The usability of a commercial game physics engine to develop physics educational materials: An investigation

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Commercial computer games contain "physics engine" components, responsible for providing realistic interactions among game objects. The question naturally arises of whether these engines can be used to develop educational materials for high school and university physics education. To answer this question, the author's group recently conducted a detailed scientific investigation of the physics engine of Unreal Tournament 2004 (UT2004). This article presents their motivation, methodology, and results. The author presents the findings of experiments that probed the accessibility and fidelity of UT2004's physics engine, examples of educational materials developed, and an evaluation of their use in high school classes. The associated pedagogical implications of this approach are discussed, and the author suggests guidelines for educators on how to deploy the approach. Key resources are presented on an associated Web site.

KEYWORDS: *accessibility; collaborative learning; computer games; concept maps; educational materials; experiential learning; fidelity; guidelines; pedagogical implications; physics education; Unreal Tournament 2004*

Computer games contain "physics engine" components, which are responsible for the computation of interactions among game actors to provide a "believable" user experience. The virtual world of a game, which I refer to as an immersive environment (IE), must reflect a believable representation of phenomena we experience in the real world, such as collisions and the movement of objects in gravity. The IE physics may be also programmed to simulate various worlds (e.g., depicting the behavior of objects on the moon). The question naturally arises: Can these physics engines be used to produce educational materials?

To answer this question, my group conducted a scientific investigation of the physics engine of Unreal Tournament 2004 (UT2004), which I report in this article. Our investigation involved several interrelated threads, here posed as questions:

1. Can UT2004's physics engine present a qualitatively believable experience, in which students may observe phenomena, change the parameters of an experimental setup, and make correct hypotheses about the underlying physics?
2. Does the behavior of this physics engine produce quantitative agreement with the formulas and equations of physics? This questions the fidelity of the physics engine.
3. Can we demonstrate a positive educational impact of our approach?

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It is important to situate the original motivation for our work. I refer to a recent report (Smithers & Robinson, 2005) suggesting that physics education for 14- to 18-year-olds is in a state of crisis because of lack of student interest in physics as a discipline. There is also a lack of specialist physics teachers (Wood & Morris, 2005). A similar crisis in recruitment into undergraduate courses has been noted by Smithers and Robinson (2005), who suggested that "physics is in danger of disappearing as an identifiable subject from much of state education, through redefinition to general science and teacher shortage" (p. 52). The Institute of Physics (2001) made several recommendations to address these issues:

1. "An increasing number of young people must be enthused by physics."
2. "The critical shortage of physics teachers in schools and colleges is the greatest threat to the future supply of scientists and engineers."
3. "There is a case for a new degree drawing heavily upon physics, being more interdisciplinary in focus and accessible by undergraduates with more modest mathematical experience."

Our work is grounded in these recommendations. We believe that the use of game engines, a lingua franca of youth, will motivate students to learn, especially because their new knowledge of physics may help them produce more interesting games. We suggest that schoolteachers should be encouraged to produce their own IE physics materials and that this is a viable option.

This article is structured as follows. In the first section, I discuss my group's development of "qualitative" physics experiments in UT2004's IE. The second section presents some results from our investigations into the fidelity of UT2004's physics engine in delivering "quantitative" results that may be compared with the formulas and equations of physics. A roundup of our pedagogical basis, introduced throughout the article, is presented in the third section, together with an exemplar IE containing several rooms with experiments and theory. The construction of this IE is grounded in the theory of "concept maps" (e.g., Novak, 1998). In the fourth section, I explore how our IEs align with principles of adaptive learning. Finally, in the fifth section, I present a discussion of our investigations and draw some conclusions. Examples discussed are available at the author's Web site[1]; follow the link "Journal Simulation & Gaming."

Qualitative physics

Traditionally, physics has been taught in close correspondence with mathematics. Physics theory produces mathematical formulas and equations that become the objects of learning and the subjects of investigation and reflection. Recently, many science educators have suggested that this correspondence may actually hinder learning, that physics is best learned not through mathematical formulas but by experiments that are fundamentally visual (Forbus, 1997; Hewitt, 2002). Working with simulations, students may experiment, change parameters, and construct hypotheses and theories (Dede, Salzman, Loftin, & Sprague, 1999). Simulations have previously been explicitly programmed (e.g., as Java applets). This requires considerable programming expertise, whereas our work with schoolchildren demonstrates that the skills needed to produce IEs can be rapidly learned, allowing both teachers and students to construct their own IEs. The fundamental idea of qualitative physics stems from the acknowledgment that many scientific domains must handle both abstract and complex phenomena; learning these is highly challenging (Barnett, Keating, Sarab, & Hay, 2000). Students are often asked to produce mental models that are abstract and have no real-life referents to inform their learning; field theory, discussed below, is a clear example. Research into students' learning of electrostatic fields (Dede et al., 1999) suggests that they do not achieve a deep understanding of the real-world phenomena when these are embodied in formal, mathematical constructs.

