Electromagnetism Supercharged! Learning Physics with Digital Simulation Games

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Abstract: Learning scientists are increasingly turning to computer and video games as tools for learning. Simulation might not only motivate learners, but provide accessible ways for students to develop intuitive understandings of abstract physics phenomena. This study examines what learning occurs when an electromagnetism simulation game is used in a school for underserved students. Students in the experimental group performed better than students in the control group (guided discovery-based science) on measures for understanding. Game mechanics enabled students to confront weaknesses in understandings, and physics representations became tools for understanding problems. Implications for the design of educational digital media are discussed. Yet, it was also these very same game mechanics posed significant challenges in terms of student engagement, motivation, and learning of physics concepts.

Keywords: computer games, simulation, electromagnetism, physics education.

Introduction

Many science educators advocate conceptual or qualitative physics, the notion that physics is best taught not by mathematical formulae, but rather through experiments, labs, demonstrations, and visualizations which help students understand physical phenomena conceptually (diSessa, 2000; Forbus, 1997; Hewitt, 2002). Consistent with the *Physics First* curricular movement, this perspective maintains that a deep, fundamental understanding of physics provides a solid basis for future science learning. How to engage younger students in complex physics thinking is a challenge, but computer simulations provide one intriguing way to engage students in the study of abstract, complex physical phenomena (diSessa, 2000; Dede et al., 1999). Digital technologies can immerse the learner in worlds that not only represent scientific phenomena, but behave according to the rules of physics. Simulated worlds can be programmed to behave by Newtonian or Maxwellian rules (Dede et al., 1999). By representing the simulation through digital gaming conventions, educators can potentially increase engagement while also fostering deeper learning, as learners engage in critical and recursive game play, whereby they generate hypotheses about the game system, develop plans and strategies, observe their results and adjust their hypotheses about the game system (Cordova & Lepper, 1996; Gee, 2003; Squire, 2003). Experiences in game worlds become experiences that students can draw upon in thinking about scientific worlds, using their intuitive understandings developed in simulated worlds to interpret physics problems. By representing complex scientific content through tangible, experienced non-textually-mediated representations, simulated worlds may also engage reluctant learners in the study of science.

The purpose of this study is to examine what happens when a 3D simulation-computer game designed to support the teaching of electrostatics is brought into middle school classrooms. Specifically, we examine:

1. What social practices emerge as students engage in collaborative and cooperative games?
2. What strategies do teachers use to incorporate the game into their curricula?
3. What is the impact of learning with Supercharged on students' learning of electrostatic concepts?

This study uses mixed research methods (quantitative and qualitative, experimental and naturalistic) to examine these questions as a part of a broader design experiment methodology.

Theoretical Background: Electrostatics and Conceptual Physics

Many scientific domains deal with abstract and multidimensional phenomena that people have difficulty comprehending. Mastery of abstract scientific concepts requires that students build flexible and testable mental models (Barnett, Keating, Barab, & Hay, 2000; Redish, 1993). Frequently, however, students are asked to develop an accurate scientific mental model that have no real-life referents, incorporate invisible factors and complex abstractions (Chi, Feltovich, & Glaser, 1991). For example, in the sub-field of electrostatics, electric fields and their associated representational formalisms are three-dimensional, abstract, and have few analogies to learners' everyday experience (Furio & Guisasola, 1998). As a result, students have trouble understanding the relationship of abstractions about electric fields to phenomenological dynamics (Chambers & Andre, 1995). Learners often have trouble understanding how the electric field would propel a test charge through the field if it were free to move (Dede, Salzman, Loftin, & Sprague, 1999). This is because they cannot visualize the distribution of forces throughout a vector field to relate how that distribution of force translates into the motion of the test charge, or even understand the concept of superimposed forces-at-a distance (Dede et al., 1999). In short, research suggests, that students lack a qualitative understanding of these electric field concepts (Andre & Ding, 1991; Bagno & Eylon, 1997). Such qualitative mental models are believed to lay the foundation for more formal understanding (White & Frederiksen, 1998). To meet this need a few researchers have been exploring how to use computational simulations (virtual reality) to assist students in visualizing basic electrostatic concepts (Dede, et al., 1999). To date, these systems have shown promise in improving student learning, the question, however, is how to scale these innovative programs. To this end, we have been exploring how to use the motivational power of computer games with computer visualizations to foster student learning in a variety of settings.

