Learning chemistry with the game “Legends of Alkhimia”: Pedagogical and epistemic bases of design-for-learning and the challenges of boundary crossing

Yam San Chee, Daniel Kim Chwee Tan, Ek Ming Tan and Ming Fong Jan

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Learning Chemistry with the game “Legends of Alkhimia”: Pedagogical and Epistemic Bases of Design-for-Learning and the Challenges of Boundary Crossing

Yam San Chee
Daniel Kim Chwee Tan
Ek Ming Tan
Ming Fong Jan

National Institute of Education, Nanyang Technological University

1 Nanyang Walk, Singapore 637616

Email: yamsan.chee@nie.edu.sg
Abstract

Typical textbooks in Chemistry present the field as a fait accompli represented by a body of “proven” facts. In the teaching and learning of Chemistry, students have little, if any, agency to engage in scientific inquiry and to construct their personal understanding of the field. An emphasis on pre-determined “knowledge” and the execution of laboratory experiments designed mainly to confirm pre-determined “findings” can lead students to a grave misunderstanding of the nature of science.

In this paper, we report on ongoing work to design a learning environment for learning chemistry that addresses the concerns raised above. Pitched at the lower secondary school level, our game-based learning innovation, using the multiplayer game “Legends of Alkhimia”, is directed at helping students learn to imbibe the values and dispositions of professional chemists and also to think like them. Drawing on Bourdieu’s construct of habitus, we seek to foster students’ capacity for practical reason as they ‘become themselves’ via engagement in the scientific practice of doing chemistry, rather than just learning about it. We explain how our design for learning seeks to develop epistemic reflexivity and the identity of students in relation to professional chemists, as part of an ongoing trajectory of becoming.

Learning innovations invariably introduce perturbations to existing schooling practices. In bringing our learning innovation into the social milieu of the classroom, we have experienced notable challenges related to boundary crossing. In the paper, we share these challenges so that teachers and school administrators can be better prepared for the changes in mindset, values, and beliefs that enacting pedagogical innovations such as game-based learning demand.
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Introduction

Typical textbooks in Chemistry present the field as a *fait accompli* represented by a body of “proven” facts. For example, a textbook (Heyworth, 2002) used in the lower secondary science curriculum in Singapore makes the following claims:

- “Atoms are so small that nobody has ever seen a single atom. But *scientists are certain* they exist.” (p. 26, italics added)
- “*Scientists have discovered* that atoms are made up of three smaller kinds of particles — protons, neutrons and electrons.” (p. 32, italics added)
- “It’s a Fact!

In 1915, Ernest Rutherford fired particles containing protons at some nitrogen gas (atoms of proton number 7). Protons entered the nuclei of the nitrogen atoms and changed them into oxygen atoms (of proton number 8).” (sidebar entry, p. 35, italics added)

The examples above are indicative of the common rhetoric of science that revolves around assertions of fact, certainty, and scientific discovery. Students with the capacity for critical thinking would invariably wonder *why* scientists are so certain of the existence of atoms if no one has ever had the opportunity to seen an atom. The textbook author provides no explanation for his existence claim. Student questioning is also not invited. The second example makes use of authorial privilege to assert a claim that atoms, although never ever seen, are composed of protons, neutrons, and electrons. But do scientists merely *discover* this “fact”, or is the atom merely a model invented by scientists to help them explain and predict chemical phenomena and does not exist at all? The final example appeals to the textbook
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writer’s authority as subject expert to assert a factual claim concerning what Ernest Rutherford succeeded in doing. Why would a thinking student believe such a claim? How would a student even begin to conceive of firing particles containing protons into nitrogen gas? Given the extensive gaps in explanation and credibility, it is hardly surprising that students’ mastery of chemistry “facts” through memorization is associated with minimal understanding of the domain and of chemistry processes.

