Applying Virtual Reality in Education: A Prototypical Virtual Physics Laboratory

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Abstract

A prototypical "virtual" physics laboratory has been constructed that allows students to control the laboratory environment as well as the physical properties of objects in that laboratory. Those environmental factors that can be controlled in the current implementation include gravity (both magnitude and direction), surface friction, and atmospheric drag. The coefficients of restitution of elastic bodies can also be altered. Trajectories of objects can be "traced" to facilitate measurements. The laboratory allows students to measure both displacements and elapsed time. Time may be "frozen" to allow for precise observation of time-varying phenomena. This laboratory will ultimately be extended into the macroscopic and microscopic domains—giving students access to direct observations that were heretofore impossible. This new application of computer graphics in education has the potential to augment or replace traditional laboratory instruction with approaches that offer superior motivation, retention, and intellectual stimulation.

Introduction

The strongest arguments prove nothing so long as the conclusions are not verified by experience.
Roger Bacon, *Opus Tertium*

Those intimately involved with education generally agree that "experience is the best teacher." The sad reality of the educational process, however, is that students are seldom given opportunities for *direct* experience of that which is to be learned. Students typically cannot relive history, conduct critical experiments, explore remote sites, or view their world through the eyes of those from other cultures or ethnicities. The best that can be offered in today's classroom or laboratory includes the reading of surveys or classics of past eras, participation in often anemic and stylized laboratory experiments, and the observation of other regions, cultures, or peoples through the two-dimensional images of photography or video. Those few who have acquired direct experiences (perhaps through field trips, apprenticeships, or exchange visits) during their education are usually characterized by increased motivation and attention during those periods in addition to superior comprehension and retention of the key elements that were a part of those experiences.

For centuries the principal media used in the educational environment have been the spoken and written word. Only in this century have recorded images (in photographs, slides, movies, or video) and sounds been introduced into schools and other learning centers. Yet, even with the most modern of audio-visual technology and the best prepared of teachers, classrooms and laboratories often remain sterile habitats in which students learn inefficiently and incompletely. The preparation of students for a world that is increasingly complex and culturally diverse has become, at best, difficult and, at worst, unachievable.

Emergence of Virtual Reality Technology

A rapidly maturing technology, first proposed in the 1960s [1,2,3], now offers an unprecedented avenue for the delivery of experiential education to students of all age levels and in all disciplines. Generally found under the rubric "virtual reality" (or "virtual environments," "synthetic environments," or "virtual worlds"), this technology can provide both visual and auditory information of such fidelity that the observer can be "convinced" that he or she is actually in another place [4,5]. Further, the technology also permits direct interaction with the "virtual" environment so that the observer, rather than being passive, becomes an active participant in events that occur in that environment [6,7]. This paper reports efforts to explore this technology (largely confined at this time to advanced military, engineering, and architectural applications as well as entertainment) in the context of physics (basic mechanics) and to develop fundamental metaphors for its future application to education in many disciplines and at all levels.

Extensive research and development in virtual environment technology has been stimulated by its application in areas such as engineering design [8], architecture [9], data visualization [10,11], and teleoperation [12]. Although virtual environment researchers have always recognized the profound effect that the technology could have on education, only modest efforts have been made in this direction. The few education-related projects currently underway are typically directed at providing students with the tools needed to construct their own virtual world and the ability to explore that world [13,14,15,16], rather than developing a reality whose implicit structure is based on pedagogical principles. Thus, this project explores new territory in the application of this collection of computing technologies to instructional design and science education. The work described here will play a critical role in defining the model for the educational application of virtual environment technology at the most appropriate moment—the emergence of low-cost, high-performance virtual environment hardware designed primarily for entertainment. The results of this activity will not only provide the basis upon which a myriad of virtual environments for education will be constructed, but it can also provide a means of gathering evidence of the technology's effectiveness and accessibility in educational settings.

