Learning physics with the Unreal Tournament engine

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Abstract
Computer games such as Unreal Tournament (UT2004 and UT3) contain a 'physics engine' responsible for producing believable dynamic interactions between players and objects in the three-dimensional (3D) virtual world of a game. Through a series of probing experiments we have evaluated the fidelity and internal consistency of the UT2004 physics engine. These experiments have then led to the production of resources which may be used by learners and teachers of secondary-school physics. We also suggest an approach to learning, where both teachers and pupils may produce learning materials using the Unreal Tournament editor 'UnrealEd'.

Introduction

Commercial computer games such as Unreal Tournament 2004 and Unreal Tournament 3 (http://www.unrealtournament3.com/uk/index.html) contain a physics engine subsystem responsible for creating a believable virtual world of interacting objects and participants. Many are equipped with an editing tool (e.g. 'UnrealEd') which allows the construction of games or 'immersive environments' (IEs) from scratch, and include 'scripting' programming systems allowing the specification of classes of game objects' behaviour. These editing tools and the underlying software provide a platform whereby both teachers and students may produce educational materials.

This article presents the results of our investigations of UT2004 which were conducted with two aims; (i) first, to probe the fidelity and internal consistency of its physics engine, (ii) second, to develop virtual experiments for use by pupils and teachers in secondary education. We discuss a range of examples of virtual experiments to illustrate our approach and supplement these with on-line resources for teachers and pupils to review our investigations, and also an on-line tutorial to encourage both teachers and pupils to develop their own IEs.

Of course there are many on-line resources to assist in learning physics, such as the increasing number of interactive Java applets. However, IEs have significant additional features: (i) they can easily be constructed by teachers and learners without any programming expertise, (ii) they can visualize interactions between rigid bodies in three dimensions, (iii) they support *collaborative experimentation*, in which several students may enter an IE, perform experiments together, share results and peer-review each other's work; this uses the multi-player facility of the game engine, (iv) they allow construction of new experiments by teachers and pupils; for example, an experiment designed to investigate the collision of two objects (conservation of momentum) may be easily extended into a project investigating Newton's cradle.

Many physics teachers may have experienced 'Gary's Mod 2007', a modification of the 'Half-Life' game engine which provides a rich toolkit

Figure 1. Visualization of interference of waves emitted from two point sources. The sources are more widely spaced (left) and more closely spaced (right).

to construct complex ‘Heath Robinson’ devices as well as more modest physics experiments (see Gary’s Mod 2007). This toolkit hooks directly in to the physics engine. The IEs generated tend to provide qualitative visualizations, whereas the focus of our work is on the generation of quantitative data which may then be used by students in their analytical activities. While the examples we present in this article are of individual experiments, we have also investigated the construction of game levels containing many rooms to explore a particular physics concept. Our resulting design methodology, based on notions of concept maps and experiential and collaborative learning theory, can be found in Price (2007a). The basic approach is to use the ‘knowledge structure’ of the expert-physicist to construct the topology of a series of interacting rooms containing experiments, theory and reflective activities for the students. We regard the ‘from pedagogy to technology’ approach as a useful methodology for the construction of educational materials.

The priority of physics engine design is to get the dynamics of mechanical interactions right. Physics is, of course, more than this. We have used the UT2004 engine to construct investigations into wave phenomena. We have also demonstrated that it is possible to ‘code’ general dynamic systems, so we may for example investigate the charging of a capacitor through a resistor, from a voltage, or a current source.

This article presents a range of virtual experiments we have produced. Further examples are available at the author’s website (Price 2007b). In the section ‘Reflections, evaluation and conclusions’ we reflect on the studies we have made, and indicate some limitations of the UT2004 engine we have uncovered.

Some examples and discussion

We provide a range of examples which show how IEs may be constructed using UT2004 to provide both qualitative and quantitative experimentation. The quantitative experiments produce data recorded in ‘Unreal Units’ (UUs); we do not labour with a conversion to the MKS system.

Interference

Here two ‘fluid surface oscillators’ are inserted into a fluid surface. The wave-speed and frequency of oscillation can be specified. The results, shown in figure 1, clearly demonstrate a good qualitative simulation for two separations of the oscillating point sources. This is a good analogue of Young’s slits experiment. The quantitative agreement is also good; for a point source separation of 608 UUs and measured wavelength of 100 UUs, the angle to first interference minimum is calculated at 4.7° from theory, which compares well to the experimental measurement of 4.5°.

