacted. Next, we outline the C7 learning program. We then describe the research method before focusing on a sample of post-intervention student reflection data and discussing the data. It should be noted that the data reported on in this paper is a small subset of all the data collected and analyzed. Other published research findings have appeared in [8] and [17]. In the final section, we conclude the paper and highlight the significance of the findings.

1. Conceptual Model of Game-based Learning

Computer games offer a powerful alternative means with and through which student learning can be enacted [13]. However, there is no single 'best' model of game-based learning. This is so because classroom-based teaching and learning are inherently situational and local in nature. What works best will depend on what the teacher wishes to achieve and the teacher's ability to find the most appropriate means of achieving her goals. Notwithstanding, as researchers and learning designers, we are able, through design, to formulate testable models of game-based learning. These models can then be evaluated for robustness and utility against the target pedagogical objectives. Our model of game-based learning is founded upon the theoretical position of learning as a process of *becoming* [12]. This model is referred to as the *Play–Dialog–Performance (PDP) Model* (see Figure 1).

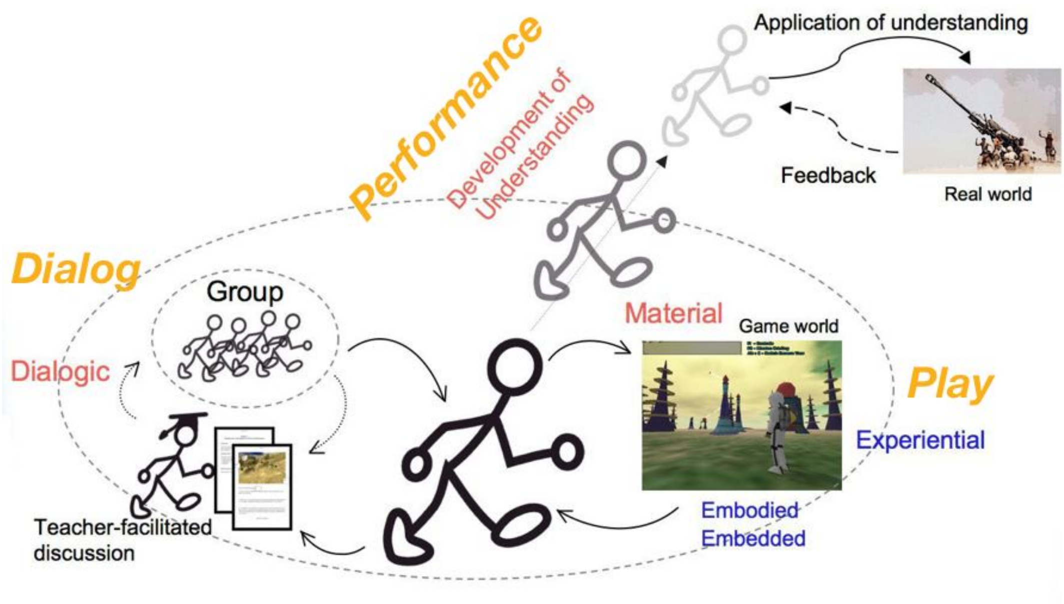


Figure 1. The Play–Dialog–Performance Model of game-based learning.

Based on our theorization, game based learning comprises (1) the Play–Dialog dialectic and (2) the Competence-through-Performance trajectory. The Play–Dialog dialectic is constituted by the interplay between (a) in-game experience in a material, albeit virtual, world, and (b) dialogic learning in a social world. The in-game experience is embodied, embedded, and experiential as described by Chee [4]. The player's sense of embodiment is achieved by means of his or her *projective identity*, an idea first articulated by Gee [6]. Arising from this projective embodiment, the player is embedded in a virtual space where the co-presence of other 'persons' (players as well as non-player characters) is deeply sensed. Joint embodiment plus embedding gives rise to in-game experience that is transactional in the sense specifically articulated by Dewey [5]; that is, students learn by doing in an environment where they act in and on the world which 'pushes back' against inappropriate conceptions and ideas by 'showing' that the ideas do not 'work' in the world. Game-play time, however, is action time, not reflection time. Students need to step back and out of the in-game experience to reflect on and take stock of the significance of all they did within the game world. In this regard, we draw upon Bakhtin's [2] notion of dialog that is enacted, as part of our learning design, at the peer group level as well as the whole class level, where the teacher facilitates the latter. The dialogic learning space allows ideas and explanations generated by students to 'rub against each other' and even to 'collide', so that contradictions and inconsistencies in meaning making can be worked through and resolved. This notion of dialogic learning goes beyond Lemke's notion of "talking science" to learn science [9].