The Problem

The Virtual Physics Laboratory was designed and built to address many of the well-documented misconceptions that physics students typically carry with them as they enter—and leave—physics courses [17]. Clement [18] refers to these as "conceptual primitives." These include misconceptions about the nature of mass, acceleration, momentum, charge, energy, potential difference, and torque (key concepts), as well as Newton's laws, conservation laws, the atomic model, and electron flow models for circuits (fundamental principles and models).

Conceptual primitives form mental constructs, the understanding of which is a basic prerequisite for many higher-order concepts. Many science-oriented students have difficulty understanding these concepts even at the qualitative level, let alone the problems that occur with quantitative formulation. Among common misconceptions are the "position-speed confusion" (ahead = faster) [19,20] and the "motion implies force" notion [21,22]. Not only are these misconceptions strongly held by students entering a physics course, but the evidence is impressive that they are very difficult to change with conventional approaches to instruction [22]. In group teaching, however, difficulties at the qualitative level can easily go undetected since a student's superficial knowledge of formulas and formula manipulation techniques can mask his or her misunderstanding of underlying qualitative concepts.

The Virtual Physics Laboratory

In its current version, the Virtual Physics Laboratory provides support for altering the magnitude and direction of the gravitational acceleration in the laboratory, as well as the magnitudes of atmospheric drag, frictional coefficients between surfaces, coefficients of restitution of objects, and the length of a simple pendulum. In addition, observations and measurements are made possible by controls that "freeze" the passage of time while objects are positioned and/or given an initial velocity. A "trace" feature displays the trajectories of objects in motion and a digital display can provide both time and displacement data. It is hypothesized that the ability of students to directly control usually inaccessible environmental variables and the ability to carry out experiments not possible in real physics laboratories can be a powerful force in aiding students to acquire and to appreciate correct perceptions of the basic physics underlying common phenomena. Moreover, the Virtual Physics Laboratory will be extended to address phenomena that generally cannot be directly observed. For example, one can envision extending this pedagogical metaphor into the realm of Special Relativity. Clearly, the results of Special Relativity can, at best, be termed "counterintuitive." What better way to drive home the unexpected principles of simultaneity, mass increase, time dilation, and length contraction than by allowing an observer to move between a laboratory frame of reference and one moving near the speed of light? The Virtual Physics Laboratory approach could be used to instantiate a "Relativity World" that enables learners to make actual measurements of mass, time, and length in different reference frames and directly compare the results. This same metaphor can be extended into the domain of quantum mechanics—another area of physics that is usually presented in the abstract. For concepts of this difficulty, virtual environments offer the power of an immersive, contextualized, interactive experience as an additional knowledge representation beyond the abstraction of mathematical formulations typical in physics courses.

Hardware and Software Environments

The hardware used to implement the virtual physics laboratory consists of helmet-mounted, color stereoscopic displays [23], a three-dimensional acoustic environment [24], and a system for obtaining input from hand gestures [7]. In addition, the Polhemus magnetic position and orientation system [25] is used to obtain the observer's viewing direction, head position, and hand positions. Two Silicon Graphics 4D/320VGX graphics computers (one for each eye) are used to render the visual scenes for the system. With such a system real-time (approximately 30 video frames per second) performance is possible with graphical environments containing on the order of 10,000 polygons of moderate complexity. The system described here was developed using VPL Research's Swivel 3-D™ (an application for creating three-dimensional objects) and Body Electric™ (an application for describing object relationships and interactions); however, work has already begun to move this Virtual Physics Laboratory into a more complete and powerful software environment (NASA's Solid System Modeler, Stereo Display Manager, and rendering software).

Description of the Virtual Physics Laboratory

Environment

The laboratory environment is modeled after the simplest possible "natural" model for a lab—a large room containing a table (see Figure 1). The walls, ceiling, and floor are clear delimiters of the working space. They are also surfaces against which the objects of the room can rest or collide. Similarly, the table represents a workspace/surface on which students can perform experiments. In addition, the table is an object (see next section) which can be slid along the floor and relocated in the room.

