Becoming Chemists through Game-based Inquiry Learning: The Case of *Legends of Alkhimia*

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Abstract: Traditional modes of chemistry education in schools focus on imparting chemistry knowledge to students via instruction. Consequently, students often acquire the mistaken understanding that scientific knowledge comprises a fixed body of “proven” facts. They fail to comprehend that the construction of scientific understanding is a human and social endeavor. Consequently, there can be alternative and conflicting views and theories.

To provide students access to an enhanced learning curriculum, Legends of Alkhimia was designed and developed as an educational game for 13 to 14-year-olds to foster the learning of chemistry through inquiry. The multiplayer game supports four concurrent players. It is played on personal computers connected via a local area network. The game embeds students in problem solving challenges related to the use of chemistry in realistic contexts. In attempting to solve these problems, students must engage in individual laboratory work using an in-game virtual chemistry lab. The game levels take students through a narrative arc that provides coherence to the entire gameplay experience. Legends of Alkhimia, together with its associated curricular materials, instantiates classroom learning based on performance pedagogy: a pedagogy that constructs learning through the lens of performance theory. Leveraging the immersive affordances of 3D game environments, the learning experience is designed to engage students in the dialectic interplay between learning in the first person, based on playing the game, and learning in the third person, based on the Bakhtinian notion of dialog. The learning process follows a developmental trajectory of becoming a chemist.

Enacting performance pedagogy in the classroom requires a shift in traditional classroom culture toward that of a professional practice community. We report on an empirical study of a game-based learning classroom intervention where students in the Alkhimia learning program participated in an 8-week curriculum sequence involving six levels of game play. We compared pre- and posttest survey responses from a class of 40 students who learned chemistry using the Alkhimia curriculum. We also compared learning outcomes of students in the said intervention class with a control class of 38 students who learned chemistry through traditional classroom instruction. All students in our study were 13-year-olds from a typical government secondary school. We noted significant shifts in intervention students’ perceptions of their identity, their epistemological beliefs, their dispositions toward science inquiry, and of classroom culture. Students’ understanding of chemistry was evaluated through a common assessment that comprised a complex separation task involving mixtures, solutes, and immiscible liquids. Two evaluation criteria were used: (1) effectiveness of separation, and (2) demonstration of conceptual understanding of chemistry. We found that the Alkhimia students significantly outperformed the control students when assessed on the extent to which effective separation was achieved in the students’ proposed solution ($t75 = 2.56$, $p = .026$) and when assessed with respect to conceptual understanding of chemistry in the separation task ($t75 = 3.41$, $p = .002$). We discuss, from a theoretical perspective, how and why learning with the Alkhimia curriculum is efficacious. Our findings are significant in that they suggest how inquiry learning can be successfully enacted in a chemistry game-based learning curriculum, and they underscore the efficacy of approaching game-based learning in terms of performance.

Keywords: performance, play, dialog, inquiry, chemistry, identity, epistemological beliefs, classroom culture

1. Introduction

Traditional modes of chemistry education in schools focus on imparting chemistry knowledge to students via instruction. The work of professional scientists, including chemists, is embedded within a classroom discourse of scientific discovery (Langley et al., 1987, Popper, 2002). Adoption of a discovery metaphor leads students to believe that there exists a body of indisputable and eternally true facts about the natural world that are just waiting to be uncovered by smart scientists. Through the process of classroom instruction, students unwittingly imbibe an objectivist epistemology of science. This situation is exacerbated by science textbooks that reinforce the common rhetoric of science revolving around assertions of fact, scientific discovery, and certainty. Heyworth (2002), for example claims: “Atoms are so small that nobody has ever seen a single atom. But *scientists are certain* they exist” (p. 26, italics added). Relying on authorial privilege and laying claim to scientific

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expertise, the author boldly asserts that, despite being humans themselves, scientists somehow are completely certain that atoms exist although no one, including the scientists themselves, has ever seen an atom. Such a claim stretches the author's credibility. In a culture of schooling and high stakes testing, however, challenging such claims is simply not entertained.

Consequently, contrary to Popper's theoretical position that scientific theories can only be falsified and never proven, students develop an understanding of scientific knowledge as statements of truth arising from a body of "proven facts." They fail to comprehend that the construction of scientific knowledge is a human and social endeavor involving peer review, critique, justification, argumentation, and rebuttal, based on the citation of evidence and provision of warrants for claims. They do not realize that theorizing is an intellectual creative act to imagine and construct explanations and models of phenomena (Schwartz and Lederman, 2002). The outcome is that students derive a badly misrepresented characterization of the nature of science making in practice.

In our attempt to improve science education in the domain of chemistry, we have endeavored to shift students' understanding of science based on the metaphor of discovery to one based on the practice of scientific inquiry (Dewey, 1938/1991, Hickman, 1998), befitting the process that scientists pre-occupy themselves with. We do so via the Alkhimia learning program, a game-based learning curriculum for lower secondary chemistry. This paper explicates the learning program and its underlying theoretical bases, and reports findings from a classroom empirical study.

In Section 2, we explain the constructs employed to achieve a shift in classroom culture through game-based inquiry learning: namely, performance, play, and dialog. Section 3 concretizes the Alkhimia curriculum through an example. Section 4 describes the research method, and Section 5 reports the data analysis and findings. Section 6 discusses the implications of our findings. We then conclude the paper.