Conceptual Physics

Many schools are using "Physics First" curricula, introducing the study of Physics early in the curriculum so that students have a deeper conceptual understand of physical phenomena which can be used for understanding complex chemistry and biology (Hetzner, 2002). At the same time, many science educators argue that teaching physics concepts conceptually or naturalistically, rather than purely mathematically might lead to deeper understandings (Forbus, 1997; diSessa, 2000). As Forbus (1997) explains, "…students should deeply understand the qualitative principles that govern a domain -- including the mechanisms, such as physical processes, and the causal relationships-before they are immersed in quantitative problems" (p.241). Students have particular difficulty in apprehending physics concepts (such as the basics of electrostatics) which have very few real-life referents and which incorporate invisible factors, forces operating at a distance, complex abstractions (Chi et al., 1991). Andrea diSessa (2000) describes understanding as a process that begins with deep *intuitive understandings,* which then become the basis for more formalized physics knowledge. However, putting physics first in the curriculum presents several challenges for educators. What instructional methods are effective in teaching conceptual physics? What supports can we provide teachers who must create entirely new curricula? Teachers may be reluctant to adopt a physics first approach or not trained in conceptual physics teaching methods (Hetzner, 2002).

Leveraging Gaming Technologies in Education

With sales of approximately $7 billion in 2002 and with the average 8th grader playing video games for approximately 5 hours per week, video games have become a cultural and social force that shape children and adolescents' lifestyles (Gee, 2003). However, the investigation of computer games as an educational tool is truly in its infancy. Only recently have educators begun to examine how such media can be integrated into classroom settings. Past research in the social sciences has shown that games can be effective instructional tools, but most often encompassing instructional activities are as important as the game in shaping learning (Ehman & Glenn, 1991). Cordova and Lepper (1996) found that students learning with instructional games in mathematics classrooms outperformed students in more traditional settings and that context, challenge, control, and curiosity increased motivation. McFarlane, Sparrowhawk, and Heald (2002), as part of a teacher evaluation research experiment found that computer games provided a forum in which learning arises as a result of tasks stimulated by the content of the games, knowledge is developed through the content of the game, and skills are developed as a result of playing the game. In another recent study (Rosas et al., 2003) found a significant difference in learning outcomes for first and second grade students whose teachers used computer games as a part of instruction compared to those who did not use games. These studies, however, are the exception as most the work to date is in the form of anecdotal stories.

Using Technologies to Support Learning

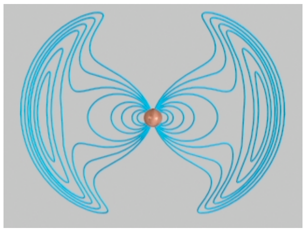
Even advanced students have difficulty grasping non-intuitive, abstract concepts such as those found in electromagnetism (Furio & Guisasola, 1998). Digital visualization technologies might help physics teachers teach conceptual physics. NASA award winning physicist John Belcher (2003) discusses animations in his teaching,

> Animation can give you access to levels of abstraction that you just can't get to with the math alone. It's particularly valuable for students who are trying to understand things at a conceptual level, because there is not too much intuition about electromagnetism... electromagnetism is largely hidden from their reality. Animations help my students visualize vector fields and other electromagnetic

> phenomena that they have a hard time conceptualizing from just the mathematics. When the students look at the topology of the moving field lines, they can understand intuitively many properties of the forces transmitted by the fields.

The aesthetic dimensions of these animations (See Figure 1), also capture some of the physical beauty of electrostatics, making the basic ideas of the discipline accessible to broader audiences (Belcher, Murray & Zahn, 1999). In short, as *representations* of electrostatic ideas, animations and visual depictions are not only tools for thinking about physics but objects that can engage, excite, and inspire learning.