Even though the workspace is finite, the user still has the ability to exit the space. Objects have no physical reality to the user, as the user can "fly" through anything. In early trial runs, users found it disorienting when they flew through one of the walls and found themselves out in an empty space. Turning around, the user can see a large box, namely, the laboratory. Most people are not accustomed to thinking of a room as a large box, since this is not the way that they typically see rooms. Therefore, a cognitive aid was added to prevent the person from getting disoriented.

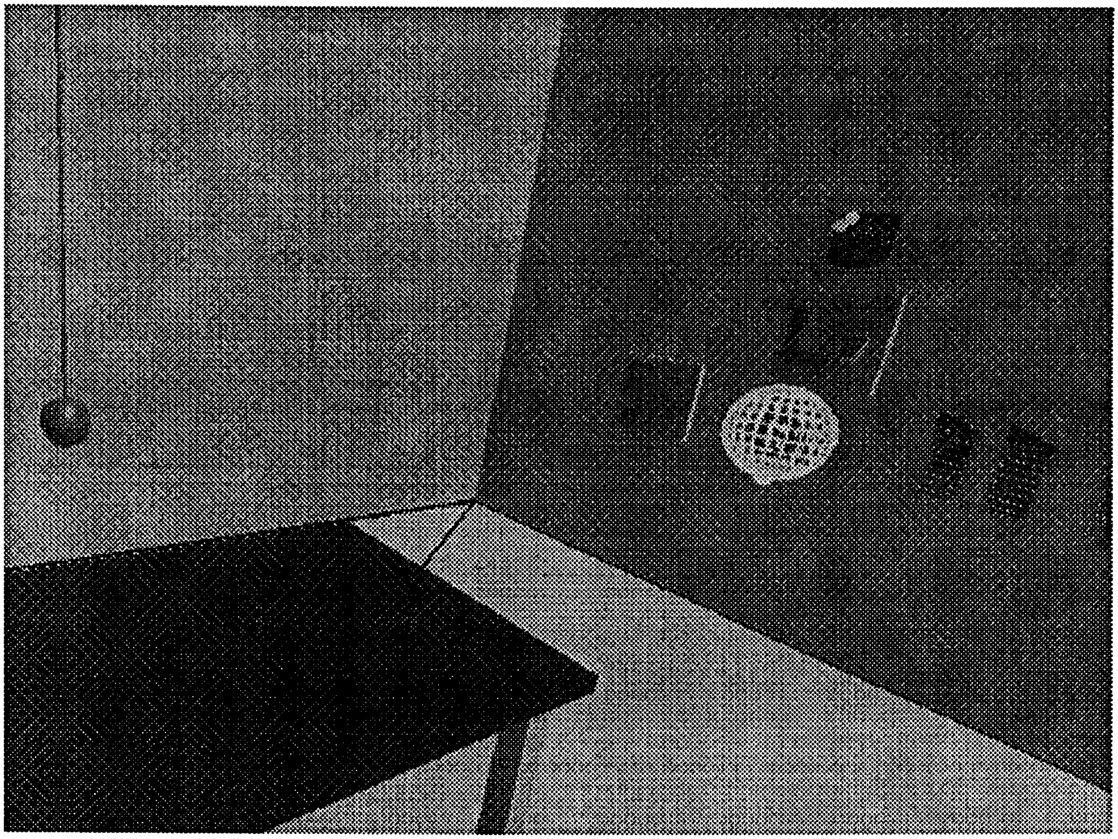

Figure 1. A view of a portion of the Virtual Physics Laboratory, showing the table, pendulum, and controls (grouped on the wall to the right.

The solution implemented here was to render any wall between the user and the lab as transparent. This essentially gives the user a cross-sectional view of the lab. This view looks substantially more natural, because the user can immediately tell that they are looking into the lab from a distance. In fact, this also can help the user get a sense of perspective on the room. Sometimes, due to the limiting nature of the view provided by a helmet-mounted display, it is difficult to get a good sense of perspective for the room as a whole. Using this design, the user can "back away" and look at it from outside, thereby getting "the big picture." Note that while the user is able to leave the laboratory, objects are restricted to the working environment.