2. Changing classroom culture through performance, play, and dialog

To the extent that digital games are used at all in everyday classrooms, such games typically adhere to what we refer to as an "educational resource model". Games of this type have restricted scope and purpose. While students may play them several times within a 10–15 minute interval within a classroom period of 40–50 minutes, their purpose is served once the lesson is over, and students do not encounter the same game again. These games effectively play the role of a technology resource to enhance the basic classroom lesson. Often, the game is simply a form of drill-and-practice embedded within a more attractive and engaging digital form.

We wish to advance the idea of game-based learning in the literal sense of the term: that is, the objective is the enaction of a coherently designed learning curriculum where a single, substantial digital game is used to help students learn a complete curriculum or curricular unit. For such learning to take place successfully, a transformation in classroom culture is needed: one that is centered on learning rather than instruction. We argue that inquiry learning is a strong candidate for achieving learning centricity based on the associated theoretical constructs of performance, play, and dialog.

2.1 Learning as performance

Computer and video games constitute a unique digital medium that supports *first-person* immersive learning. However, traditional teaching and learning, especially as it is commonly practiced in schools, emphasizes third-person learning. Given the orientation toward fostering subject content mastery, teachers expend a great deal of time and effort *telling* students about domain content. They engage in telling to achieve the first level of *knowledge* in Bloom's taxonomy of thinking skills in the cognitive domain. They hope that students will also *comprehend* what they are told and thereby advance their thinking ability to the second level in Bloom's taxonomy. To the extent that anything needs to be *done* by students, teachers then assign students a task and instruct them to *apply* what they have learned, to advance student thinking to the third level in Bloom's taxonomy. For real world tasks, which naturally tend to be somewhat complex, this instructional approach tends to lead quickly to breakdown. To illustrate, consider a child learning to swim for the first time. Suppose that the swimming instructor delivers a series of outstanding lectures about swimming. He then tests the child's "comprehension" of swimming using multiple-choice questions. Suppose further that the child attains a high score on the test. The instructor then instructs the child to “apply” what she has learned by swimming three lengths of the pool. Is the child likely to succeed?

The example above illustrates that knowing is distinct from knowing *about*. There is no easy way to translate information narrated in third-person terms to the capacity to act in first-person terms. Knowing in a linguistic, conceptual, and third-person sense, is a very different phenomenon from knowing in an embodied, enactive, and first-person sense (Gibbs, 2005, Johnson, 1987). To assume that people learn to do by being told is a common fallacy. We are not suggesting that being told is necessarily unhelpful to the process. Rather, we wish to suggest that learning to do, that is, performative mastery, can *only* be attained by direct engagement in doing. Classical epistemology commits the error of assuming a knower who exists independently of that which is known. However, as Dewey and Bentley (Dewey, 1949/1991) argue in their essay “Knowing and the Known”, there is no such possibility because every knower is always already situated in and part of the world. Coming to know, therefore, requires a process of direct engagement with the phenomenon of interest in the world. It mandates that learners be engaged in the performance of meaningful tasks that allow the development of enactive capacities pertinent to valued social practices.

In the context of education, the philosophy of pragmatism stakes the claim that learning outcomes must make a practical difference to students’ lives by developing their capacity for *effective action*. On this account, learning necessarily takes place in situated action (Coulter, 1989, Wertsch, 1998). We propose the construct of *performance* as a productive basis for understanding learning through the theoretical lens of *being* and *becoming* (Chee et al., 2009, Semetsky, 2006). The construct of performance is drawn from performance theory and performance studies (Bell, 2008, Schechner, 2006). According to Bell (2008), performance has three key characteristics. First, it is *constitutive*; that is, it is established, created, and given form through enactment. Second, performance is *epistemic*: that is, performance is a way through which human actors come to know themselves, know others, and know the world. Third, performance is *critical*; that is, it provides a means for actors to stake claims about knowledge and the creation of knowledge. Performance is also deeply constitutive of *identity* (Benwell and Stokoe, 2006). Implicit and explicit claims about that which is valued by human actors, as well as how these actors as members of a group ought to act, are manifested through performance. Because game play involves *being* a person on a developmental trajectory of *becoming* within a fictional game world, it inherently entails players constructing a sense of who they are and the kind of person they want to become—their identity—through the very act of game play.

Aligned with Dewey’s pragmatic stance (Bernstein, 1960), performance entails living, experiencing, and acting in the here-and-now. Through performance, performers wrestle with human experience as a lived and always dynamic process. They develop participatory and embodied ways of knowing and being. Experience is made available for contemplation, thereby providing opportunities to *think* and to think *differently*; in short, to learn in an experientially grounded way.