Figure 1: Creating a dipole. Image courtesy of John Belcher

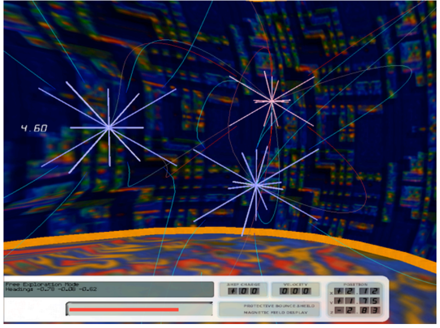


The increased graphics power of desktop computers open wide new opportunities for representing abstract scientific concepts in real time 3D. Only a few years ago, such simulations were in the sphere of virtual reality. Dede and colleagues used computational simulations in virtual reality to assist students in visualizing basic electrostatic concepts, finding that 3D electrostatic simulations were valuable learning tools in electrostatics (Dede et al., 1996). Dede and colleagues also reported that although learners found virtual reality applications engaging, they were frequently unsure of how to interact with their virtual reality applications and expected a more game-like experience. We believe that educators might use gaming structures such as fantasy, challenges, cooperation, or competition to create even more powerful learning tools, coupling the intrinsically rewarding aspects of games with the pedagogical power of simulations (e.g. Cordova & Lepper, 1996). As learning scientists better understand how learning occurs through game play, even more opportunities will exist to use emerging game technologies and design to engage students in meaningful learning (Games-to-Teach team, 2003; Gee, 2003).

Enabling Technology: Supercharged

To investigate the pedagogical potential of 3D simulation games, researchers created *Supercharged!* an electromagnetism simulation game developed in consultation with MIT physicist John Belcher. Players explore electromagnetic mazes, placing charged particles and controlling a ship which by altering its charge. The game play consists of two phases: planning and playing. As the player encounters a new level, she is given a limited set of charges that she can place throughout the environment; she will move either toward or away from the charge, enabling her to shape the trajectory of her ship. In the ‘playable’ portion of the game, the player switches her charge (either positive, negative, neutral, or dipole), and manages a limited amount of fuel that can directly propel the ship. Each level contains a set of obstacles common to electromagnetism texts, including points of charge, planes of charge, magnetic planes, solid magnets, and electric currents (see Figure 2). Each of these obstacles affects the player’s movement according to laws of electromagnetism. The goal of *Supercharged!* is to help learners build stronger *intuitions* for electromagnetic concepts.

Figure 2: Screenshot of a SuperCharged! Game Play Environment



Free Exploration Mode
Headings: -0.78 -0.08 -0.62

SHIP CHARGE +00
VELOCITY 000
POSITION
x +2.12
y +1.75
z -2.83

Methods

This study was a part of a larger design experiment examining the pedagogical potential of Supercharged (Brown, 1992). We examine what classroom practices emerged when *Supercharged!* was used as the basis for an electrostatics unit in three middle school science classrooms and compare learning in a classroom where Supercharged! is used to support learning with an inquiry-based learning unit. This pilot study occurred in an urban/suburban middle school. Chamberlain middle school has 700 students and only has a 7th and 8th grade student body. The student body makeup is 30% Latino, 20% African-American, 15% Asian-American (Indian and Vietnamese primarily), 25% Caucasian, and 10% Eastern European. In addition, 17% of the student population has been identified as students who require special needs or care. This study occurred in one 8th grade teachers' classroom and included a total 96 students in five separate classes.

In coordination with the teacher we identified two classes to serve as a control group (N= 35) which left the other three classes to play Supercharged and to serve as the experimental group (N= 61). Each group (control and experimental) was expected to learn the same content. To this end, the control group was taught about electrostatics through guided inquiry methods such as interactive lectures, experiments, observations, and demonstrations of the teacher's design. The experimental group primarily played Supercharged during their class time with supplemental materials and interactive lectures from the same teacher.