Several researchers from the artificial intelligence community have attempted to develop a theoretical basis for qualitative physics. Examples are the "naive physics" of Hayes (1985) and the qualitative physics of Kleer and Brown (1984). In Hayes's "Second Naïve Physics Manifesto," a research program was suggested on the basis of four criteria for such a program:

1. **Thoroughness:** It should reflect a wide range of everyday phenomena.
2. **Fidelity**: It should contain sufficient detail.
3. **Density**: There should be more facts than concepts.
4. **Uniformity**: There should be a solid theoretical substrate. This is perhaps the most controversial criterion. Here, Hayes suggested that there should be a formal theoretical underpinning for qualitative physics. In particular, he advocated the use of first-order logic, in contrast to the use of the differential calculus associated with quantitative physics.

We used the first three criteria in designing our qualitative physics IEs; we found, following a pilot study with 16- to 18-year-old physics students, that "fidelity" emerged as a vital criterion (see "Discussion and conclusions" below). Two examples of qualitative experiments used in this investigation are presented here; a full list is available from the author's Web site.

Interference of waves

The IE comprises a UT2004 fluid surface and two oscillators producing waves that overlap and interfere, producing well-known patterns of constructive and destructive interference. This is clearly visible in the screenshot of the IE shown in Figure 1. The student "experimenter" is able to move around to observe the phenomena from various viewpoints. Moreover, the student is able to change the parameters of this experiment, such as the distance between the oscillators, the frequency of oscillation, and the wave speed in the fluid surface, and observe directly the effects of these changes on the interference pattern. Having three adjustable parameters opens up an enormous space of experimentation, so students are typically encouraged to focus on just one. Following individual investigations, students may invite their peers into their IEs to discuss the phenomena and move toward a collaborative understanding.

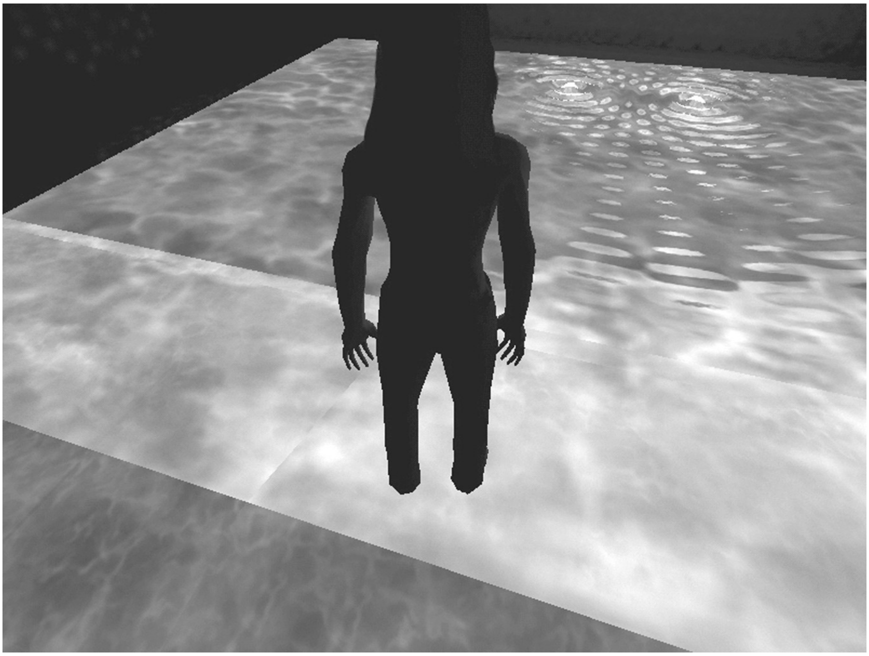

FIGURE 1: An experimenter observes the constructive and destructive interference of waves

Field theory: The motion of particles in fields

As mentioned above, field theory is a highly abstract concept that often challenges students' understanding. It offers an alternative paradigm to the force-based, Newtonian approach of "action at a distance between objects." These objects may be planets in the solar system or electrons in a cathode ray tube. The idea is to construct a field (which may be thought of as a landscape comprising rolling hills) produced by various objects (e.g., the sun and the earth), which then informs a "third party" (such as the moon or a space shuttle) how to move. An example is shown in Figure 2, in which three balls are shown moving on a field defined by the mathematical function

$$(1 - e^{-\alpha x^2}) / (1 - e^{-\alpha}). \qquad (1)$$

The form of this function, generated using Matlab software, is clearly visible in Figure 2. This was easily imported into UT2004 as a terrain "height map." Students investigating this IE soon discover that balls that start deep inside the trough oscillate much faster than those that start near the extremities. On the basis of observations of the balls, and of the shape of the potential hill, students find it easy to reason, qualitatively, why this is so. In a connected IE room, students compare this behavior with that