2.2 Performance–Play–Dialog: The pedagogical model

The pedagogy underlying the design of the *Legends of Alkhimia* curriculum is that of learning *as* inquiry, in the spirit of Dewey (1938/1991). Dewey argues that the origin of thinking arises in a feeling of perplexity or doubt in the non-cognitive background of embodied experience. Inquiry begins in doubt and concludes when the stimulus of doubt is removed. In the activation of thinking, the qualitative immediacy of experience is transformed from the level of feeling to a level where possibilities and connections are recognized. Such possibilities and connections are exploited at the cognitive level for use as ideas and plans of action. Even as cognitive events transpire, substantial portions of the non-cognitive dimensions of experience are retained, and they serve to regulate the thinking experience. On Dewey’s account, thinking represents the emergence of a new organization of experience (Holder, 1995). Educational aims must be translatable into teaching methods that fit the activities of those receiving instruction, and education administrators must foster the kind of environments required to liberate and to organize the thinking capacities of students. Figure 1 depicts the Performance–Play–Dialog model of game-based learning designed to achieve these goals.

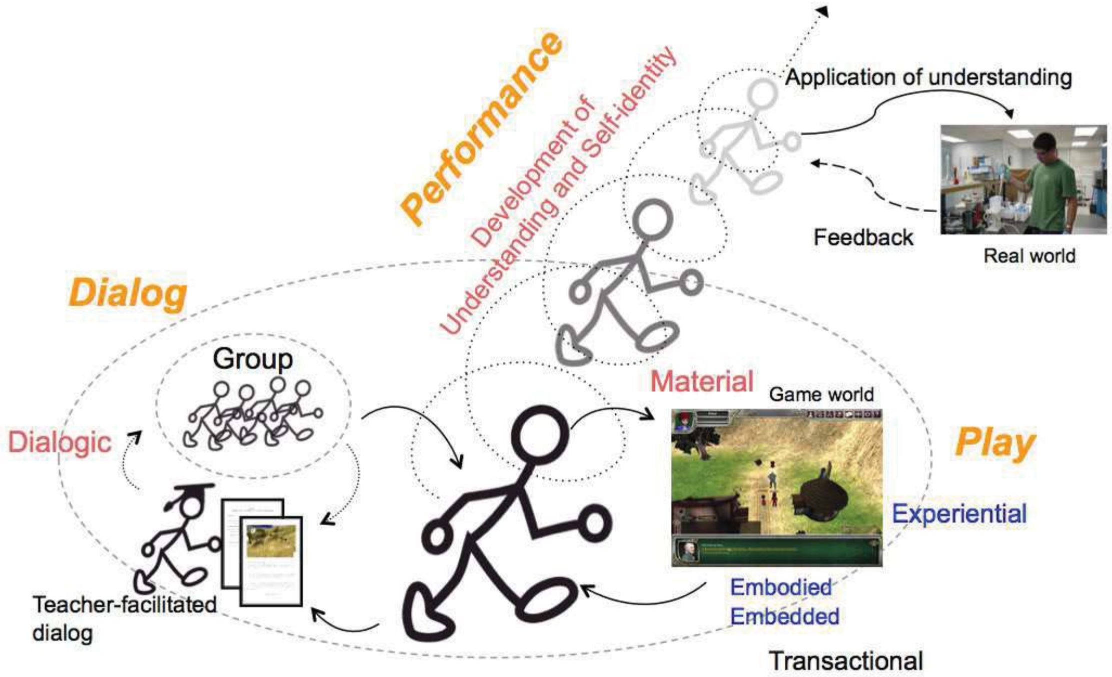


Figure 1: The Performance–Play–Dialog model of game-based learning

As shown, the primary thrust of learning is driven by performance that encompasses the development of understanding in the subject domain and the construction of self-identity with respect to that domain. Through performance, students develop new ways of seeing and understanding the world and of understanding themselves in relation to that world. The construction of an expansive yet coherent worldview, coupled with the agency to act, is central to learning that is developmental and empowering. Figure 1 shows this future-oriented pathway of a learner as a trajectory of becoming through which the learner develops understanding in and practice of a professional domain. Performance itself is realized through the sub-constructs of play and dialog.

Students' learning is mediated by engagement in play via a material, digital game world. The space of play is experiential, and learning actions are transactional (Dewey, 1925/1988). The player's experience is embodied, by virtue of being represented in the game world by his avatar, and the player is embedded, or immersed, in the virtual space of the game world. In the design of our learning curriculum, students play multiple levels of the game. Game levels build incrementally on one another to help them develop the dispositions and habits of mind related to professional practice in the domain of chemistry.

Dialogism, a key Bakhtinian (1981) idea, is central to our pedagogical design of the curriculum. For Bakhtin, dialog is not constituted merely by words or by talking. Dialog is also ontological: it is a way of life. In the context of the classroom, dialog is intended to help students achieve comprehension rather than to provide explanation. Dialogism generates internally persuasive discourse that is *open*, allowing students to construct new ways to mean. Fostering dialog in the classroom creates a more open yet more critical disposition toward discourse and the knowledge construction process. As ideas collide and are interrogated, students learn that the practice of science is itself a process of sense making, and, hence, a dialogically constituted activity. Consistent with pragmatism, they learn that scientific "facts" are warranted assertions and hence tentative in nature rather than eternally "proven" claims. Dialogism thus sustains inquiry as an open process and allows students to participate in the social construction of reality (Berger and Luckmann, 1966). The construct of dialog builds upon and extends the common concern amongst science educators that students develop the skills of scientific argumentation and understand that knowledge claims are socially negotiated. Consequently, there may not be complete agreement on the validity of any particular theory. Based on the model, play and dialog stand in dialectic relation to each other. Play sustains dialog, and dialog informs play.