The Competence-through-Performance trajectory denotes the cycle of repeating Play–Dialog activities, extending projectively into the future, through which students develop a deep understanding of the subject domain. Engaging in this form of game-based learning, student learning outcomes are both performative and articulatory. These outcomes are robust to real-world demands, avoiding the widespread problem of inert knowledge referred to earlier.

2. The Centauri 7 Learning Program

The Centauri learning program consists of the 3-D game, *Escape from Centauri 7* (*EC7*), designed for learning related to the concepts and principles of Newtonian Physics.

EC7 (see Figure 2) is modeled on puzzle games, where students solve puzzles of increasing complexity with each successive mission or level. In the game, students take on the role of explorers who crash-land on a deserted planet where they encounter alien technologies that produce particles and fields. To successfully complete the game, they need to make use of fields to direct particles around obstacles to reach generators that will eventually power-up a giant coil-gun. Successfully powering up this coil gun propels a distress signal into space to enable the explorers to be rescued from the planet.

Figure 2. The *EC7* interface showing representations of charged particles and fields.

To direct the path of the charged particles, students need to decide on the type of fields to use, the strength and direction of the field, and the position of the field with respect to the particles. However, they are not told which type any particular field belongs to, and the game does not assume that students already know how fields affect charged particles. In order to complete missions strategically without resorting entirely to trial-and-error, they must use their understanding of Newtonian Physics to make sense of how charged particles interact with fields. Hence, the students' challenge is to make sense of phenomena that are unknown to them through a process of inquiry involving experimentation and reasoning. To scaffold the sense-making process, activity cycles comprising game-play, small-group discussions, and whole-class forums were employed to facilitate the game-based learning experience.

During game-play, students played in groups of three and actively experimented with the use of electric and magnetic fields to control the motion of charged particles. In the process of solving various problems encountered in different game scenarios, students gained a first-hand embodied sense of how fields affected the motion of particles. Small-group discussions provided them with the opportunity to articulate their thoughts and negotiate meanings with fellow team-members before converging on generalizations that they subjected to further interrogation by other teams during whole-class forums.

An Exploration Log was used to scaffold the students' sense-making process during each activity cycle. Scenarios and discussion questions provided in the Exploration Logs drew students' attention to various key aspects of the phenomena encountered during game-play. The logs were designed to scaffold students' participation in a dialogic process that employed a scientific social language that is characterized by description, explanation, and generalization [11].

The missions in *EC7* and the Exploration Logs were closely aligned such that Physics concepts were introduced progressively at each activity cycle. In this way, students were helped to make sense of concepts and build upon them as they advanced from simpler to more challenging game levels. During Cycles 1 and 2, for example, students went through the process of investigating the effect of uniform electric fields on positively charged particles. During Cycle 3, they encountered a new type of particle that behaved differently from what they had already experienced in previous cycles. The scenario provided in the Exploration Log used in Cycle 3 (see Figure 3) established the context for the students as they examined the reasons underlying the difference in particle behavior.

As students worked through the activity cycles, they directed their own learning during game-play, small group discussions, and whole-class discussions, with teachers facilitating their learning by providing timely information and questions to guide the students' sense-making process as well as to probe or to challenge their understanding. In this way, the Centauri learning program aimed to foster in students a deeper understanding of Physics and the practice of science by engaging them in the practices and methods related to science-in-the-making used by scientists. Instead of just focusing on learning *about* science, that is, just learning the established results of science [14], the students were engaged in *doing* science as inquiry.

3. Research

3.1 Participants

The C7 learning program comprised eight class sessions. Each session lasted one hour and thirty minutes. In this research intervention, we worked with a school for boys only. The students were 14–15 year olds, and 36 students volunteered to participate in the C7 learning program as part of a subject elective within the curriculum. The class teacher also participated in the intervention. He played two roles: (1) providing just-in-time facilitation during game play and while students were dialoging within their peer groups, and (2) managing and facilitating the whole class discussion.