Overall, the presentation style reflected in the textbook is dogmatic, and it does not entertain any form of interrogation or challenge by the student reader. The underlying message is clear: “Do not question; just accept what you are told.” In a classroom where the teaching of chemistry is conducted in a traditional manner, teachers further reinforce the image of science as a form of proven dogma. Teachers verbalize and expound the facts. The students’ role is to memorize and profess the “right facts”. If not, they risk being penalized in their chemistry assessments. Regrettably, students have little, if any, agency to engage in scientific inquiry and to construct their personal understanding of the field. An emphasis on pre-determined “knowledge” coupled with the execution of laboratory experiments designed mainly to confirm pre-determined “findings” can lead to students leaving school with a grave misunderstanding of the nature of science. Students will not realise that scientists actually require imagination and creativity to invent explanations and models to explain phenomena and that scientific knowledge is tentative, subjected to change and can never be absolutely proven (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002; Schwartz & Lederman, 2002). They will also be surprised when they find out that there is competition among rival theories and camps of scientists, that experiment data can be interpreted in more than one way depending on the theory one subscribes to, and that theories can contradict each other (Niaz, 2001). These issues are seldom brought up or discussed in class. In general, then, students are not provided with access to authentic science education (Roth, 1995).
Neither are they helped to understand that engagement in the practice of doing science is the human activity that makes knowledge as a process of constructing reality (Berger & Luckmann, 1966; Knorr-Cetina, 1999).

In the next section of the paper, we first share our general framework for human learning that provides a basis for design-for-learning with our chemistry game. We also explicate, in particular, the pedagogical and epistemic bases of our learning design. The following section describes what it is like to play Level 1 of the game “Legends of Alkhimia”. At the time of writing, the game is still under development, with Level 2 being close to completion. The next part of the paper then articulates the challenges that we have faced in conversing with teachers about taking up and implementing the Alkhimia game-based learning curriculum in their schools. Positioned in terms of boundary crossing, we explain how pedagogical innovations that demand changes in mindsets and practices face institutional and professional barriers to change. The paper concludes by summarizing a set of issues that teachers can consider in advance to facilitate the process of change.

**Design-for-Learning**

The specific design-for-learning that we have adopted in our Alkhimia learning environment is based on the general framework for human learning that is shown in Figure 1. This framework is inspired by Collen (2003) who proposed a philosophical foundation for a general methodology for human systems inquiry. In this original framework, the philosophical basis for human systems inquiry comprises three fundamental ideas from Greek philosophy: namely, ontos, logos, and praxis. Together, they yield a praxiology for human inquiry.

In our design-for-learning with respect to the Alkhimia chemistry curriculum, we have found it fruitful to adopt a view of learning as a form of inquiry (Postman, 1995; Postman & Weingartner, 1969). We have appropriated Collen’s framework into the context
of learning as it provides us with a tractable model for considering the fundamental components of human learning. Ontos, or ontology, is the study of human being, human existence, and of what is. Logos, referring to epistemology, is the study of human knowing, what can be known, and what constitutes human knowledge. Praxis, or praxiology, is the study of action, the practices of human beings, and of what we (as humans) do. To understand human learning in its authenticity as well as complexity, it is vital that learning be studied in the context of humans in situated action, including speech acts (Austin, 1975; Bruner, 1990; Clancey, 1997; Dewey, 1938; Gergen, 1999). In adopting this position, we explicitly reject learning outcomes where students can only talk about chemistry, without the ability to engage in the practice of chemistry. The framework in Figure 1 emphasizes that human knowing is inseparable from human doing (Dewey, 1916/1980) and human being (Heidegger, 1953/1996). The components of the framework are of necessity embedded within a context of axiology, the study of human values. Knowing, doing, and being are inherently value-laden activities (Ferré, 1996, 1998; Putnam, 2002). Humans make basic value distinctions related to the processes and outcomes of learning. These distinctions guide their learning actions toward outcomes that have positive value.

![Figure 1. General framework for human learning.](image-url)
Pedagogical Basis

In striving for a chemistry learning environment that can support authentic,
disciplinary learning, we have taken professional practice as a basic reference point for our pedagogical design. We seek to foster a form of learning that will enable students to begin to think, feel, and act like professional chemists. Our first level of theoretical reference, therefore, in designing the Alkhimia learning environment, is to the work of Bourdieu (1977, 1998) and to his theory of practice. As a social theorist, Bourdieu wrote extensively about social structures in relation to everyday human practices. A key concept in Bourdieu’s discourse of practice is that of habitus, which expresses the way in which individuals ‘become themselves’ through the development of attitudes and dispositions related to a professional field on one hand, and the ways in which individuals engage in everyday practices of the field on the other. The notion of habitus mirrors the concept of practical reason (also referred to as practical sense) that refers to a person’s ability to understand and negotiate positions within the sites of cultural practice that are comparable to a sportsperson’s ‘feel’ for the game. It should be evident from the foregoing, that this orientation is praxiological. It is altogether situated in practice and the enaction of behaviors that signify the values associated with a practice. It seeks to help students develop the vocabulary-in-use, the discourses, and the practices of a professional community, such as a scientific community. In short, it helps students learn to be a chemist, an orientation that is ontological.