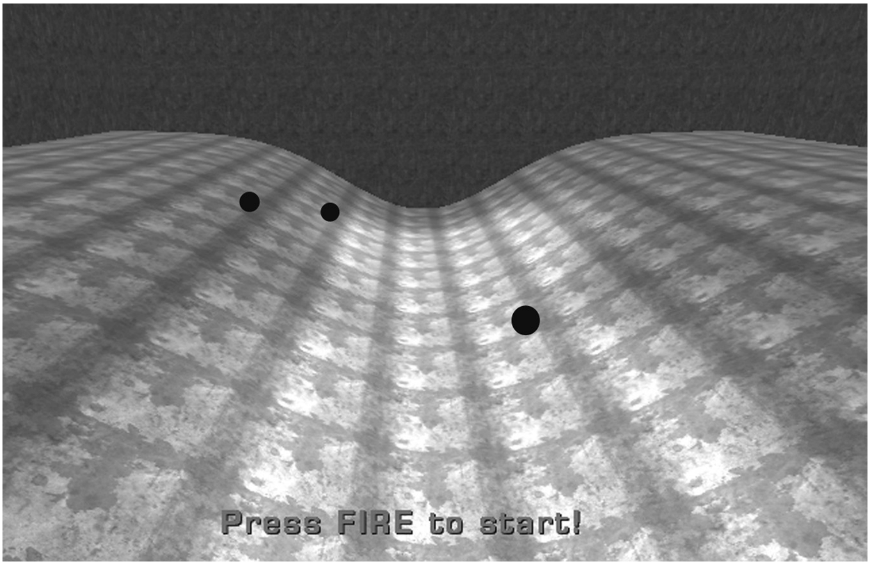

FIGURE 2: Three balls are positioned to oscillate in the potential field represented in the immersive environment as a terrain hill

produced by another field based on the function $y = ax^2 + c$. Here, all balls oscillate with the same frequency. Again, students can reason, qualitatively, why this is so.

Quantitative physics

Although we advocate the use of qualitative physics as a first step in learning, the activities of professional physicists must also be acknowledged. These activities involve experimentation, the construction of theories, computational-numerical analysis, and finally simulation of the underlying mathematics. Can a commercial game's physics engine be used to mirror these activities? UT2004's Karma physics engine was designed to accurately reproduce the behavior of individual objects and also interactions among these objects according to a precise mathematical (dynamic) system of equations. We investigated the use of this engine to produce virtual physics experiments with the intention of making meaningful quantitative measurements. These measurements were related to underlying mathematical formulas, such as the parabolic motion of an object moving under gravity. We programmed various UT2004 actors, which can log experimental data ready for analysis and comparison with theory. These are placed in various IEs, into which students are immersed and in which they conduct experiments by changing initial conditions and parameter values. Analysis of the logged measurements can be handled with tools such as Microsoft Excel and compared with physics theory. Our findings are encouraging: In general, we found that it is possible to produce high-fidelity quantitative experiments, but there are one or two caveats (see "Discussion and conclusions" section).

Parabolic motion under gravity

The motion of an object, typically a projectile, has a long history of discussion in physics that may be traced to the pre-Galilean era (Arons, 1965). Contemporary wisdom takes Newtonian (not relativistic) dynamics as the appropriate theory; after all, it got us to the moon and back. We constructed an IE experiment in which an object is assigned an initial velocity in 3D space where gravity is operating. The object is released and, as expected, follows a parabolic path. This path may be observed qualitatively and logged quantitatively. Given the initial components of velocity, v_x^0 and v_y^0, the equation for the parabolic motion in space is given by the classical formula

$$y = \frac{v_y^0}{v_x^0} x + g \frac{x^2}{2(v_x^0)^2}, \tag{2}$$

where g is the value of gravity. Inserting the values from a typical experiment, in which the x and y velocity components were 1,000 and 1,500 Unreal units and gravity was set to –1,500 Unreal units, the above equation becomes

$$y = 1.5x - 0.0075x^2 \tag{3}$$

A screenshot of the experiment is shown in Figure 3a, in which the trajectory of the object has been logged via our programmed actor. The object's location as it moved was recorded in a text file, imported into Excel, and fitted to the theoretical curve (equation 3). The results are shown in Figure 3b, in which clearly, the fit of the experimental data to the theory is excellent (agreement to within 0.1%). Many experiments were performed, with various initial velocities and gravity.

Simple harmonic motion

The concept of harmonic motion is central to physics education, underpinning both classical and quantum mechanics. Its applications range from an understanding of molecular spectroscopy to car suspension systems. We developed a raft of IEs to explore this concept. In the first IE experiment, a mass is connected by two springs to neighboring fixed objects and is constrained to oscillate along a line. The period, T, of the oscillations is given by the formula