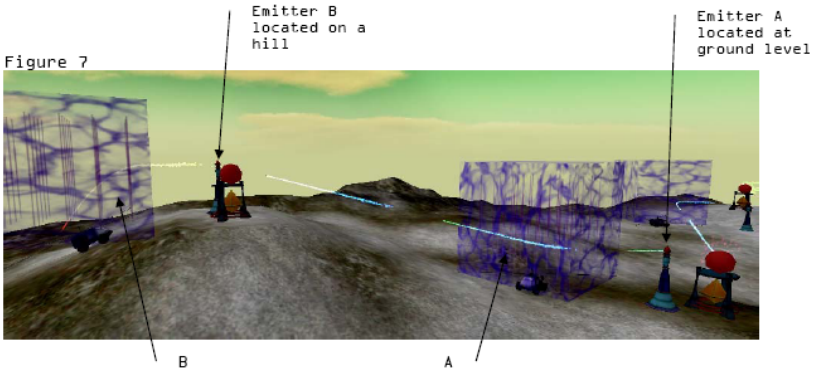
Exploration Log 3: Generalising patterns of behaviour

Log entry by (Team) Date

At every reconnaissance we conduct we uncover new phenomena or new aspects of the same phenomenon. We found ourselves modifying our hypotheses as we go along. For example, just when we thought we had figured out the behaviours of the particles, they start behaving in a way that goes against our expectations.

Scenario 3
Figure 7 shows a sky-cam shot of a situation encountered at Tergis. The behaviour of the particles in the regions labelled "A" and "B" is different even though the same type of field and similar field strengths are used. The field is directed downwards towards the ground in both regions. In this situation, particles from Emitter A travel towards the left to hit the generator powering Emitter B.

Figure 7



(a) How do I explain the difference in behaviour of the particles at "A" and "B"?

Figure 3. A scenario presented in the Exploration Log used during Activity Cycle 3.

3.2 Data Sources

We focused our data collection on four student groups. These groups were video-recorded and all their learning artifacts, including logs and presentation charts used during peer and whole class discussion, were collected. Other student groups were audio-recorded. Pre- and post tests based on an adapted version of the Force Concept Inventory [7] were administered. At the end of the intervention, all students were asked to write a reflection on their learning experience. About 20% of the students were also interviewed. As previously stated, this paper considers only the qualitative reflection pieces that the students wrote. They are used to provide the reader with a qualitative sense of the ways in which the C7 learning program impacted students' learning.

4. Student Reflections and Discussion

At the end of the learning program, students were asked to reflect upon their learning experience. Reflections from four students are shown below. These reflections were selected to illustrate a range of issues that students took up in their reflections; for example, how they understood what it means to learn Physics, the science making skills that they acquired, their thoughts about game-based learning, and their reflexive understanding of their own learning.

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Student 1:
"Personally I thought this DMP is a new experience. It provided me another view on science. Now we are no longer on the learning end, but creating our own rules, our own theories. This challenged my perception of physics. During the first session of this DMP, I was still trying to identify the field, explain the particle, and just trying to find the fastest way out, and I simply thought of it as another puzzle game. But after the first class discussion and reflection, I saw the point of this DMP. It was not to test our library of knowledge on science, nor was it to race each other to complete the level, but to learn the process of scientific inquiry, to formulate knowledge out of observations and experiences as a community. And in the subsequent logs, we were not just simply answering the questions, but taking down minor logic steps that led us to the final answer. It was not simple at first, but as we progressed, and learnt that using visuals such as diagrams to compliment our explanations, we were able finish the thinking process. This was not a game of solving puzzles, but a game of formulating observations into generalizations. Overall, I saw the other side of science and found fun in not learning what others formulated, but formulating our own science. And the creation of the manual further ensured that we were making science."

In the above reflection, DMP refers to the Direct Modular Program that allowed the students to engage in free elective subjects over a three-week period. The reflection illustrates how the student's conception of learning science changed from one based on learning facts that others had created (expressed as being "on the learning end"; that is, on the receiving end) to one of "formulating our own science" through making sense of and translating observations into generalizations within a community of learners. In effect, the student learned that science *making* arises from generalizing the stability patterns of experienced phenomena and expressing them in the form of propositional claims and assertions. He realized that "learn[ing] the process of scientific inquiry" was not about "test[ing] our library of knowledge on science". This realization marks a significant epistemological shift in grasping the socially constructed nature of scientific knowledge. With respect to learning with games, the student understood that efficiency in solving in-game puzzles was not the primary purpose of the technology. Rather, the game provided a virtual simulated space within which first-person learning actions could be executed and hypotheses could be tested. It is noteworthy that the student did not find the learning experience "simple". Nevertheless, when he grasped the pedagogical intent behind the design of the learning program, he acknowledged that he "found fun in not learning what others formulated, but formulating our own science." Thus, the experience was enjoyable and engaging despite being challenging.

Student 2:
"During these very missions I learnt important skills such as problem-solving in daily life through the application of Physics concepts. I realized that it is important to be tolerant in life with ideas presented in the group presentation and learnt that it is important to take criticism constructively. Through the group presentation I also gained confidence in my presentation skills and it also very much stimulated my mind to think further beyond the classroom. Listening to others' ideas also helped me realize that there is always a lot to learn form one's peers."