3. The Alkhimia learning program

The Alkhimia learning program is an eight-session chemistry curriculum for lower secondary school science. The curriculum is game-based. It centers on students playing the multiplayer game, *Legends of Alkhimia*, as well as participating in learning activities that embed game play. As used in the study reported in this paper, *Legends of Alkhimia* comprises six levels of game play. The game was designed and developed by our research lab. In-house development allowed us to exercise fine control over the interweaving of game design and pedagogic intent so as to achieve a strongly coherent pedagogy in practice. The game is played on PCs over a local area network that is typically located in a school computer laboratory. It supports four concurrent players. Based on the research context within which our classroom-based investigation was carried out, the first and last sessions of the curriculum were devoted to the administration of research surveys and student tests. The intervening six sessions were devoted to students engaging in the game-based learning sessions proper, with each level of game play and associated learning activity comprising one session.

To help readers acquire a concrete feel for the game, we briefly describe Level 5 of *Legends of Alkhimia*. The curriculum focus of this penultimate game level concerns the separation of miscible and immiscible liquids. At the commencement of the level, and following the narrative arc of the game at the close of Level 4, students find themselves trapped in an underground chemistry lab once used to conduct bizarre experiments that have produced strange creatures the students have been battling with in the ancient town of Alkhimia. Students are positioned by the game as members of a team apprenticed to the Master Chemist, Aurus. As part of the equipment available to them, they each have a weapon to protect themselves with. They find that the ammunition for their weapon, in the form of chemical substances, is of little effect when they fire their weapons at the metallic door preventing their escape from the lab (see Figure 2). To their horror, the air vents of the room begin to exude a toxic gas. The flow of gas increases with the passage of time. An in-game timer begins to count down. The players need to find a way to escape from the lab as quickly as possible. They find samples of liquid mixtures on the lab benches. The samples do not all look the same. A player may try to fill his weapon's ammunition cartridge with one of the samples and attempt to penetrate the metal door by shooting the substance at it. Her underlying hope would be that the ensuing chemical reaction between the substance and the door will create a hole that she and her team members can wriggle through to safety. The substance chosen is the highlighted topmost item in the selectable ammunition pane on the right side of the screen (see Figure 2). To the player's dismay, however, the mixture is of very low effectiveness in penetrating the door (indicated by a hit score of -1). Based on gameplay in Levels 1 and 2 where students were engaged in the separation of other kinds of mixtures (for example, sand from acid, and salt from water), students know that they should proceed to the in-game chemistry lab to see if they can separate out pure forms of the substances with a view to testing whether the pure substances are more effective in penetrating the metal door.

Figure 2: Players trapped in the underground chemistry lab

Teleporting to the virtual chemistry lab (see Figure 3), the players engage in carrying out separation techniques on their own. Figure 3 shows a player attempting fractional distillation with a mixture of immiscible liquids (indicated by the orange upper layer resting on the lower blue layer). Based on the game design, the simplest method of separating immiscible liquids is by using a separating funnel. The underlying pedagogy of game-based learning employed here, however, explicitly encourages students to experiment with multiple approaches to solving a problem so that they can derive a concrete sense of what works in relation to what does not work and, most importantly, to determine why. At times, there may be more than one functional solution. As curriculum designers, we want students to consider which solution should be regarded as the “better” solution and on what grounds.

There are actually three distinct types of liquid mixtures employed in Level 5 of the game. After students complete their separation techniques in the virtual lab, they return to the in-game chemistry lab shown in Figure 2 and test the effectiveness of their separated liquids on the metal door. Unknown to the students (but known to us as game designers), it is the use of gasoline, separated from water, or ethanol, separated from water, that leads to effective solutions when either of these substances is fired at the door with the weapon’s heating element attached. The challenge facing students at this stage is to speculate what kinds of substances these might be. The heating element ignites the substance and causes the metal to melt when it hits the door. All these events should be understood as taking place within the fictionalized space of gameplay.

After completing gameplay, students transition from the space of gameplay to one of classroom dialog facilitated by the teacher. Following the Performance–Play–Dialog (PPD) Model of game-based learning (Chee, 2011), students step back to reflect on their gameplay experience and to make sense of the chemistry underlying why the different substances that they used in the game and experimented with in the virtual lab behaved in the way that they did. The model provides the conceptual basis for designing a classroom environment where “ideas collide” and find substantiated resolution through the negotiation of meaning. It is also used to enact a learning context where student voices are heard, valued, harnessed, and respected in service of student learning (Alexander, 2004, Michaels, O'Connor, and Resnick, 2007). In addition, the dialogic learning space is used to help students theorize and generalize from their cumulative learning experiences, in and out of the game, so as to be able to articulate knowledge claims in more generalizable and parsimonious terms.

Temperature at 79 Degrees. Carry on heating?

Figure 3: Players trying to separate a mixture comprising two liquids using fractional distillation in the virtual chemistry lab

As students participate in one level of the game-based curriculum after another, they enact a trajectory of learning chemistry by doing chemistry (albeit virtually). This trajectory instantiates the learning principle of competence-through-performance (Gee, 2007). The goal here is not merely to learn *about* chemistry, a third-person perspective on knowledge, but rather to learn chemistry as a performance capacity to engage in *doing* chemistry, a first-person perspective. This performance orientation entails not only physical behaviors related to doing but also speech acts and discursive moves appropriate to enacting professional practice. In this manner, students do not merely learn *about* chemistry. Rather, they learn to *become* chemists by imbibing the dispositions and values of professional chemists. In short, they develop their identity as chemists.