$$T = 2\pi\sqrt{\frac{m}{k}}, \tag{4}$$

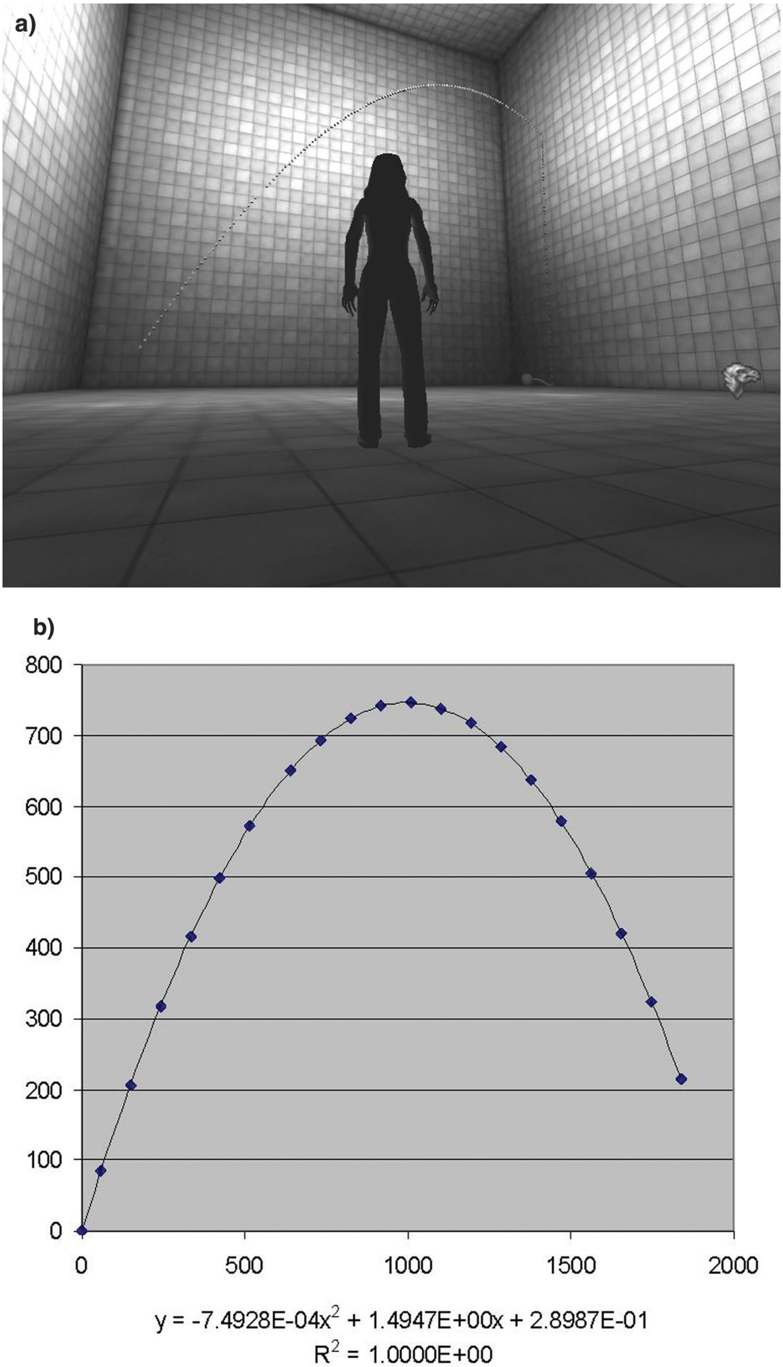

FIGURE 3: (a) Parabolic trajectory in the game; (b) fit of theory to the logged experimental data

b)

Mass	T (Theory)	T (Experiment)	Ratio T(Expt) / T(Theory)
1	0.993	1.1	1.11
4	1.978	2.17	1.09
9	2.980	3.28	1.10
16	3.974	4.34	1.09
25	4.967	5.42	1.09

FIGURE 4: (a) Experimental arrangement, in which the small movable mass at the center is connected to larger static masses by invisible springs; (b) measured and theoretical oscillation periods and their ratio

where m is the object's mass and k the stiffness of the springs (the sum of the individual springs' stiffness). Figure 4a shows the Unreal IE and Figure 4b the results of measuring the period of oscillation for a wide range of masses. Measurements were made by programming the object to record the times at which its velocity reversed direction. Figure 4b shows a comparison of the theoretical and experimental periods, which are clearly not in agreement. In fact, they differ, consistently, by a factor of 1.1. The Unreal physics clock is apparently running an extra 10% slow. This fact has been seen consistently over all experiments we have performed in which time was explicit in the associated formulas. This internal inconsistency has also been reported by the Unified System for Automation and Robot Simulation group (Wang, 2006). This problem does not appear in analysis of experimental results in which time is factored out, such as the parabolic motion experiment described above.

A second series of simple harmonic motion experiments was performed using a simulated pendulum, in which the length of the pendulum was varied. Agreement with the theoretical formula was excellent, but only when the factor 1.1 was taken into account.

Terminal velocity

This experiment consists of an object starting with zero initial velocity that then falls vertically under gravity in a medium with fluid friction (such as treacle). Frictional force is mediated via the "fluid damping" parameter *b*.The object's velocity is seen to rise to a maximum "terminal" velocity, $v_T = g/b$, where *g* is gravitational acceleration. Mathematical analysis of the forces on the object leads to the following equation, which describes the object's velocity as a function of time; the velocity rises toward the terminal velocity:

$$v(t) = v_T(1 - e^{-\frac{b}{m}t}). \tag{5}$$

The observed behavior of an object deployed within our IE clearly conforms to this sort of function (i.e., shape of curve), as shown in Figure 5a. The measured terminal velocity is 749.99 Unreal units, which compares closely with the theoretical value given by g/b = 1,500/2.0 = 750. To further probe the fidelity of this correspondence, we transform the above equation into a straight line by taking the logarithms of both sides,

$$1\text{n}[v(t) - v_T] = -1\text{n}v_T - \frac{b}{m}t\,, \tag{6}$$

and apply the transformation to our logged data. Figure 5b shows the results: The straight line fitted has a gradient of –1.9107, which when corrected by the factor 1.1 becomes –2.102. This compares favorably with the gradient from equation 6, which has a value of $-b/m = -2.0$. We performed an extensive series of similar experiments, varying mass *m* and damping *b*. An interesting result emerged: Whereas damping *b* produced data that agreed with theory, varying the value of *m* had absolutely no effect on the behavior of the object's dynamics! Apparently, someone forgot to include mass in the damping term within the physics engine.