Chaos—coupled bars

It is well known that two linked bars or pendulums may demonstrate chaotic dynamics. Figure 2 shows a screenshot of such a situation. Observing the motion of the bars in the IE, the chaotic motion of the bars is clear to see. The bars

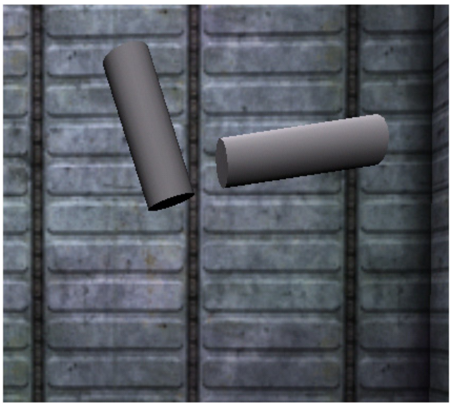

Figure 2. Chaotic movement of two linked bars. The lower bar is connected to a point about a third of the way up the top bar. The top bar is pivoted close to its top.

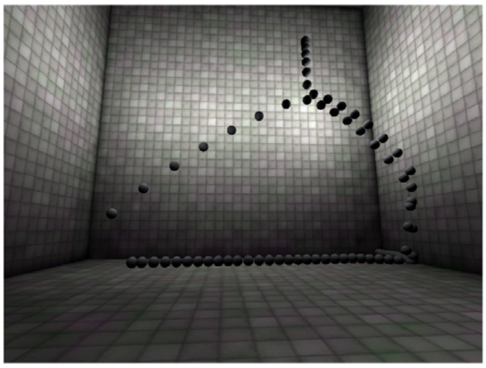

Figure 3. The monkey and hunter experiment. Two balls are shown moving in gravity. The leftmost ball, starting near the floor, is given an initial velocity directed at the right ball which starts near the ceiling. The inevitable collision is visible.

were programmed to log their location in a data file; analysis also revealed movement to chaotic dynamics.

Monkey and hunter

This is a classic experiment demonstrating the independence of motion in orthogonal directions, here in a uniform (gravitational) field. The hunter, on the ground, fires a bullet directed at a monkey who is hanging in a tree. At the instant of firing, the monkey lets go of the tree and falls vertically under gravity. The result surprises many students; providing the aim is good, the bullet will always find its target, irrespective of the bullet's speed and the value assigned to gravitational acceleration. Figure 3 shows this in action. Here students may change the bullet's initial velocity and confirm the behaviour.

Activation energy

A dynamic visualization of activation energy may be also of use to teachers of chemistry. Here, two rooms are connected via a passageway as shown in figure 4. Each room has a different floor height which corresponds to a different energy of the associated system state. The passageway represents an energy barrier between the states. This is metaphorical, using gravitational potential energy as a metaphor of system state energy. After a while, a dynamic equilibrium is observed (following collisions of spheres with each other and the room boundaries), and a distribution of balls between the lower room (more balls) and the upper room (fewer balls) is obtained. But this is a *dynamic* equilibrium with balls continuing to make transitions between the two energy states.

Light-gates

This well-known experimental use of light-gates in many mechanical measurements, such as free fall under gravity, the study of collisions, and the determination of velocity of projectiles, can be easily simulated in our IEs. We have programmed light-gate actors which log the time when an object intersects with the gate. The logged data may be used as usual to study the dynamics of the object. Figure 5 shows such an experiment, here presented in the editor window of UnrealEd, where the student or teacher constructs the experiment.

Forced harmonic motion and resonance

To probe the quantitative fidelity of the UT2004 physics engine we have programmed two actors which apply a driving force to a damped oscillator. The first applies a step force, which is useful for measuring the natural frequency of oscillation of the damped oscillator. The second applies a sinusoidal force whose period may be varied. A typical experiment involves measuring the amplitude of the driven oscillator as a function of the frequency of the driving force. If ω_0 is the natural frequency of the undamped oscillator and ω_d is the frequency of the driver, then