Objects

In order to maintain real-time performance, there are only three primary objects in the current Virtual Physics Laboratory prototype. There are two balls, one colored red, and the other blue. There is also a pendulum hanging from a rod mounted on one of the walls. These objects are described as primary, because these are the only objects that actually obey the laws of physics. Additionally, the table is an object in addition to being a surface. Similarly, controls should be considered as objects because they can be manipulated. Each of these objects have a sense of "state." The states of the primary objects are particularly complex and are worth describing in some more detail.

States are characterized by four categories of variables:

- Static variables
  These are the unchanging variables For example, the red ball is partially characterized by its radius. Since the ball's position is determined by the position of the center of the ball, the radius is needed to determine whether the ball is in contact with a surface. The radius is not changeable from within the world.

- External variables
  For an object to obey the laws of physics, it is often important for it to be aware of other factors in the world, besides its own state. Due to the nature of Body Electric™, it was necessary for objects to frequently maintain their own "copies" of information about the external world in their own state. A strict definition of an external variable is any variable in the object's state that must be altered directly due to a change in another object's state. For example, the pendulum length is an external variable, because it is dependent upon the state of the pendulum length control. Another example is the magnitude and direction of gravity in the room. Note that many static variables can be turned into external variables. This is a powerful feature of virtual environments. The static variable of a ball's radius could be varied by a control, thus turning it into an external variable. Hence, the user has gained the ability to alter something that is typically static in the real world. Not all external variables are changed by controls. For example, the predicate "Am I currently being grabbed?" is an external variable because it is based on the location and gesture of the hand (the state of the hand). In essence, external variables are the links that the object has to the world.

- Recursive variables.
  These are variables that must be continuously updated based upon the previous state of the object. This is, in one sense, the most important category of variables. The recursive variables for the primary objects are position and velocity (for the pendulum, it is angular position relative to the direction of gravity and angular velocity). It is the object state represented by the recursive variables that support interaction, physical modeling, and the ability to perform experiments. Since Body Electric™ imposes severe computational constraints, the recursive variables are "updated" through algebraic equations. This presents certain issues and tradeoffs. For example, if the equations are structured to accurately reflect conservation of energy, there may be some slight errors in the way that momentum is conserved. To update the recursive variables, Newtonian mechanics is represented as a recursive procedure that is continuously carried out for each object. Essentially, every object in the system takes turns updating its position and velocity based on how much time has elapsed since the last update. For every cycle of recursive variable updating, a new scene is rendered. Using this method, "true" motion can be reasonably represented. A major difficulty in implementing this approach was the lack of explicit recursion in Body Electric™.

- Internal variables
  These are variables that depend only upon calculations based on other variables (static, external, recursive, or internal) contained in the state. For example, energy is an internal variable that can be calculated from other variables. Similarly, certain predicates such as "Am I resting on a surface?" are calculated from within the object from other variables.

Based on this description of variables, an object may be formally defined as a state (consisting of a list of variable values), along with functions to update the object's state.

The approach taken here (each object "containing" its own code for updating when their are clear similarities between objects) is inefficient. For example, the program as described above essentially says that each object is responsible for knowing about gravity and updating its own position and velocity based on this information. Providing each object access to a universal "function" (like gravity) requires a programming language with the ability to make states into "first class" objects that can be passed as arguments to and returned from functions. This facility is not available in Body Electric™.