Damped harmonic motion

In this series of experiments, we extend the simple harmonic motion IE discussed above. Damped harmonic motion involves the addition of various amounts of viscous damping, mediated again via the parameter *b*. The amplitude, $A(t)$, of oscillations decays according to the well-known equation

$$A(t) = A_0 e^{-\frac{b}{2m}t}, \tag{7}$$

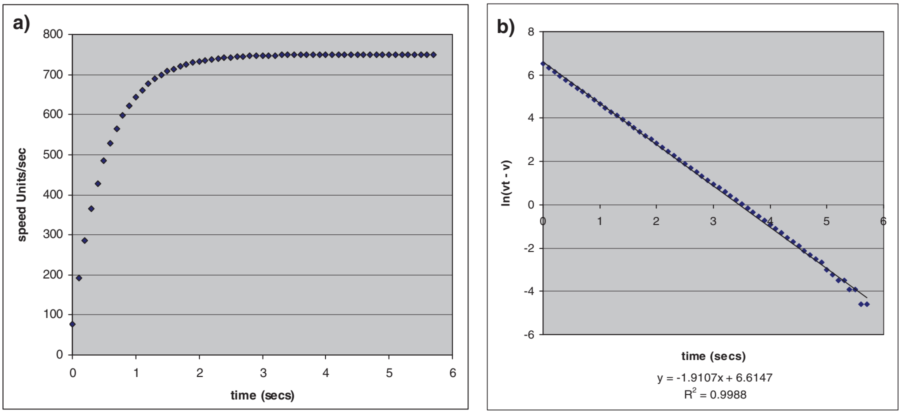

FIGURE 5: (a) Increase of the object's speed with time to its terminal velocity; (b) log-log plot of the same data showing good correspondence with equation 6

which again can be transformed into a straight line suitable for analysis by taking the logarithms of both sides:

$$1\text{n}[A(t)] = 1\text{n}A_0 - \frac{b}{2m}t. \tag{8}$$

Using experimental values of mass (m = 1.0; see above discussion) and damping (b = 0.5), the results obtained are shown in Figures 6a and 6b. Again the observed gradient of –0.2809, when corrected for the 1.1 time factor, becomes –0.255, which is close to the theoretical gradient of $-b/2m = -0.25$. We performed a series of experiments with different values for mass. Although this affected the period as expected, it did not affect the damping, as noted above.

To factor out the dimension of time, we performed a further series of experiments varying the damping coefficient, b, and measuring the experimental damping observed. The results are shown in Figure 7, in which we plot the measured damping, which should be $-b/2m$, for various values of b. The results are encouraging; the expected gradient is –0.5, and the observed gradient is –0.497, which is close. But there is evidently an additional damping of –0.0324 present somewhere in the engine.

Dynamical systems

One area of the "new physics" is the study of nonlinear systems, which are typically described by a system of differential equations. We investigated the feasibility of creating "dynamical objects" whose motion follows dynamics prescribed via such a system of ordinary differential equations. UT2004's programming interface allows the definition of a game object's movement using such differential equations. We

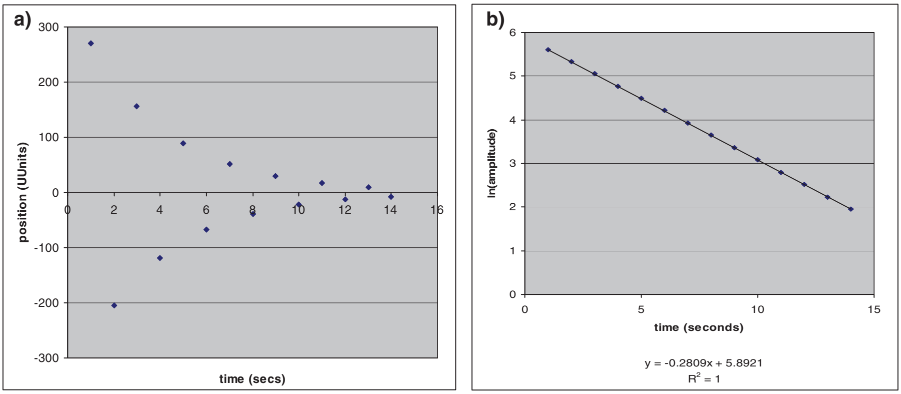

FIGURE 6: (a) Amplitude decaying with time; (b) log-log plot agreeing with equation 8