4. Method

The research study reported in this paper examines changes in students' perceptions of their identity, their epistemological beliefs, their dispositions toward science inquiry, and of classroom culture. It also investigates whether learning lower secondary chemistry is more effective with the inquiry-based Alkhimia curriculum compared to learning chemistry using traditional classroom teaching. It does so by comparing the learning outcomes of an intervention class that enacted the Alkhimia learning program with those of a control class. The learning outcomes are based on a summative test that assessed students' ability to solve a complex separation task in chemistry. The task was designed to be effective in discriminating how well students understand the properties of substances in the context of separation of mixtures, a key topic in the syllabus. Our work as researchers entailed direct observation of all classroom enactions of the Alkhimia curriculum, administration of pre-intervention and post-intervention research instruments, and the conduct of post-intervention student and teacher interviews.

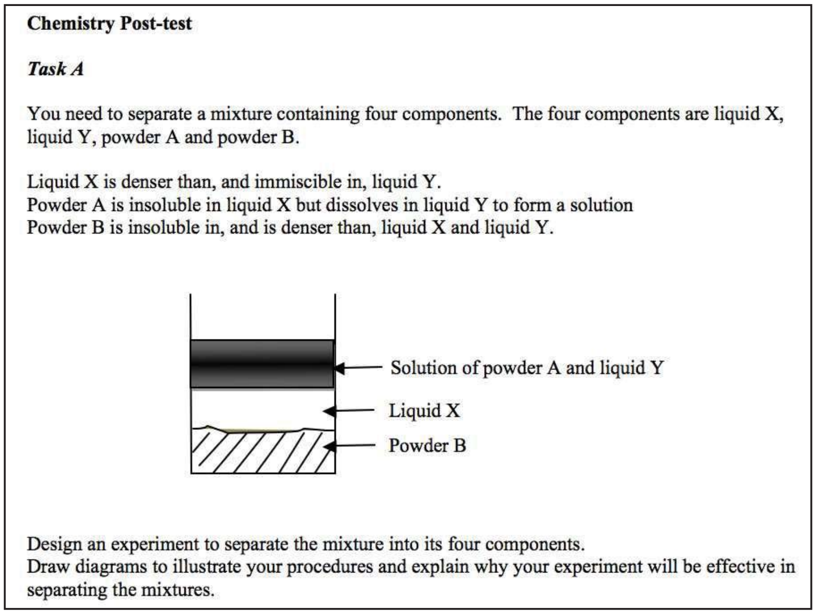
4.1 Subjects

The subjects in our intervention class comprised 40 students from a high-ability class in the Express academic stream of the school where we conducted our research. 22 students were boys (55%), and 18 students were girls (45%). The average age of students was 13 years old. The control class consisted of 38 students who were also from a high-ability class and in the same ability band as students belonging to the intervention class. 18 students were boys (47%), and 20 students were girls (53%). Students in the control class were taught chemistry in the traditional way, based on the use of PowerPoint slides and the lecture method. The conduct of hands-on laboratory sessions, as part of executing the standard chemistry curriculum, was common to both groups of students. As is often the case in schools, the lab sessions required students to adhere strictly to predetermined procedures to obtain and verify predetermined results.

4.2 Materials

Students belonging to the intervention class made use of *Legends of Alkhimia* to play the six levels of the game. During the post gameplay time following each level of gameplay, students engaged in learning activities that helped them to focus on the different stages of the inquiry cycle, prior to the class-level engagement in teacher-facilitated dialog. Each game level targeted one focus. The six foci were: (1) question, (2) hypothesize, (3) investigate, (4) analyze, (5) synthesize and claim, and (6) evaluate. Activity sheets were provided to structure the learning activities. As an example, the first level of gameplay was associated with the questioning phase of the inquiry cycle. The activity sheet took the form of a large poster that invited students to express the questions they wanted to find answers to as a result of playing Level 1 of the game. Students in the control class received as well as took notes on the subject during curriculum time.

An attitudinal survey, comprising 27 items, was administered to the intervention class before the Alkhimia intervention commenced, as well as after it ended. A common summative test, shown in Figure 4, was administered to students in both intervention and control classes. The test was devised by the second author.



Chemistry Post-test

Task A

You need to separate a mixture containing four components. The four components are liquid X, liquid Y, powder A and powder B.

Liquid X is denser than, and immiscible in, liquid Y.
Powder A is insoluble in liquid X but dissolves in liquid Y to form a solution
Powder B is insoluble in, and is denser than, liquid X and liquid Y.

Design an experiment to separate the mixture into its four components.
Draw diagrams to illustrate your procedures and explain why your experiment will be effective in separating the mixtures.