Interactions

- Gestures.
  The basic gestures are provided by Body Electric™. The intrinsic hand object mimics the gestures made

with user's glove. Certain gestures are defined to take on significance because they perform certain actions. For example, movement in the world is done by using the glove to "fly" through the world. This is performed by making a "gun" gesture with the hand (clenching the third, fourth, and fifth finger while pointing the index finger in the direction in which one wants to travel) and squeezing the thumb/trigger in order to accelerate in the direction in which the index finger is pointing. Another fundamental gesture is the grabbing gesture. If one is situated near an object, one can grab the object by reaching out, intersecting the hand with the object, and making a fist while contacting the object. As long as one is grabbing the object, one can move the object with the hand. As soon as the hand is opened, the object is released. To enable the user to move in the laboratory while grasping an object, some modifications of the Body Electric™ metaphor were made. A "sticky" mode (aka, the auto-grab feature) was created. When one's hand is in sticky mode, objects will stick to the hand regardless of its shape. The normal grab gesture now works as a toggle in and out of this sticky mode, in addition to its typical action. While the auto-grab feature was intended to allow the user to fly and carry an object at the same time, it is also useful for other things such as "catching" an object. In order to remind the user of the "toggle" state, the palm of the hand is solid when auto-grab is off and transparent (wire-frame) when auto-grab is on.

- Controls
  All the controls are located along one wall. They are grouped in a logical way according to functionality and type of control.

  - Switches.
    There is a simple toggle switch for friction and for air drag, where on is the up position, and off is the down position. The friction switch is labeled with a large "F" and the drag switch is labeled with a large "D." To manipulate a switch, the user simply touches the switch with a flick of the finger (or hand) and the switch will change position.

  - Sliders
    Sliders are used for manipulating variables which a range over some bounded set. A slider has two main components: a graduated panel, and a marker. The marker provides the ability to manipulate and read the current setting. These controls are used to establish the coefficient of restitution for each ball and the length of the pendulum. To operate the slider, the user uses the natural gesture of sliding the arrow up and down with the index finger. Since measurement of parameters (like the pendulum length is necessary), the slider control may only assume certain discreet states (from 0 to 10 feet in one foot increments for the pendulum and from 0 to 1 in 0.1 increments for the coefficients of restitution). A special feature of the coefficient of restitution sliders is the provision for the marker to be slid up higher than the top end of the panel. While it is not clearly marked out at this point, this allows a user to set a coefficient of restitution greater than 1. This means that the ball gains energy on each bounce.

- Gravity Control
  To control gravity's magnitude and direction, a set of reference objects were created, so that the position of the marker makes sense with respect to these objects (see Figure 2). The most important reference point is the origin. This is a small wire-frame ball that indicates zero G. A large letter G surrounds this central point, to denote the control's function. The acceleration of gravity is determined by the vector that goes from the origin to the current location of the marker (another wire-frame ball). For magnitude to be shown clearly, a reference wire-frame sphere that denotes unit G (the acceleration of gravity on the surface of the earth) surrounds the origin sphere. To achieve precision in setting gravity's magnitude and direction, a switch is provided to turn a grid-lock mechanism on and off. The switch is labeled L for lock and is located directly behind and above the gravity control. When the mechanism is on, the marker ball snaps to half-G intervals.

- Measurement Tools
  These tools are grouped together and placed on one small control panel (see Figure 3). The panel provides several facilities that allow the user to make useful observations and measurements in the lab.

  - Digital Display
    The digital display is the most prominent feature on the control panel. The display contains four digits, each of which simulates the functionality of a LED digit with eight segments. Each digit is programmed for the capacity to turn the appropriate segments visible/invisible based on the numeral that it is to be displayed. To provide total measuring capabilities, the digital display can be toggled between two modes. The first mode is a timing display. In the second mode, the digits are organized so as to display distances. There is a circular button directly below the digital display that permits toggling between the two modes. It is important to note that the display mode is independent of the contents of the display. In other words, if one turns on the stopwatch and then toggles over to