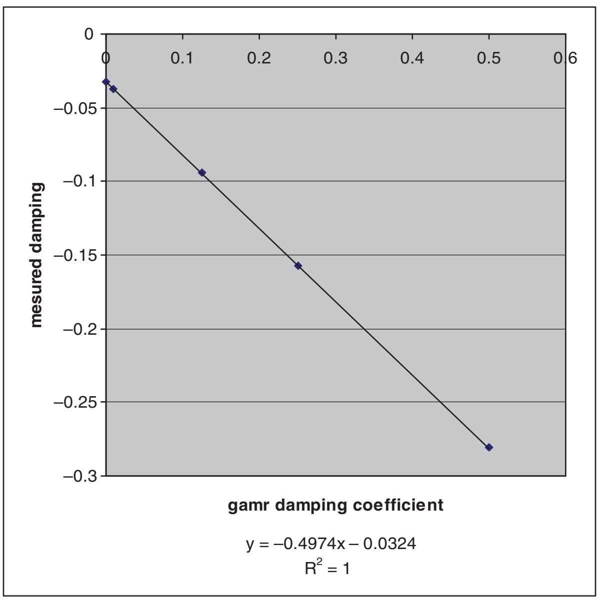

Figure 7: Measured damping for various values of the damping coefficient *b* specified in the game
NOTE: The theoretical gradient is 0.5, and the observed gradient is close to this value.

experimented with the Van der Pol equation and the Lorentz equations. The latter, discussed here, are a system of three equations originating in climatology (Lorentz, 1963; Zwilliger, 1997):

$$\begin{aligned} \dot{x} &= \sigma (y - x) \\ \dot{y} &= x (\rho - z) - y \\ \dot{z} &= xy - \beta z \end{aligned} \tag{9}$$

Solutions to this 3D system of equations are best viewed in a 3D virtual world such as that provided by UT2004. We programmed an actor to behave according to this system dynamics and to drop data points into the level at intervals in time as well as into a log file. The result is shown in Figure 8 for the values $\sigma = 10$, $\beta = 8/3$, and $\rho = 20$. The results agreed with textbook images and online simulations. However, within UT2004, a player is able to wander around the orbit as it is being dynamically created and observe various features, such as the existence of two distinct surfaces containing the orbit and the fact that the orbit does not intersect itself. This 3D qualitative investigation is a useful complement to a theoretical study and textbook 2D diagrams. This investigation confirms the usefulness of UT2004 for solving and visualizing the behavior of complex dynamic systems and thus as a tool for producing a wide range of simulations.

Pedagogical reflections

In this article, I have reflected on three aspects of using IEs to produce educational materials:

1. How should we best use qualitative versus quantitative physics IEs?
2. How can we inform the design of IEs?
3. How can we deploy these materials in various educational settings (i.e., how can we provide an adaptive eLearning experience)?

As far as the best use of qualitative versus quantitative physics IEs, my group proposes introducing learners first to qualitative IEs, with which they will build up concepts and perhaps the relations among them. When these are mastered, quantitative IEs can be introduced, so that links with theory can be made. This proposal rests on the learning psychology of Ausubel (1963, 1968), who suggested that meaningful learning must draw on the previous knowledge of the learner. We propose that qualitative experimentation may provide these first knowledge structures. This psychology underpins Novak's (1998) "concept maps" and has been judged suitable for constructivist learning. Concept maps are 2D graphical devices that attempt to represent and organize knowledge. They were introduced by Novak in his research on how children build up their scientific knowledge. They are also based on Ausubel's theory. They aim to produce a learning structure in the mind of the learner that reflects the knowledge structure of the expert and that is in direct correspondence to

FIGURE 8: Solution of the Lorentz equations
NOTE: The experimenter is free to wander around the data points and view the structure of the attractor.

the associated learning activities. We propose the use of concept maps to define the topology of the various learning rooms within the IE. An example, the study of harmonic motion is shown in Figure 9. At the top are found physical laws, their expression in the quantitative theory of dynamic systems, and the procedures of data analysis. Moving downwards we find concepts and various experiments. Links between concepts are shown by arrows, which may be labeled. Concepts are arranged in a hierarchy with the more inclusive close to the top. Another feature associated with concept map theory is that the links may change as the learner progresses. This is possible within our methodology when the learner, at a more advanced stage, is invited to construct a personal IE containing several rooms representing various concepts. This concept map yields directly a topology that specifies the geometrical layout of rooms and corridoors.