Figure 4: The summative chemistry separation posttest

4.3 Procedure

The Alkhimia learning program was conducted twice a week during four weeks of July 2010. Each session lasted 120 minutes. By special prior arrangement with the school administration, the sessions were held as part of the intervention students' regular science curriculum. The sessions were held on Tuesdays and Thursdays. Tuesday sessions ran from 10.30 a.m. to 12.30 p.m., during normal school hours. Thursday sessions commenced at 12.30 p.m. and ran until 2.30 p.m., an hour past normal school hours. Two schoolteachers participated in the program. Each session began with the lead teacher introducing the session, including the inquiry focus for the day's session. Students then played a level of the game. The amount of time spent playing a level ranged from 30 to 45 minutes. Due to the school's inability to support one student to each PC in the computer lab, we ran with a dyad model, with two students sharing one computer. The students of each dyad took turns to control gameplay. The school decided to use their Macintosh computer lab, with 20 computers, to run the lessons. Consequently, the game was run in Microsoft Windows installed in Boot Camp on the Macintosh.

After the gameplay segment of each session, students were divided into two groups. One group remained in the computer lab with the lead teacher while the other group proceeded to a separate classroom so that both groups could engage in the learning activities and dialogic conversations with a smaller teacher-to-student ratio. This form of organization was intended to facilitate more effective conversations, with each student having greater opportunity to participate in class dialog. After working on the learning activity for the session, teachers helped students to make sense of their gameplay in relation to the chemistry embedded in the particular game level played. They also helped students to deepen their understanding of the inquiry focus for the session. For the session that focused on questions, for example, teachers helped students to interrogate what makes a good scientific question, and they encouraged students to self-evaluate the quality of the questions they proposed to pursue. The sessions culminated in students being invited to propose suitable names for the new substances they encountered in each level of gameplay. This activity was intended to mirror authentic scientific practice in relation to how scientists choose and give names to new elements on the periodic table. Teachers assisted students in interrogating what makes a “good” choice of name in the context of the work of professional chemists. An extended description of this activity can be found in Chee, Tan, Tan, and Jan (in press).

5. Data analysis and results

In this section, we report on the data analysis and results from the attitudinal survey and the summative chemistry posttest.

5.1 Survey data

The intervention class comprised 40 students. However, one student was absent when the survey was administered at the posttest. Consequently, the data analysis, using one-tailed independent samples *t*-tests, is based on the responses of 39 students. Table 1 shows a summary of the survey findings. Statements 1–7 focus on identity as scientist or student. Statements 8–15 examine student dispositions toward inquiry in science learning. Statements 16–17 focus on affect related to learning in the science classroom. Statements 18–20 examine epistemological beliefs related to textbook knowledge. Statements 21–27 focus on student voice as part of classroom culture. It should be noted that the wording shown in Table 1 follows that of the pretest survey instrument. In the posttest, all references to “a science classroom” were replaced by “the Alkhimia Learning Program” so as to draw a distinction between students’ conception of their typical science class and their experience of an Alkhimia science class.

Table 1: Summary of findings from survey administered before and after the Alkhimia intervention

Item	Statement†	*n*	Pretest		Posttest		$t_{(38)}$	*p*
			Mean	SD	Mean	SD		
1.	I feel like a scientist when I am in a science classroom.	39	4.15	1.04	4.97	0.78	5.28	.000**
2.	I feel like a student when I am in a science classroom.	39	4.59	1.12	4.03	1.29	-2.22	.064*
3.	My teacher sees me as a scientist in a science classroom.	39	3.87	1.24	4.49	1.25	2.696	.020**
4.	My teacher sees me as a student in a science classroom.	39	4.72	0.94	4.26	1.25	-2.04	.096*
5.	My classmates see me as a scientist in a science classroom.	39	3.21	1.45	3.74	1.50	2.12	.082*
6.	My classmates see me as a student in a science classroom.	39	4.72	1.07	4.69	1.13	-0.12	.999
7.	I am a good learner in a science classroom.	39	4.67	0.84	4.74	0.88	0.48	.999
8.	I ask myself questions when I want to find out more about something in a science class.	39	4.64	0.96	4.92	0.81	1.97	.108
9.	I ask others when I want to find out	39	4.79	0.84	5.08	1.09	1.22	.464