Data Sources

This paper uses both quantitative and qualitative data to provide a holistic view of the course and reciprocally identify patterns and probe further to uncover meanings in the data. Prior to the intervention each group was administered a conceptual electromagnetism exam. The exam consisted of twelve questions with space provided for the students to describe why the chose their particular answer. Also prior to the intervention a subset from each group ($N_{control}$=36, N_{exp} = 15) were randomly chosen and interviewed. The interview was constructed to specifically elicit student responses that would provide the research team with a better understanding of students' performance on the pre-test. The interview was semi-structured and focused on better understanding of students' understanding of electrostatic forces, electromagnetic forces, and electric and magnetic fields. During the interview, students were asked to draw pictures of their ideas regarding electric and magnetic fields, and were provided with manipulatives to demonstrate their understanding of how charges interact with one another.

In addition to the quantitative methods, naturalistic strategies were leveraged to better understand how the students used and interacted with Supercharged and each other as they engaged in the game play. Each class was videotaped with five video cameras. One camera was focused on the teacher to track the teacher's movements and comments. Another camera was a "roving" camera moving around the room to capture "interesting" classroom moments. The other three cameras were focused on a specific group of students who were playing Supercharged. In addition, two researchers were always present recording their observations concerning student discussions, interactions with each other and the game, and students' frustrations and successes with the game into a database. At the conclusion of the intervention the students were again administered the conceptual electromagnetism exam and students from each group were interviewed again (N_{cont}=33, N_{exp} = 16). Given the constraints of the school structure it was difficult to always post interview the same students that we pre-interviewed. However, we did successfully to conduct 25 pre-post experimental pair interviews and 12 experimental pre-post control pair interviews.

Data Analysis

The quantitative data was analyzed using SPSS and the qualitative data was entered into a database and correlated with the appropriate question on the conceptual exam. This allowed us to us to look across the data to understand student thinking about both a large and fine grain level. The data was entered into SPSS and analyzed using ANOCA and ANCOVA techniques. In order to develop a more fine grained understanding of how students' conceptions of electrostatics changed we purposively selected a subset of students whose scores increased (3), decreased (3), and stayed about the same (3) for a more detailed analysis of their understanding.

The qualitative data is analyzed using naturalistic methods (Guba & Lincoln, 1983) techniques to examine the classroom practices that emerged through game play, how students approached the game, and how learning occurred through game play. Researchers met informally between class sessions, and in three data analysis sessions following the program. Using the constant-comparative method (Glaser & Strauss, 1967), researchers generated themes from the data, consulting video tapes and field notes to search for supporting and disconfirming evidence.

Preliminary findings are reported as described by three themes: (1) engagement and gender, (2) game design and conceptual learning, and (3) instructional practices in game-based learning environments.

Results and Discussion

Consistent with the design experiment approach (Barab & Squire, in press), we used a combination of research methods to uncover patterns in students' learning across conditions and probe potential causes for these differences more deeply. Consistent with a situated view of cognition (e.g. Kirshner & Whitson, 1999) we also use qualitative techniques to examine what classroom practices emerged when Supercharged! entered a middle school classroom of underserved students and characterize the classroom culture that emerged.

Learning in Game-Based Environments

In general the experimental group outperformed the control group (see Table 1) on the conceptual exam questions ($\underline{M}_{exp} = 5.4$, $\underline{M}_{cont}=4.7$). The boys' scores also showed a larger change that the girls scores (see Table 2).

Table 1: Comparison of Means and Changes in Pre-Post Scores

Group	N	N_{boys}	N_{girls}	Pre-Test	Std. Dev	Post-Test	Std. Dev	Change
Experimental	58	30	28	4.2	1.70	5.4	.20	1.2
Control	32	20	12	3.9	1.72	4.7	.27	0.6

Table 2: Comparison of Means for Boys and Girls in Experimental and Control groups

Group	N_{boys}	N_{girls}	Boys Pre	Boys Post	Change Boys	Girls Pre	Girls Post	Change Girls
Experimental	30	28	4.0	5.2	1.2	4.4	5.4	1.0
Control	20	12	4.1	5.1	1.0	3.9	4.1	0.2

A two-way ANOVA was also calculated with post-test scores as the dependent variable. Intervention (Experimental or Control) and Gender (Boy or Girl) were between-subjects variables. There was a significant difference between the experimental and control groups, $F(2,89) = 4.8$, $p < 0.05$, $\_^2=0.59$. There was no significant effect due to gender.