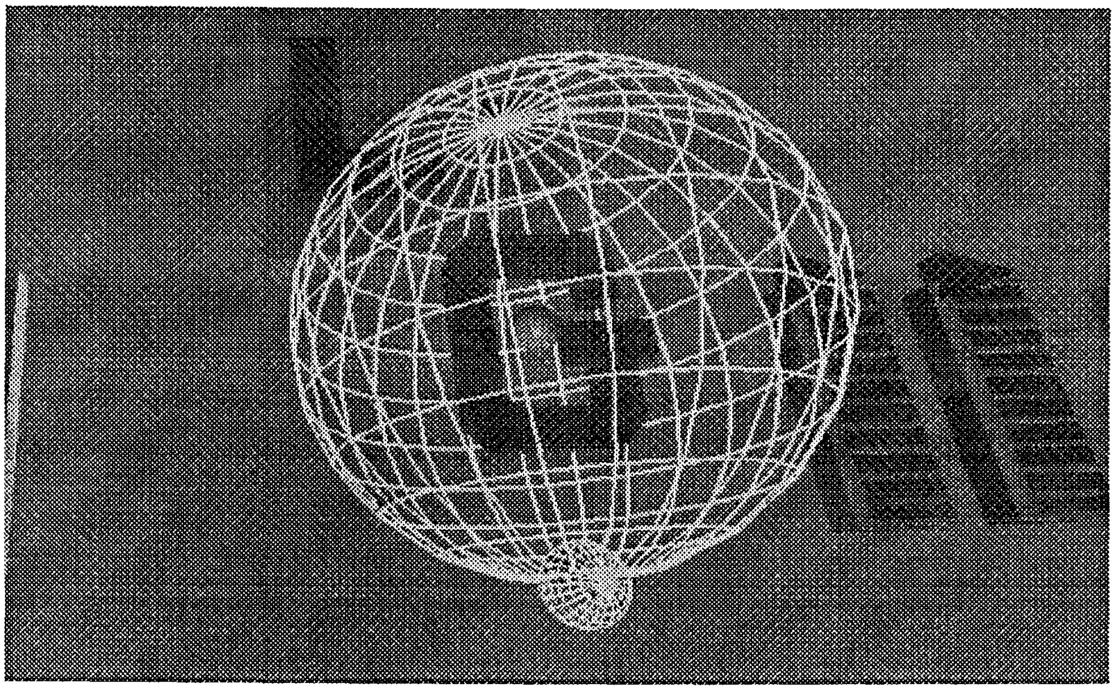

Figure 2. The Gravity Control consists of a large wire-frame sphere, an origin (at the center of the large sphere), surrounded by a large "G," and a marker (shown at the base of the large sphere. The user adjusts the magnitude and direction of the gravity by placing the marker at a apecfic point relative to the origin. The sphere surface representes "1 g."

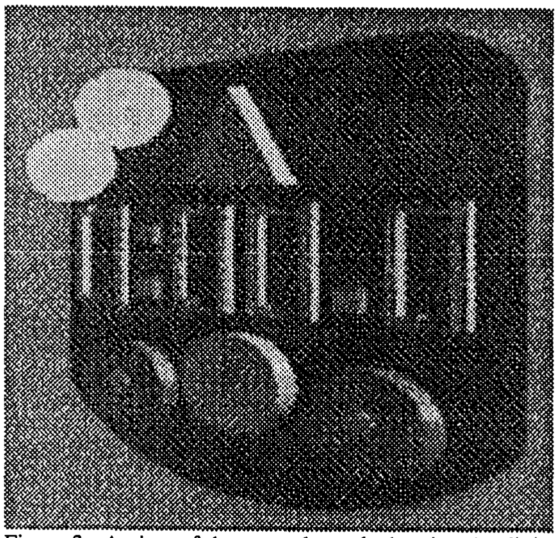

Figure 3. A view of the control panel, showing the digital display (in time mode) and buttons for freezing time, turning the ball trace mode on and off, and toggling between the displays for time and displacement measurement. At the upper left are the two balls used to mark the points between which displacement is measured.

the measurement display, the passage of time is still measured. Switching back to the time display mode, the correct elapsed time is shown.

- Buttons
  In addition to the display mode button, the bottom section of the display contains two additional buttons. These buttons are also toggle buttons, toggling between three modes: normal (the default), tracer on, and tracer on continuously. The "tracer on" traces the motion of one of the balls for a pre-defined distance and then stops. In the "tracer on continuously" mode, once the pre-defined limit is reached, the older portion of the trace is erased as the newer portion is generated. The two tracers can coexist independently.