Item	Statement[†]	*n*	Pretest		Posttest		$t_{(38)}$	*p*
			Mean	SD	Mean	SD		
	more about something in a science class.							
10.	I think to myself what could be possible answers when I have a question in a science class.	39	4.79	0.73	4.87	0.95	0.44	.999
11.	In a science class, I take steps to see if the possible answers to my questions are reasonable.	39	4.44	0.91	4.97	0.74	3.94	.000**
12.	I ask myself to what extent my question is a good question.	39	4.33	1.15	4.56	1.05	1.12	.540
13.	I ask myself what are the strengths and weaknesses of the questions I ask in a science class.	39	4.15	1.01	4.74	1.07	2.85	.014**
14.	I can conduct scientific inquiry independently.	39	4.28	0.92	4.77	0.96	2.31	.052*
15.	I have a good understanding of scientific inquiry.	39	4.23	1.06	4.87	0.83	3.53	.002**
16.	The way science is learned in the science classroom makes me more curious about science.	39	4.46	1.25	5.03	1.14	2.64	.024**
17.	The way science is learned in the science classroom makes me enjoy science more.	39	4.79	1.17	5.05	1.21	1.40	.336
18.	Reading textbooks is a good way to learn science.	39	4.03	1.29	3.87	1.28	-0.81	.842
19.	Reading textbooks is an efficient way to learn science.	39	3.90	1.41	3.90	1.29	.000	1.000
20.	Scientific knowledge described in textbooks is always right.	39	3.45	1.13	2.79	1.45	-3.12	.008**
21.	In my science classroom, my teachers' viewpoints about science are often the only viewpoints.	39	3.69	1.22	3.56	1.29	-0.57	.999
22.	In my science classroom, I hear many different viewpoints from my classmates.	39	4.56	1.14	4.90	1.02	1.33	.380
23.	In my science classroom, I have plenty of opportunities to voice out my opinions.	39	4.36	1.20	5.00	0.79	2.81	.016**
24.	I can disagree with what teachers say about science in my science classroom.	39	4.21	1.13	4.31	1.40	0.50	.999
25.	It is important to have my own viewpoints about science in my science classroom.	39	4.97	0.90	5.23	0.63	1.61	.230
26.	My opinions are important to other classmates in my science classroom.	39	4.10	0.91	4.67	0.87	3.37	.004**
27.	Knowing different viewpoints is important for learning science.	39	5.13	0.98	5.46	0.55	2.12	.082*

**p<.05; **p<.10; p values are for a one-tailed t test

[†] The statements shown above are based on the pretest questionnaire.

Examining the statistical test outcomes for statements 1–7, we observe that students felt like scientists in the Alkhimia classroom (statement 1), and also perceived being viewed as such by their teachers (statement 3). These outcomes are matched by corresponding shifts (marginally significant) in feeling less like a student (statement 2) and being perceived less as a student by teachers (statement 4). In addition, students also felt they were perceived more like scientists by their classmates (statement 5; marginally significant).

Concerning student dispositions toward inquiry in science learning, students' responses indicate that they had learned to take steps to examine whether possible answers to their questions were reasonable (statement 11) and to examine their own questions more critically (statement 13). They also reported having developed a good understanding of scientific inquiry (statement 15) and expressed the ability to conduct scientific inquiry independently (statement 14, marginally significant).

With respect to affect related to learning in the science classroom, students' responses indicate that, with the Alkhimia program, they became more curious about science (statement 16). For epistemological beliefs related to textbook knowledge, they reported that they no longer believed that scientific knowledge described in textbooks is always right (statement 20; decrease in mean score).

Concerning student voice as part of classroom culture, students' responses indicate that they had ample opportunity to be heard (statement 23) and that their viewpoints were important to their classmates (statement 26). In addition, they indicate that knowing different viewpoints is important for learning science (statement 27; marginally significant).

5.2 Summative posttest

The second author, a faculty member, and a teaching fellow evaluated students' written responses to the summative posttest. The faculty member is a science education professor who specializes in chemistry. Each evaluator assessed the responses of one class (intervention or control), and then acted as an independent corroborator for the responses of the other class. Where differences arose, they were discussed and resolved mutually. Students' responses were scored on two separate criteria: (1) effectiveness of separation achieved and (2) conceptual understanding of chemistry demonstrated in the student's solution. The maximum separation score attainable was 8, and the maximum concept score attainable was 6, based on the agreed scoring scheme. A one-tailed independent samples *t*-test was used to test the hypothesis of equal means for students in the intervention class compared to the control class. One student was absent when the posttest was administered to the intervention class. Hence, the statistical test is based on the responses of 39 students.

For the separation score, the mean and standard deviation of the intervention class was $M = 3.28$ and $SD = 2.61$ respectively, while that of the control class was $M = 2.00$ and $SD = 1.71$ respectively. The one-tailed independent samples *t*-test shows that the hypothesis of equal means is rejected: the intervention students significantly outperformed the control students when assessed on the extent to which effective separation was achieved in the student's solution ($t_{75} = 2.56$, $p = .026$). For the conceptual understanding score, the mean and standard deviation of the intervention class was $M = 4.08$ and $SD = 1.84$ respectively, while that of the control class was $M = 2.68$ and $SD = 1.74$ respectively. Again, the one-tailed independent samples *t*-test shows that the hypothesis of equal means is rejected: the intervention students significantly outperformed the control students when assessed on the criterion of conceptual understanding of chemistry demonstrated in students' response to the separation task ($t_{75} = 3.41$, $p = .002$).

6. Discussion

Our findings demonstrate that game-based learning, designed on the model of performance, play, and dialog, has efficacy with respect to changing the culture of traditional instruction-centered classrooms to one that is more centered on student inquiry. As the survey findings indicate, classroom culture is shifted in the direction of a community of inquiry where students feel and identify themselves with the endeavor of science making. They are no longer "regular students" in the eyes of one another and those of their teachers. In this community, they develop the dispositions of critical and interrogative thinking. Students appear to be more self-aware and more self-regulatory in their thinking. They express greater curiosity about science. They are also more critical and discerning about textbook knowledge. These outcomes suggest that students develop a deeper appreciation of science making as a human endeavor and have a more critical disposition toward textbook authority. As part of the desired cultural shift in the classroom, students express their understanding of the importance to speak, to be heard, and to be open to multiple points of view. All these dispositional shifts are of great significance in advancing a classroom culture of "talking science" (Lemke, 1990) and of practicing scientific inquiry.