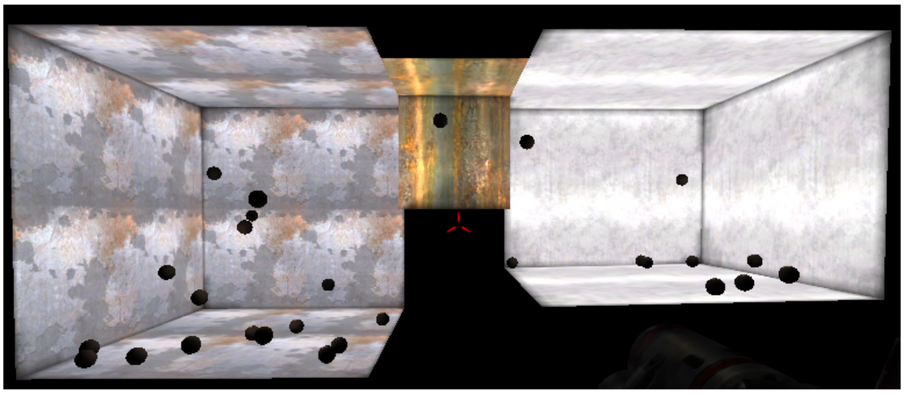

Figure 4. Qualitative investigation of 'activation energy'. This is a metaphor for activation energy where two states of differing base energy are connected via a barrier.

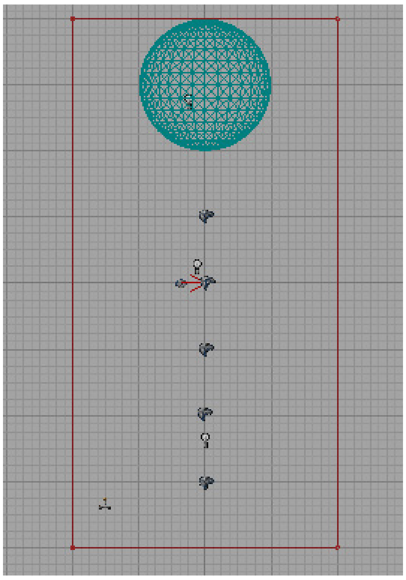

Figure 5. The use of light-gates to study motion can be simulated in our IEs. Here, a sphere falls under gravity through a series of light-gates which record the time of intersection.

the amplitude $A(\omega_D)$ of the driven should vary according to

$$A(\omega_D) = \frac{F_0}{m} . \frac{1}{\sqrt{[(\omega_0^2 - \omega_d^2)^2 + b^2\omega_d^2/m^2]}}, \quad (1)$$

where F_0 is the amplitude of the driving force. A series of experiments for various values of damping b was performed. Figure 6 shows the results of one experiment for parameters

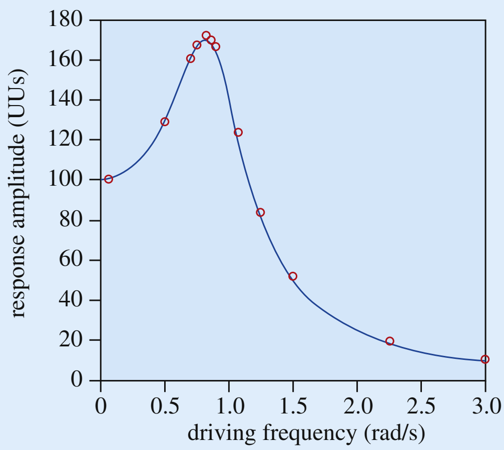

Figure 6. The circles show experimental measurements of the oscillator amplitude for various driving frequencies. The curve represents the theoretical prediction, see (1).

$m = 1, k = 1, b = 0.61644$. This value of b was chosen to lower the resonant frequency by 10% from ω_0.

The predicted amplitude from (1) has been calculated using values of ω_0 and ω_d corrected by a time factor 1.1 (see the section 'Reflections, evaluation and conclusions'); there is clearly good agreement between theory and experiment.

This example also illustrates the power of the IE to produce a compelling visualization of physical phenomena. Observing within the IE, the experimenter sees the initial transient decay away, and then the emergence of regular oscillations. The phase relationship between driver and driven

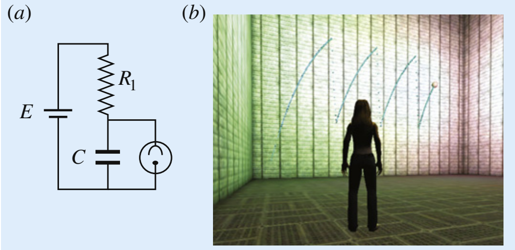

Figure 7. (*a*) On the left is an electrical relaxation oscillator circuit. (*b*) The right side shows the IE visualization of the dynamics of the voltage across the capacitor.

is strikingly visualized, from in-phase below resonance and out-of-phase above. But most of all is the compelling visualization of the $\pi/2$ phase relationship at resonance.