There is a second level of theoretical reference for our pedagogical design. This level is that of designing for students to participate in scientific inquiry. Like authentic scientists, students are made to engage in “world construction” and meaning making processes to construct their personal, and justifiable, understanding of the chemistry-related regularities that operate in the game world of “Legends of Alkhimia”. The scientific inquiry process involves, constructing pertinent questions for inquiry, framing candidate hypotheses that
address the questions, engaging in empirical investigations to test the hypotheses, analyzing the data collected from the investigations, constructing an explanatory model of the experience phenomena, and evaluating the robustness of the model.

*Epistemic Basis*

The epistemic basis of learning with the Alkhimia learning environment is depicted in Figure 2, which shows our Play–Dialog–Performance (PDP) Model of game-based learning (Chee, in preparation). This model instantiates a *performance epistemology*, which views knowledge as constituted in action, rather than existing a priori to action, and performance as the activity that allows students to develop competence in the field they are trying to master. By engaging in game play accompanied by speech acts in the form of dialogic conversations that help to make sense of what took place in the game world, students manifest their understanding of chemistry phenomena in the game world of Alkhimia by performing (by word and deed) the actions that lead to successful in-game and out-of-game outcomes. Game play takes place in the virtual world of the game; the learning experience is *embodied* through the student’s in-game avatar, *embedded* in the game world, and richly *experiential* in nature (Chee, 2007). It is necessary, however, to step out of the world of realtime game play and into a dialogic space of conversation where different ideas and viewpoints, or “voices”, can interact with one another (Bakhtin, 1981). From the Bakhtinian perspective of dialogicality, a voice refers to a “speaking personality.” Utterances come into existence by being produced by a voice. As Clark and Holquist (1984) explain: “An utterance, spoken or written, is always expressed from a point of view, which for Bakhtin is a process rather than a location. Utterance is an activity that enacts differences in values.” Dialog is thus an activity that creates a space for different student ideas and values to collide and interact with one another.
This process is facilitated by a teacher within a broader context of structured post-gameplay activities that scaffold students’ meaning making efforts.

As students engage in multiple levels of game play, they iterate over the Play–Dialog cycle that places them on a forward trajectory of competence-through-performance. That is, they are envisaged to develop a performative capacity to think, talk, and act increasingly like professional chemists. This trajectory of learning, projected forward into time, is depicted by images of the student that become more faint as they move upward in Figure 2. Learning in this manner operationalizes the dialectical interplay between first-person learning by doing and third-person learning by thinking/reflection that is key to Dewey’s epistemology of learning by doing. In addition, performative learning is characterized by the gradual development of a self-identity that becomes professional practice in the domain; in this context, chemistry. This conception of learning is consistent with Thomas and Brown’s
(2007) call for student learning to shift away from “learning about” to “learning to be.” As an
approach to learning that places identity development as a key focus, the development of the
student’s professional identity constitutes a trajectory of becoming (Rogers, 1961, 1980).
Learning can thus be conceived as a journey of becoming a certain kind of professional
person.

Returning to the sociology of Bourdieu, the epistemic design outlined here is intended
to encourage students to be reflexive about their learning, critically interrogating assumptions
and biases that may shape the construction of their understanding. In this way, students are
encouraged to practise epistemological vigilance, so that social and cultural biases in their
thinking can be exposed.

In summary, our design-for-learning seeks to address all three aspects of the general
framework shown in Figure 1. Student learning is conceived of as knowing that arises from
doing within the broader context of learning to be; that is, becoming.

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The game “Legends of Alkhimia” was designed to serve as the technology-mediated
component of a broader learning environment that instantiates the PDP Model of game-based
learning. The learning environment includes not only the game but also associated curricula
materials for in-class use that provide the activity structure for the dialogic component of
learning. The game is conceived of as an eight-level multiplayer game that support up to four
players simultaneously. It is played over a local area network, typically in a computer
laboratory in school. The game has been developed to run on PCs. At the time of writing, two
out of the eight levels of the game have been completed. Our in-class research use of the
game is scheduled to commence in July 2010. The research intervention will take place in
two schools.
The game begins in Level 1 with a scenario where the four student players crash-land in the region of the ancient town of Alkhimia. While exploring their environs, they suddenly find themselves attacked by a group of fireball-hurling monsters that emerge from a ravine (see Figure 3.)