With regard to informing the design of IEs, we propose that both game design theory and the concept map approach may usefully inform the IE design process, especially the "topology" of the IE: which room is connected to which others and why. Learning is also a dynamic process grounded in student tasks and activities. Here, we take on board experiential learning theory, especially the work of Kolb (1984). In his four-stage learning cycle, Kolb suggested that *concrete experience*

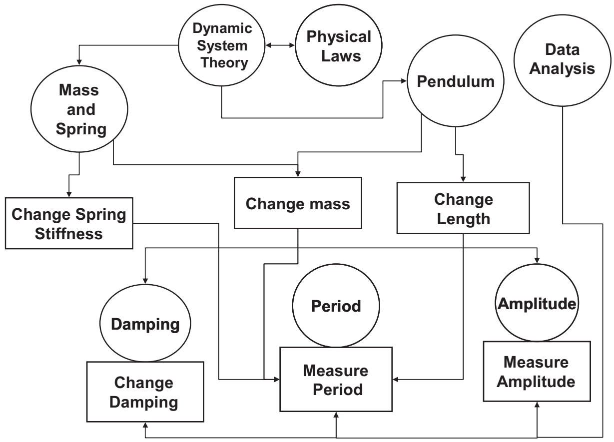

FIGURE 9: Concept map for harmonic oscillations
NOTE: Circles represent concepts and rectangles experiments. This map is used to construct the various rooms of an educational immersive environment.

provides a basis for *observations and reflections*, which are refined into *abstract concepts*, which can be *actively tested* through new experiences. Each of the concepts in Figure 9 may be realized as a cluster of four rooms implementing this cycle. We also embrace theories of collaborative learning, from both the cognitive aspect (Dillenbourg, 1999) and the social aspect (Vygotsky, 1978). Collaborative learning is directly supported by the multiplayer affordance of UT2004, in which groups of students may enter the IE, wearing headphones and microphones, and so work together on solving problems and learning.

As far as deploying these materials in various educational settings, we suggest the following strategies used to deploy educational IEs (informed by the recommendations of the Institute of Physics mentioned above):

1. **Teacher-based**: Here, teachers develop IEs that enable students to investigate physics concepts that are first presented formally and theoretically in class. Experiment follows theory.
2. **Learning by inquiry**: Here, teachers construct IEs with the aim of eliciting student discovery, before the theory is presented (i.e., qualitative physics first). This is the Physical Science Study Committee's (1960) methodology and the Nuffield Curriculum Centre's methodology.
3. **Autonomous and constructivist learning**: Here, we propose that students as well as teachers be instructed how to create IEs. Students will elaborate on the base IEs provided by their teachers; they will construct and evaluate their own experiments. They will become "serious scientists for a day." They will be able to invite their peers into their IEs and engage in peer review and collaborative learning.
4. **Higher education**: Here, the situation is a little more complicated, because ultimately, a deep understanding of quantitative physics must be obtained. We suggest that

students be invited to reflect on what physics behavior (and therefore associated theory) is required to make a good game (i.e., to make a game engine). The corresponding theory is then discussed, and students experiment within several IEs to relate theory and experiment. Numerical and computational aspects of physics may also be discussed.

Virtual physics investigations situated with IEs can have a direct impact on constructivist learning:

1. The actual immersion is extremely compelling and can produce a believable experience (Dede, 1995), making concepts explored more memorable.
2. It has been shown that spatial metaphors can reveal the meaning of data and provide alternative insights (Erickson, 1993).
3. The multiplayer IE naturally supports collaborative learning (Turkle, 1995), in which several students may enter an IE and perform experiments, discussing and interacting via the rich IE audiovisual communication.

Although previous virtual reality systems were cumbersome (involving head-mounted displays, haptic feedback, etc.), IEs produced using commercial games are powerful, inexpensive, and easy to produce. They are compelling, and, most important, they are well understood by youth.

Toward adaptive learning

Much interest is currently being shown in the use of adaptation in learning, especially eLearning, designed to statically or dynamically tailor learning materials to individual learners (Brusilovsky, 1999). A useful classification of adaptive methods applied specifically to hypermedia is found in Burgos and Specht (2006). This classification itself implies a division into pedagogy (e.g., the learner model) and technology (e.g., the use of metadata or intelligent agents). Although we have not yet investigated adaptation to any great depth within our IEs, it may be useful to reflect on the UT2004 engine affordances and to align them with the Burgos-Specht classification:

1. Those learning-process components that may be adapted. Good examples are of sequencing components and providing remedial help. This is easily incorporated into an IE in which doors may open after students successfully solve a quiz, introducing the next component activity. Similarly, remedial, extension, and "hints" rooms may be connected and selectively opened. See also Brusilovsky (2001).
2. The learner model provides information used for adaptation. An assessment of learners' progress through the IE can inform adaptation. Also, the learners may do this autonomously, for example, through choosing to revisit various concept rooms and cycle through the Kolb clusters until sufficient confidence is obtained to progress.
3. The system must gather information to direct the process of adaptation dynamically. Our IEs may make explicit measurements, such as the results of quizzes, or else measure implicitly through the recording of the learners' behavior (rooms visited, time spent there, activities started and completed) as they progress through the IE. For example, a lack of full coverage of the whole concept map and reluctance to engage with the Kolb clusters would suggest surface learning.

4. Why does the system adapt? This focuses on the pedagogical models based on adaptation. As well as concept mapping and experimental learning theory, we also suggest that "collaborative adaptation" is important here and, as mentioned above, comes "for free" in a multiplayer game. We are currently programming nonplayer characters based on artificial agent technology that will "mentor" learners moving through an IE.

Our technical evaluation of the UT2004 engine considering the above alignment of adaptation categories with UT2004 affordances suggests a potentially new area for research and development. The bottom line is the powerful nonlinear IE topology, coupled with the learner interactivity and potential for collaboration.