Relaxation oscillator

As mentioned above, the UT2004 physics engine mainly supports mechanical experiments. The question arises, how can we use this engine to study non-mechanical phenomena, such as electrical circuits? We do this via an implicit approach: we have programmed actors which can solve a set of ordinary differential equations (ODEs), linear and nonlinear, and so visualize the behaviour of general dynamic systems. The example presented here involves the use of resistor–capacitor (RC) circuits, as applied to the study of a relaxation oscillator. We have also investigated the Van der Pol oscillator and the Lorentz equations. An RC experiment is shown in figure 7(*a*). A capacitor C is charged from an emf E through a (large) resistor R_1. When the capacitor voltage V reaches the striking voltage of the neon tube, V_S, then the resistance of the neon tube drops from infinity to a low value R_2. The capacitor then discharges through the neon, until its voltage falls below the extinguishing voltage of the tube V_E. At this point, the neon returns to its infinite-resistance state and the capacitor starts charging once more. The process is clearly cyclic, visible in the IE, figure 7(*b*), where data points have been spawned at regular time intervals.

A little analysis leads to the formula for the period of oscillation (assuming R_2 is zero),

$$T = R_1 C \left[\frac{E - V_E}{E - V_S} \right]. \tag{1.1}$$

Table 1. Experimental and theoretical periods for the relaxation oscillator of figure 6.

$R_1 C$	T_{exp}	T	T_{exp}/T
2.5	2.76	2.75	1.004
5	5.54	5.49	1.009
7.5	8.27	8.24	1.004
10	10.94	10.99	0.996
12	13.27	13.18	1.007
15	16.47	16.48	0.999

Our UT2004 actor is programmed to solve the charging ODE and the discharging ODE, which are, respectively,

$$R_1 C \frac{\mathrm{d}V}{\mathrm{d}T} + V = E, \qquad R_2 C \frac{\mathrm{d}V}{\mathrm{d}t} = -V. \tag{1.2}$$

Experiments were performed with the parameters $C = 1$, $E = 10$, $V_S = 7.5$, and $V_E = 2.5$, for a range of values of R_1. The observed and theoretical oscillation periods are compared in table 1. Agreement between theory and experiment is clearly excellent.

Reflections, evaluation and conclusions

Through construction of a large number of IEs we have demonstrated that UT2004 may provide useful qualitative and quantitative learning materials for use in schools. Our experience of working with school children and their teachers has been rewarding and informative. Over the past two years we have invited local schools to spend a whole day learning how to create IEs using UT2004. This project has chalked up some 400 student-hours of activity. We see that familiarization with UnrealEd is rapid; after only 2 h of instruction both students and teachers work autonomously to generate individual IEs following their individual inspiration.

We have also conducted an in-depth scientific investigation into the accuracy and fidelity of the UT2004 physics engine, only hinted at in this article. Through extensive experimentation with various IEs and analysis of the resulting numerical data we have unearthed the following caveats concerning the usefulness of UT2004 in this context. (i) The game engine runs 10% too slow. This means that whenever time is explicitly used (e.g. in oscillation experiments) there needs to be a correction factor. When time is implicit (e.g. parabolic motion under gravity), then no correction is necessary. (ii) In situations involving damping, e.g., terminal velocity, or damped harmonic motion, the mass of the object as well as the damping coefficient of the medium is a significant factor. The UT2004 physics engine ignores the value of mass in computing the damping factor. (iii) Collisions are not accurately simulated. Realistic values of the coefficient of restitution seem not to work, and they seem to be linked to the masses of colliding objects.

Nevertheless, we suggest that UT2004 can provide students and teachers with an important resource for the study of many physical systems. An associated website at (Price 2007a) contains materials and tutorials to enable teachers and students to explore our ideas further.

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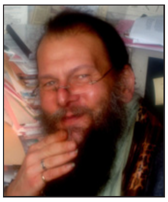

Colin Price started his career teaching physics at the British School of Brussels, Belgium for some six years. After obtaining a PhD in electronic engineering from the Catholic University of Leuven he joined the university staff and taught physics to first year undergraduates. He is currently Principal Lecturer in Computing at the University of Worcester where he teaches computer game development, Java programming and concepts and philosophy of computing. His research interests involve computer science education, theory and application of serious games, and self-organising pattern forming systems in biophysics. He collaborates in teaching and research with Moscow State University.