![Figure 3. Players fending off a monster attack in Level 1 of the game.](image)

The players try to repel the monsters with the weapons they are carrying. These weapons, a form of gun, can shoot ammunition drawn from cartridges attached to the weapons. The players find that their weapons are not very effective against the monsters. Furthermore, their weapons frequently jam, making it even more difficult to destroy the monsters. After a short but furious battle, the monsters retreat into the ravine, leaving the
players wondering about the composition of the ammunition in their cartridges and why the ammunition was ineffective in destroying the monsters.

The narrative above establishes the context for students to engage in a process of inquiry. Receiving an instruction from their master, Aurus, to return to their headquarters, the students are asked to act on their master’s suspicion that their ammunition in their weapon cartridges was contaminated, thus causing their weapons to jam. Aurus suggests that they perform separation techniques to purify the ammunition substance. The students proceed to their respective lab benches and perform the separation technique that each one thinks will work best. Each student then chooses what she believes is the purified substance and loads her cartridge with this substance.

Unknown to the players (but known to us as the designers of the game), the original substance comprises a mixture of acid and sand. A separating funnel (shown in Figure 4) is thus not an effective apparatus for separating the original mixture as this apparatus works only for immiscible liquids. If a player uses the coarse filter paper, she will obtain two derivative substances, and she can choose to load her weapon cartridge with one of the substances. When the players encounter the monsters a second time in Level 1 of the game, they will find that they are no better off than before. If a player used the separating funnel, the mixture of sand and acid will flow straight through the funnel; hence, their experience in trying to ward off the monsters will be the same as before. If a player used the substance in the beaker that was derived from mixture separation with the coarse filter paper, she will find that her ammunition is more effective than previously, but her weapon still jams occasionally. However, if the player used the substance collected in the filter paper as her ammunition, she would find her weapon jamming even more frequently than before. In addition, she will find that her ammunition is not totally ineffective against the monster. It is only when a student uses the fine filter paper and she chooses the filtered substance in the beaker as her
ammunition that she will experience the most success in killing the attacking monsters. Thus, the game space allows students to experiment with quite different solution paths and to put the different solutions to the test in the second battle with the monsters. In this manner, the game allows divergent solution paths; students are not all required to do the same thing at the same time. This design allows for greater personal agency in game play and in learning.

Figure 4. A player performing a chemistry separation technique at the laboratory bench.

Assuming that students execute different methods of mixture separation and based on the fact that the associated consequences of those actions will manifest differently in the second encounter with the monsters, the question that students will invariably ask is why? For example, why was Peter able to kill the monsters when I was not able to do so?
The cognitive dissonance generated by students’ game play transitions into a classroom space of dialogic learning where, under the guidance of a teacher, students learn with one another to construct the answers to their pressing questions. This form of dialogic learning can take place first at the student group level, then at the whole class level. In this process, students engage in making sense of their collective game experience. They reason to establish what different ammunition effects were observed, then work to identify the causal chain of actions that led to the observed effects. This process requires systematic reasoning that parallels the cycle of scientific inquiry involving questioning, hypothesizing, testing, analyzing, modeling, and evaluating.

As students continue playing “Legends of Alkhimia,” the chemistry involved becomes increasingly complex. Like the apprentice scientists that the game positions them to be, they are required to develop their own classifications of the substances that they encounter in the game world. They do not experience the world as a pre-labelled and a pre-configured place. This pedagogical design inducts students into an authentic practice of science making by requiring them to construct functional and concise representations and organizations of knowledge. Drawing upon the knowledge constructions of different student groups, the teacher will be able help students to make critical evaluations about the constructions proposed by different groups. In this manner, students will begin to appreciate that the construction of scientific knowledge is a social enterprise that is based upon a set of values that esteem explanations that are simple, parsimonious, and generalizable. Students thus learn to imbibe the values, dispositions, and beliefs that undergird the practice of science making. It should be evident that learning chemistry in this manner will yield rather different outcomes compared to traditional emphases on content mastery.
**Challenges of Boundary Crossing**

School teachers are faced with significant challenges when they consider the adoption of modes of teaching and learning that are implied in our pedagogy of game-based learning. Because our pedagogy embeds deep epistemic change, teachers need to adopt a different mind set in approaching their role and responsibilities. Adopting this different mind set, in effect, requires crossing a boundary into a new mode of teaching practice that is based on quite different epistemic assumptions.

We outline below the kinds of challenges that teachers face when contemplating adoption of a game-based learning pedagogy. The distillation of these challenges arises from the conversations that we have had with teachers working with us on this research project. It is our hope that by identifying the challenges explicitly, teachers who are not familiar with the pedagogy can be better equipped to understand the issues they are likely to have to consider to enact the pedagogy successfully.