Examination of the pre-post interviews and student comments revealed a number of student difficulties in understanding the nature of electrostatics. For example, one student, Maria (Experimental group), following comment during her pre-interview is representative of the majority of student beliefs regarding how two like charges interact with one another:

> Interviewer: Now lets imagine we have two positive charges next to one another. What is going to happen when I let them go?
> Maria: The are attracted because they are the same, so they will want to go toward one another.

In addition, Alex (control group), believed that electric fields simply consist of like charges around a charge (see Figure 2). Other students, like Janet (experimental group), called upon her knowledge of atoms as noted in the following pre-interview excerpt:

> Interviewer: Ok, now what do you think the electric field looks like around a positive charge?
> Janet: Well, it probably looks like this (draws circles around the positive charge)
> Interviewer: Why do you think it looks like that?
> Janet: It looks like the picture in the book from last year. You know, like an atom. The negatives are out here [pointing to here drawn circles] and the positive are in there [pointing to the center positive charge].

The post-interviews revealed that both set of students had improved their understanding of basic electrostatics. However, there were some qualitative differences between experimental and control group students. The most striking difference were in students descriptions of electric fields and the influence of distance on the forces that charges experience. For example, Maria during her post interview described an electric field as:

> The electric goes from the positive charge to the negative charge like this [drawing a curved live from a positive charge to a negative charge]. I know this because this is what it looked like in the game and it was hard to move away or toward it because the two charges are close together so they sort of cancel each other out.

In the control group, the students also performed well in drawing what an electric field looked though their reasons for their explanations revealed a different type of thinking:

Interviewer:	Ok, what do you think the electric field looks like around a positive charge?
Alex:	It has lines going outward from it like this [drawing lines with arrows pointing outward]
Interviewer:	Why do you think it looks like that?
Alex:	I don't know. The teacher said so and showed us a picture and that was what it looked like.

From the above interview excerpt it appears that students in the experimental group was recalling experiences and challenges that were a part of design of *Supercharged*, whereas, students in the control group were relying more on their ability to memorize information. Playing *Supercharged* enabled some students to confront their conceptions of electrostatics, as they played through levels that contradicted their understandings. Students used *representations* of electric fields depicted in the game as *tools for action*. These initial findings suggest that the primary affordances of games as instructional tools may be their power for eliciting students' alternative misconceptions and then providing a context for thinking through problems. Adept game players appropriate game representations as tools for thinking, which, for some students such as Maria, were later taken up in solving other physics problems.

Challenges Implementing Games in Classrooms: Appropriating Supercharged

Challenge #1: Many students were somewhat confused by the activity, and sought more specific guidance. After 15 minutes of playing *Supercharged*! many students complained that they did not understand the point of the activity, or how they were learning physics through the game. Similarly many students were reluctant to engage in discussions, with one student commenting, "We're just not really used to talking in class." For these students, learning science through exploratory activities was uncommon, and students had little reference (or no script) for how to participate in non-teacher led activities. It was clear to the researchers that consistent with previous studies of digital tools in classrooms (Squire, MaKinster, Barnett, et al., 2003), the classroom culture was affecting how the tool was appropriated in significant ways.

By the second day, the teachers recognized that students were playing Supercharged, but few were critically reflecting on their play (Gee, 2003). The teacher created log sheets for students to record their actions and make predictions, which reinforced the purpose of the activity and encouraged students to detect patterns in their play. By Day 3, the teacher provided even more structure, using the projector to display game levels, encouraging the class to interpret the events happening on screen and make predictions about how they thought the simulation would behave. This added structure added more focus to students' play and allowed the instructor to prompt deeper reflection on game play. The teacher's move to appropriate *Supercharged* reinforces the importance of designing tools transparent and flexible enough to be appropriated by teachers in response to local needs and conditions.