- Distance Measurement Balls
  On the upper left-hand corner of the control panel, there are two green balls contained in green wire spheres. When both balls are in their containers, the digital display will show no distance measurement reading when in measurement mode. However, if either ball or

both balls are removed from the spheres, then the measurement display will always show the distance between the two balls.

- Freeze Button
  Pressing the button freezes time for the world (all objects in the room cease to move) and the time displayed on the stopwatch. Note that while objects do not move when time is frozen, the user still has the freedom to manipulate these objects. So, for example, a user could grab the red ball from a frozen state, and throw the ball. As soon as the user releases the ball, the ball will freeze immediately in the air (since time is frozen) but it retains the new instantaneous velocity that was imparted to it by the throw. This is a logical solution to the issue of how to let the user interact with a frozen world. Pressing the button again, turns it back off, thus unfreezing time. Also, the stopwatch is reset to zero and begins counting again.

- Reset Button
  The reset button has the functionality of resetting the velocities of the balls and the angular velocity of the pendulum to zero.

- Overall Panel Manipulation
  Initially, the control panel is located on the control wall, directly above the gravity grid lock mechanism. It can be grabbed and moved with the auto-grab mode. A "summoning" gesture was created to enable the user to bring the panel instantly to any part of the room.

Sample Experiments

- Measure the period of pendulum for different lengths and different magnitudes of gravity.

  The controls permit the user to measure the period of the pendulum with different lengths (a typical "real" laboratory experiment) and with different gravitational accelerations (not possible in the "real" laboratory). Atmospheric drag can also be reduced to zero or set to a predefined value.

- Measure the average rate of loss of energy of a ball caused by air drag when dropped from different heights, and under different gravitational accelerations.

  Using the trace and freeze facilities, one can easily record the trajectory of a ball. Varying its coefficient of restitution and atmospheric drag permits the measurement of the energy lost on collision with a surface or through interaction with the atmosphere. It is also possible to drop two balls with different coefficients of restitution and observe their subsequent behavior as they bounce repeatedly from the floor.

- Compare the trajectories (especially range and maximum height) of an object projected in two dimensions with and without atmospheric drag.

  The trace facility allows the user to record the entire trajectory of an object, and the measuring facility provides the means to directly measure range and maximum height. Thus, one can project one of the balls in the room with drag "on" and characterize its trajectory and then repeat the process with drag "off."

Conclusions and Future Work

Work is now underway to re-implement the laboratory using software that is free of the constraints imposed by Body Electric™. Concurrent with this re-implementation is the addition of more objects (such as a spring) and the provision for new experiments (such as the observation of harmonic motion and collisions between objects as well as the effects of Special Relativity and quantum mechanics). In addition, high school and college students will serve as "evaluators" of the virtual physics laboratory's features as a means of improving the ease of use of those features.

This Virtual Physics Laboratory permits students to interact with a compelling visual and acoustic "world". Anecdotal observations have already demonstrated that student attention is complete and motivation to explore the virtual world is high. It is anticipated that experiences in the Virtual Physics Laboratory will provide for an intuitive grasp of complex concepts and vivid retention of what has been experienced. Controlled trials with individual subjects will be utilized to compare learner mastery of physics concepts based on experiences in this type of virtual reality to student outcomes using more traditional approaches (*e.g.*, small-screen, two-dimensional simulations using off-the-shelf commercial software such as Knowledgeware's "Interactive Physics"). This cognitive research will aid in clarifying the relative utility of virtual environments for leveraging learning and will suggest design principles for optimizing the educational value of artificial realities. This system also provides a testbed for the creation of efficient methods for the construction of virtual environments as well as for their application in the educational process. The results of the evaluations to be conducted with both pre-college and college-level students will establish the efficacy of the technology in education (especially in the sciences) and provide the necessary foundation for the successful integration of this technology into the educational infrastructure.

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