*Learning outcomes and epistemology*

Traditional ways of teaching lower secondary school chemistry focus on students’ mastery of content that arise from didactic teaching on the part of the teacher. We have argued that student learning outcomes associated with this mode of teaching are weak because students have no opportunity to engage in the practices of doing science and constructing meaning in science. A performance epistemology values learning outcomes that enable students to enact authentic practices related to the doing of science as part of a broader goal of learning as being and becoming. This orientation represents a fundamental change in student learning goals toward identity development and professional practice. It is based on an epistemology of learning by doing rather than learning by being told.

*Curriculum and assessment*
Conventional curricula goals and forms of assessment place great emphasis on students’ mastery of subject content. Teachers are concerned that the adoption of game-based learning should not harm traditional content mastery given the same number of teaching hours. While this outcome may be desirable from a pragmatic perspective, it is not likely to hold in practice. Student mastery is likely to correlate highly with what a pedagogy seeks to promote. Thus, teaching for content mastery will lead to student excellence in content mastery, while teaching for performative outcomes will lead to student excellence in performative outcomes.

Teachers are also concerned about modes of student assessment and conforming to standard tests across a class level in school. The modes of student assessment need to be broadened to encompass more qualitative and rubric-based assessments given that outcomes are no longer evaluated purely in terms of getting the answers to standard questions right or wrong. In addition, the practice of common tests works against pedagogical innovation when the innovation replaces old learning goals with new ones.

*Concerns relating to student prior knowledge*

Many teachers voice the fear that students will not know how to play the game successfully if they are not first taught the facts of the subject domain. This challenge reflects the difficulty that teachers face in recognizing that from a learning-by-doing perspective, competence is achieved only with performance. That is, students gain performance mastery in the domain through what they do. Distilling the knowledge products of learning is merely a by product of learning by doing. The promotion of learning by doing does not take place in lieu of learning content. Rather, the latter is ancillary to the former.

*School logistics*

The structure of student learning in schools is organized in terms of discrete blocks of time that range from about 35–60 minutes. Enacting a game-based learning curriculum
typically requires blocks of approximately 120 minutes in order for game play and dialogic interaction and reflection to take place without feeling rushed. It is necessary, therefore, for schools to make special arrangements with respect to timetabling in order for a game-based learning curriculum to be enacted.

Furthermore, we have found that, in practice, the “official” amount of time allocated to any portion of curriculum usually cannot be met because of the many other co-curricular activities and school events that intrude into curriculum time. Thus, a curriculum segment that is allotted, say, 10 weeks may have to be compressed to fit within the space of 8 weeks. Time needed and time available are often not aligned.

*Sustaining innovation*

Game-based learning, as a pedagogical innovation, takes place within the cultural space of schools. Schools are inherently culturally-bound spaces that are largely resistant to change. As stable systems, school practices have an inherent tendency toward self perpetuation. Given that game-based learning requires change at a deep, epistemic level, there is often no assurance that a teacher who adopts an innovation will continue with it in future. This challenge is the outcome of deep tensions and is not easily resolved because the tension is systemic in nature.

*Conclusion*

In this paper, we have articulated our conception of how lower secondary school chemistry can be enacted with game-based learning. We have argued that traditional ways of teaching chemistry, based on information dissemination and the assertion of scientific truth claims, is weak because this mode of teaching fails to deliver performative learning outcomes on the part of students. In lieu of traditional pedagogy, we have argued, based on a general framework of human learning, that learning must address ontological, epistemological, and
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praxiological dimensions. Game-based learning, as we have constructed it, allows us to reconceive learning in a way that incorporates the processes of knowing, doing, and being, processes that we view as vital to an authentic approach to learning.

We elaborated on the pedagogical and epistemic bases of our design-for-learning and explained how learning in the Alkhimia learning environment would proceed. As mentioned, game development is not yet complete at the time of writing. However, a pilot test based on Levels 1 and 2 of the game is scheduled for late October 2009. We also set out some of the known challenges to boundary crossing facing teachers contemplating the adoption of game-based learning. The distillation of challenges arose from conversations that we have had with teachers collaborating with us on the Alkhimia research project.

To conclude, we hope that this paper helps to inform teachers about the vision and opportunities for enhancing pedagogy through game-based learning. At the same time, we also hope to alert teachers to the challenges they may face in adopting this pedagogical innovation.

References