Overall, both boys and girls were immediately drawn to playing Supercharged! and eagerly played the game, but many boys lost interest after having perceived to have "beat" the game. On the first day, researchers noted students' enthusiasm to play the game. Even though *Supercharged!* is a relatively simple computer game lacking the graphical flair of most commercial games, students initially perceived it as a game, and judged it more on its merits as game than by production value alone. One researcher wrote, "Look at their enthusiasm! I was a little concerned that they wouldn't even see Supercharged as a real game, given that it was made by some academic researchers on a fraction of a normal game budget. But they are engrossed in the game." The teachers echoed these comments noting that many of these students were failing school and generally disinterested in science.

By the second day, some students had lost interest in the game, citing poor controls, technical issues, or repetitive game design. After Day 1, students had played through several levels, and the developers created new levels for Day 2, but some students felt as if they had already "beat" the game and wanted more variety in game levels. For many students, but boys in particular, the point of the exercise was to beat the game, and the thought of replaying levels to try different strategies or learn about electromagnetism was uninteresting. For other students, many of whom were girls, the experience was less about beating the game and more about exploring the game simulation. These girls wanted to be able to record their actions, review levels, and share their results with peers.

The level design provided opportunities for students to intuit some electrostatic concepts which they used as tools, but most students did not readily adopt the game vocabulary or interpret game events in terms of electrostatic concepts. Students readily intuited concepts such as the attractive force between opposite charges, and like charges exerting repulsive forces, concepts which many students had difficulty with in pre-interviews (many students used intuited algebraic meanings on positive and negative charges). Results from interviews and post-tests show that most students also intuited that charges experience force over distances and that this force grew weaker over distance. Some students, such as Maria, also used the concept of field lines, which were visual representations in the game as a tool for solving post interviews. In general, students readily intuited the *kinetic* elements of the game and developed intuition about the general nature of electrostatic forces.

Results from interviews and post-tests also revealed that students did not infer some of the more complex concepts depicted in *Supercharged*. Few students appropriated terminology presented in game and misconceptions persisted about the interaction among charged particles within an electric field, which are reported more fully in the paper. Most likely this is because physics terminology is introduced in cut scenes (which many students skipped or ignored) and is not instrumental to the game play. Post-interviews revealed that students had idiosyncratic methods for interpreting game events, and this interpretation was mediated by play styles and social discourses.

Educational Significance

James Gee (2003) in his recent book stated: “when kids play videogames they experience a much more powerful form of learning than when they are in the classroom”. Gee’s statement reflects as much about the potential impact that videogames can have on learning as it does on the increased interest by educators to develop new and innovative tools to support learning (Gordin & Pea, 1998; Yair, Mintz, & Litvak, 2001). However, there are few empirical studies that have examined the use of video games within classroom settings (McFarlane et al., 2002; Rosas et al., 2003). Therefore, if instructional designers are to leverage the motivational power of video games to support learning, studies are critically needed that examine how and in what ways videogames either support or inhibit learning (Holland, Jenkins, & Squire, in press). This pilot study provides evidence regarding how computer video games can be used to support or inhibit student learning and also describes (in the larger paper) the challenges that students and teachers experience when attempting to use computer video games in a classroom context. In post-interviews, students used game concepts to solve complex Physics problems. These findings suggest that the active nature of computer game play, the goal-based nature of the activity and the way that visual representations are used to solve problems may be useful in getting students to think with scientific representations.

These findings suggest that simulation computer games can be effective tools in helping students understand complex physics phenomena. Educational games need not necessarily rival commercial entertainment games in production value to gain students’ interest, although poor design or execution can turn away students quickly. These findings suggest that educational game designers need to be mindful of the different ways of playing games, finding ways of engaging competitive and exploratory players alike. Further, designers need to be mindful of how *teachers* appropriate games, designing games that are flexible enough to be adapted to local needs. This study also shows that teachers can play a critical role in providing students’ focus and guiding conversation. This finding also suggests that a game such as Supercharged might be viable in the one computer classroom, as some of the richest classroom discussions occurred as the teacher led the class through collaborative play.

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