The major takeaway of Student 2 appears to be in respect of learning problem solving skills and collaborative knowledge building skills. The activity of presentation was coupled with learning to take criticism constructively. Listening to learn from peers became a valued activity because it was no longer just about hearing 'the right answer'. Rather, listening was beneficial in helping to develop a deeper understanding of a non-trivial challenge. From a developmental perspective, the student's confidence grew.

Student 3:
"I was very excited coming into this course. Playing a game to learn new concepts sounded like a great idea. Unfortunately my interest waned over time. After Lesson 7, I was thinking that all we have learnt was how two different fields work. Learning so little in 12 hours seemed like a complete waste of time. However I was enlightened in Lesson 8, where it was revealed that all along we have been discovering Physics by Inquiry. That was what differentiated this module from all the others… In short, this module was very unique, and it was an enjoyable experience to become the scientist for once."

The reflection of Student 3 stands in marked contrast to that of Student 1 above. While Student 1 grasped the rationale of the learning program's design early, Student 3 did not. This reflection highlights the importance of transforming students' implicit beliefs about learning and about the nature of knowledge. Traditional schooling leads students to believe that success in learning is all about mastery in content acquisition. But we see here that this student grasped the idea of "discovering Physics by Inquiry" belatedly. It is also evident that he valued the personal agency of "becoming the scientist for once", and this form of learning-by-becoming was an enjoyable experience for him.

Student 4:
"I find that this DMP is a pretty interesting way to learn about electric and magnetic fields. However, I find it rather unnatural to actually put down all my thoughts in ink instead of just leaving them in my head. For me, I prefer to be sure more or less before I speak out. However, this defeats the purpose of this course more or less because the focus is on the process not the result. This means that for my case the benefits is rather diminished and most of my benefits still came out of reading my textbook, unfortunately. I guess that most other people will not have this problem as my personal habit is to do more things in my mind, which also results in my abysmal primary school math results. So in conclusion, from this course, in addition to learning about the properties of EM fields, I also learn to write down whatever goes on in my mind so that it can be used for more effective checking later."

In the above reflection, we see that Student 4 wrestles with a very different kind of difficulty. It appears that he has a habit of doing things mentally ("in my head") such that the requirement for externalized representation of reasoning confronts him with quite a challenge to his customary thinking style. He also seems to be afraid of, or at least reluctant to, think out loud because of a personal preference "to be sure more or less" before he speaks out. This disposition suggests a common fear amongst students of being seen to be wrong that is cultivated in a classroom culture of constantly being required to "give the right answer." It is most encouraging, therefore, to observe that Student 4 says "I also learn to write down whatever goes on in my mind," suggesting success in overcoming the initial difficulty of externalizing thinking and also demonstrating an attitudinal shift in valuing that this externalization ability is useful for "more effective checking later."

The above data from student reflections after enacting the C7 learning program demonstrate that students' learning gains are of a much deeper nature. The learning experience is developmental in nature and at a personal level. The learning gains are disciplinary in nature, revolving around understanding science as a socially-grounded process of inquiry and sense making. Learning also entails epistemic shifts, in ways that impact deeply held values and beliefs related to personal understanding of learning itself. These learning outcomes are very powerful.

5. Conclusion

In this paper, we have described a curricula package for game-based learning that is based on the game *Escape from Centauri 7*. We have explained how the Centauri 7 learning program is theoretically grounded on the game-based learning model of Play–Dialog–Performance, or PDP. Focusing on qualitative data based on student reflections of the learning program after the research intervention, we showed how well-designed game-based learning can be applied as a transformative pedagogy to enact student learning that is impactful at a deep, personal level. In this form of learning, students are "given the space" to exercise agency in personally meaningful ways. They learn, in a deep way, that the construction of scientific understanding is a collaborative and social enterprise. Students learn to engage in the processes of science inquiry, involving observation, generalizing stability patterns of phenomena, constructing models, articulating hypotheses, testing them, and drawing conclusions from the results of testing. Students no longer learn about science. Instead, they make science by doing science. In so doing, they emulate and learn to embody the practices of scientists.

Acknowledgements

The work reported in this paper was funded by a Learning Sciences Lab research grant, number R8019.735.SG01. We wish to acknowledge Ahmed Hilmy and Liu Qiang for their work on the design and programming of *Escape from Centauri 7*. We also thank the teacher for his support and commitment and the students for their participation.

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