Discussion and conclusions

The research discussed in this article has been carried out in parallel with course development at the University of Worcester, in particular our new degree course in computer games and multimedia. Also, as part of our widening participation activities, we have run "game development camps" for 2 years. These have involved schoolchildren (ages 16 to 18) and their teachers in the production of IEs using UT2004. We observed how easily both students and teachers mastered the construction of sophisticated IEs following about 2 hours of training. We have also conducted a pilot study to investigate the efficacy of qualitative physics materials with secondary school physics students and their teachers. Together with our quantitative investigations, these activities provide an evaluation of our proposal. In this pilot study, teachers were asked to scale the fidelity of the IE (i.e., how well the IE manifested true physical phenomena). The students' learning was evaluated by attitude pre- and posttests using a Likert-type scale. Students were asked to answer questions such as "How well do you understand the concept of harmonic motion?" which were presented before and after exposure to the associated IE. The results, shown in Table 1, are informative.

There is a correlation between the students' expression of learning experience and the teachers' expression of fidelity. When the teacher viewed the IE as providing a good metaphor of a physics situation, the students indicated that they had learned. For example, Newton's cradle clearly did not work well according to the teachers, and the students did not learn from this IE. Although these IEs present qualitative physics to students, they have nevertheless been constructed using quantitative physics. The reason is simple: The quantitative mathematical approach currently provides the best understanding of the real world, even though we may not understand why (Wigner, 1960). Constructing our IEs using quantitative physics ensures that they are qualitatively viable.

Concerning quantitative physics, we have engineered some 30 or more IE experiments. We conclude from these probing experiments that UT2004 is capable of producing experiments that agree with theory. However, there are caveats. Currently, we have identified the following limitations of the UT2004 engine:

TABLE 1: Evaluation of qualitative experiments

Topic	*Fidelity (teacher)*	*Learning Experience (student)*
Gravity and collisions including rigid-body dynamics	5	4.5
Energy levels visualized with interacting balls	5	4.5
Investigation into momentum	4	4.0
Simple pendulum	5	4.5
Newton’s cradle	1	0.5
Diatomic molecule	4	2.0
Simple harmonic motion	4	4.5
Normal modes of oscillation	1	1.0
Coupled pendulums	3	2.0
Solitons	1	1.0
Finite state machine	5	4.5
Potential hill (harmonic potential)	4	4.0
Potential hill (anharmonic potential)	4	4.0
Electron gun potential surface	4	3.5
Snake	5	4.5

NOTE: For each topic, the teachers’ evaluation of fidelity (how well the immersive environment represents real physics) is scored on a scale ranging from 1 to 5. The learning experience of students is the average response on Likert-type pre- and posttests. There is a clear correlation.

1. Time runs slow by 10%.
2. The object mass has been omitted from the damping calculations.
3. There appears to be a small amount of “hidden” damping in the engine.
4. In experiments involving colliding objects, although momentum is conserved, the energy calculation is incorrect.

Two parameters involved in this calculation, the “coefficient of restitution” and the objects’ masses, do not correctly describe (or influence) the correct behavior of colliding objects.

This investigation has probed one game engine to evaluate its usefulness in producing educational materials. What have we learned from this investigation?

1. The UT2004 physics engine is capable of supporting quantitative experiments, with the caveats mentioned above.
2. It is possible to export numerical data to be analyzed using other applications, such as Excel.
3. The construction of experiments is straightforward and is feasible for teachers and students.
4. The scripting interface of UnrealEd allows the programming of new actors that can be added into the engine.
5. Qualitative experiments developed with UT2004 have a clear impact on learning.
6. Concept maps provide a good design methodology, although other approaches need to be researched.
7. The multiplayer aspect of UT2004 provides a natural stage for collaborative learning.

How can other practitioners engage with our work?

1. This article provides a justification for the use of UT2004 in physics education, through the results of our scientific investigation into its workings.
2. We have suggested a theoretically based design methodology.
3. We present examples of IEs on associated Web pages to allow practitioners to review our work.
4. We provide online tutorials to allow practitioners to learn how to construct IEs.

In conclusion, we have performed an investigation to probe the usefulness of the UT2004 physics engine to develop educational materials. Our evaluation criteria have been

1. the ability of students and teachers to produce IEs
2. the efficacy of qualitative physics experiments in education
3. the fidelity of the UT2004 physics engine to generate numerical results that agree with physical theory

The results of our investigations are positive in these three areas, with some caveats in the latter. There are, however, some clear limitations: The UT2004 physics engine has been designed to provide a believable gaming experience, but this is based on mechanics and fluids (waves). Other physics topics (e.g., electricity) are not explicitly supported and so must be generated by analogy or metaphor. For example, electrical conduction (resistance, Ohm's law) can be simulated by colliding bodies (electrons and atoms according to the Drude theory). This is another project, the development of "metaphorical physics," yet we hope that our research will inform and motivate physics educators to reflect on the potential affordances of computer game technology and to construct their own IEs.

Note

1. Available at http://www.worc.ac.uk/departs/bm_it/colin/index.htm

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