The Alkhimia curriculum also has efficacy in helping students strengthen their understanding of chemistry, as manifested by the outcomes of the summative assessment. We believe that this outcome arises directly from adopting a performance-oriented pedagogy—embedding embodied learning and enaction of discursive practice appropriate to a professional discipline—such that the primary instructional goal is not students learning *about* chemistry but students learning (to do) chemistry. From the perspective of performance pedagogy, what students can articulate of their understanding of chemistry, the so-called “knowledge”, is a derivative of their hard-earned understanding. It is, strictly, a language-based form of knowledge *representation*, rather than “knowledge” per se. This epistemological positioning is rooted in the process philosophy of Mead (1934, 1938), James (1890/2007), and Dewey (Dewey and Bentley, 1949).

A critical learning affordance provided by *Legends of Alkhimia* concerns the way in which the virtual chemistry lab allows students to learn by exploration and by generally “messing around with things” in the lab. As evidenced by the entrenched schooling practice of allowing students to only do “what is right” in a real-world chemistry lab, classroom lessons tend to mirror the same ethic: students are drilled to learn and remember only “what is right”—the posited “knowledge” deemed to be “true”. The side effect of students learning in this way is that they never come to an understanding of *why* “what is right” is indeed “right”. Hence, they lack the justificatory basis for the “rightness” of their answers. Regrettably, students are unable to justify their “right” answers because what is “wrong” is quickly backgrounded into oblivion in the classroom on the premise that it has no educational value. (“Wrong” answers do not earn credit in tests or examinations.) Working in the chemistry lab, however, with unlimited opportunities to reattempt experiments gone wrong, allows students to develop a deep understanding of why “wrong” solutions do not work and, hence, why the “right” answer to the problem is indeed correct. The principle articulated here parallels de Saussure’s (1986) argument that the meaning of signs—their *value*—can only be understood in relation to the entire signifying system. The relation that creates value is known as *difference*. Thus, “black” can only be understood in relation to its antithesis “white”. Likewise, “right” can only be (really) understood in relation to “wrong”. Giving students the opportunity to be exposed to “wrong” is thus a vital requirement for developing *understanding* (not just “knowledge”) of what is “right”. In this sense, giving students access to the “negative space” of play in *Legends of Alkhimia* is as important as giving them access to the “positive space” of play because meaning making is fundamentally a relational enterprise.

The superior performance of intervention class students with respect to achieving effective separation of the mixture shown in Figure 4, compared to the control class, can be attributed to the virtual chemistry lab representing and constraining the operations with mixtures and substances in a consistent and systematic manner such that students discern a regular pattern of behavior underlying the chemical materials that they work with. This systematicity allows them to construct understandings that are efficacious for performing effective separations of mixtures. The superior performance of these same students in relation to conceptual understanding of chemistry arises from the game’s design and narrative arc creating a need to know chemistry in its canonical form coupled with the implicit embedding of this “need to know” through experiencing the arc of gameplay. These principles are applicable to the effective design of game-based learning in general.

Enacting the Alkhimia curriculum represents shifting to a more student-centered mode of teaching and learning within the context of twenty-first century education and its emphasis on new literacies. Moving away from a psychological construction of literacy to one that is social (Lankshear and Knobel, 2006), the challenge is to help students develop ways of knowing, acting, and speaking that have value in a globalized world. Based on our experience to date, this shift requires accommodation by teachers, students, and education administrators. On their part, teachers need to develop the skills of facilitation necessitated by dialogic learning. In an inquiry-driven spirit of open learning, teachers no longer necessarily know more; neither are they the final arbiters of what is “right.” “Rightness” becomes relative, and the skills of critique and argumentation become more vital. Students also need to develop an understanding of the new “rules of the game.” Whereas effective memorization of facts may have served them well in the past, this well-honed skill no longer delivers the sought after rewards. They now need to develop independent problem solving and critical thinking abilities. Not all students necessarily welcome this development. In addition, education administrators need to shift their thinking away from the model of a school day subdivided into multiple slots of 30 to 45 minutes of curriculum time. Inquiry based learning and learning by doing require substantial stretches of focused time. Students’ short attention span is a valid concern when the classroom activity focuses on information dissemination. When students learn by doing, however, engagement comes quite naturally, and attention span no longer needs to be a determining factor for timetable scheduling.

7. Conclusion

In this paper, we have argued that the prevalent metaphor of scientific discovery does not serve science education well because it leads students to a misrepresented understanding of the nature of science. In its place, we have argued for learning by inquiry. We described the Alkhimia learning program, a chemistry curriculum for lower secondary school science, that instantiates a game-based and inquiry-centered mode of learning, based on the pedagogical model of performance, play, and dialog. Our findings, based on a pre-post survey of student perceptions and a summative chemistry separation task, showed that (1) the Alkhimia learning program effectively fosters a shift in classroom culture toward one of inquiry, and (2) the intervention class outperformed a control class on measures of separation effectiveness and conceptual understanding of chemistry. We discussed the likely reasons for the efficacy of game-based learning, as enacted, and how the learning innovation requires change on the part of teachers, students, and education administrators in order to effectively enact game-based learning in terms of performance.

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